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Numerical Study of K-α Emission from Foil Targets Irradiated by Ultrashort Laser Pulses

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1. Introduction

Irradiation of solid targets by ultrashort laser pulses is accompanied by intense X-ray line and continuum emission. Namely, K-α radiation is of particular interest for its efficient generation, very short pulse and synchronization with the laser pulse. The K-α emission from a copper foil target irradiated by an ultrashort laser pulse is studied here numerically using a combination of hydrodynamic, PIC and Monte Carlo simulations. Our PIC code treats plasma ionization and the influence of ionization on the hot electron distribution is studied. It is demonstrated that ionization may significantly change the distribution of hot electrons, when the plasma density profile has a relatively slowly decreasing weekly ionized subcritical part, produced by inherent long lasting irradiation with low intensity ASE. Our new results of K-α emission yield are in a reasonable agreement with experiment [1].

2. Numerical model

Our numerical model calculates the K-α emission in three successive steps. First, we use a 1.5D hydrodynamic/atomic Ehybrid code [2] to treat the laser driven expansion of plasma from a solid target, induced by ASE and by intrinsic laser prepulse. As a significant influence of ASE prepulses on K-α yield even for pulses with low fluence was reported [3], the results of Ehybrid code are used to estimate shape and scale of plasma density profile and its average ion charge at the time of the main laser pulse arrival. Second, the interaction of the main laser pulse with the preplasma calculated by Ehybrid code is computed by our 1D3V relativistic electromagnetic PIC code, which evolved from the code LPIC++ [4]. The code was enhanced to treat both field and collisional ionization, which makes it possible to start the simulations with more realistic initial conditions and follow the evolution of plasma during the interaction. The ionization processes are included in a Monte Carlo probabilistic way, similarly like in [5]. The final step of our model consists in postprocessing of hot electrons resulting from the PIC simulations by our Monte Carlo code [6], which is specially tailored to calculate K-α emission from the target surface with temporal and spatial resolution.

3. Results and discussions

Our calculations were tested on the simulation of experiment [1] performed in Max-Born-Institute in Berlin. The target, 20 μm thick copper foil, is irradiated by a 45 fs, 5 mJ Ti:Sapphire laser pulse. The laser pulse is p-polarized, incident at an angle of 25° and focused to the spot of 6.7 μm FWHM producing the maximum intensity of 10^{17} W/cm^2. The main laser pulse is preceded by ASE and an intrinsic prepulse, which is located 6.5 ps before the main pulse. Their intensity contrast ratios are 10^7 and 10^5 respectively. K-α pulses with 5×10^6 photons/sr and emission spot sizes of about 10 μm FWHM were measured both in the reflection and transmision geometry.

In our Ehybrid simulations, the ASE and the prepulse are approximated by a 1 ns long laser pulse with a constant intensity of 10^{10} W/cm^2 and a 2 ps gaussian pulse with intensity of 10^{12} W/cm^2. As the Ehybrid material data files for copper are not available, therefore we use silver and germanium instead. The results for both elements are very similar hence the same behaviour of copper is expected.

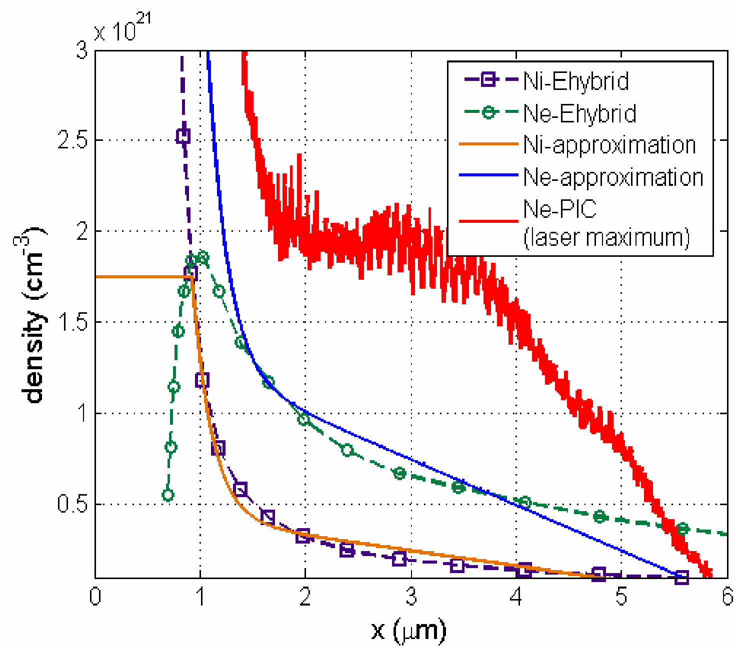

Fig. 1: The ion (Ni) and electron (Ne) plasma density profiles as calculated by Ehybrid code for 1 ns irradiation of Ag target by 800 nm, 10^{10} W/cm^2 laser pulse and their approximations used in PIC simulation. The red electron density profile Ne–PIC is added to ilustrate the evolution of electron density in PIC simulation of laser plasma interaction with ionization.

In the subcritical part of the profile calculated by Ehybrid code (Fig.1), the density decreases almost linearly, while the decrease in the vicinity of the critical surface is nearly exponential and its scale length is 0.6λ. In PIC simulations the Ehybrid profile is approximated by a sum of a linear and an exponential ones. For comparison, we use only the exponential one with an appropriate density scale length, too. A constant initial ion charge Z=3, consistent with the Ehybrid results, is assumed in the whole PIC simulation box. The simulations are carried out both with ionization switched on and off.

The distribution calculated both with ionization and with Ehybrid profile differs more than 2 times in number and about 4 times in energy of hot electrons (Fig. 2). We explain this difference by the field ionization, which takes place in the subcritical region of the profile and which instantly damps the laser wave propagating inside the plasma to the critical point. When the amplitude of the laser wave exceeds the ionization threshold, the electron density in the subcritical region starts to increase very rapidly and a slightly overcritical density plateau, which can be seen in Fig. 1, arises. During the ionization stage, which turns off at about the same time, when the laser pulse maximum reaches the critical surface, this surface moves againts the vacuum, the plasma density scale length changes significanty and only a minority of resulting fast electrons are accelerated. The same situation as with Ehybrid profile, applies, when the exponential profile is introduced but the subcritical plasma layer is much thinner and the effect of ionization on the resulting hot electron distribution is almost insignificant.

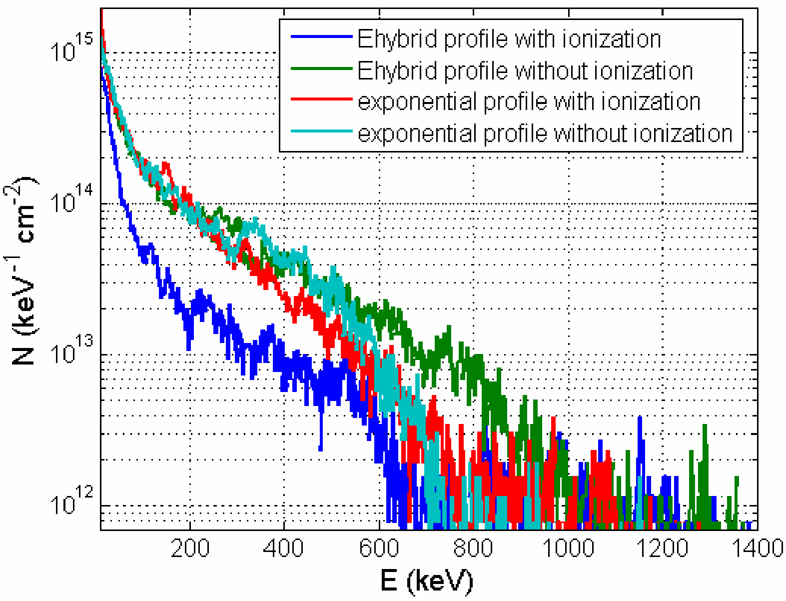

Fig. 2: Hot electron distributions calculated by PIC code with and without ionization. The results denoted by ‘Ehybrid profile’ start with the initial density profile denoted ‘approximation’ in Fig. 1. For comparison, we include the results calculated with only the exponential part of this profile. The parameters are: 45 fs, 800 nm, p-polarized laser pulse with intensity 10^{17} W/cm^2 and angle of incidence 25°.

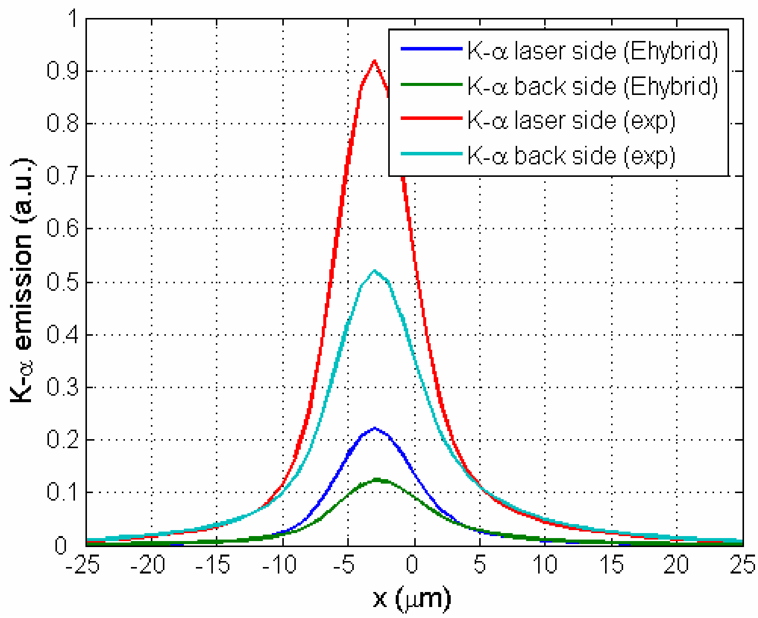

Fig. 3: K-α emission spot sizes calculated by our MC code with hot electrons resulting from PIC simulations. We denote ‚Ehybrid‘ the hot electron distribution plotted in Fig. 2. with blue color and ‚exp‘ the cyan one.

The K-α yield calculated using our MC code with hot electrons resulting in the PIC simulation with ionization and Ehybrid profile is in the best agreement with experimental results, it is only about 2 times higher. All the other MC simulations with PIC hot electrons overestimate the experimental K-α yield almost an order of magnitude. As our PIC code is 1D, the spatial laser intensity profile is taken into account by convolving the K-α spot obtained for a point source of hot electrons with an appropriate gaussian function and the results are presented in Fig. 3. The total K-α emission from both sides of the target differs only within 20%, but the emission region on the laser side is smaller and produces a narrower emission profile.

4. Conclusions

We have numerically studied the generation of fast electrons in PIC laser plasma interaction simulations including the field and collisional ionizations. We have demonstrated that a subcritical weekly ionized part of the plasma density profile, which may develop during the irradiation with ASE preceeding the main laser pulse, may significantly influence the fast electron acceleration mechanism so far as the subcritical plasma may become overcritical due to the field ionization during the laser plasma interaction. The emission of K-α radiation from the target as well as the spot size of this emission were also studied and the results of our simulations, which include ionization and the long subcritical part of the plasma profile are in much better agreement with experimental measurements [1] than the simulations without ionization or with a simple exponential profile.

Acknowledgments

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