NUKLEONIKA 2015;60(2):233–237
doi: 10.1515/nuka-2015-0045

ORIGINAL PAPER

DE GRUYTER
OPEN

Hot electron refluxing in the short intense laser pulse interactions with solid targets and its influence on K-α radiation

Vojtěch Horný,
Ondřej Klimo

Abstract. Fast electrons created as a result of the laser beam interaction with a solid target penetrate into the target material and initialize processes leading to the generation of the characteristic X-ray K-α radiation. Due to the strong electric field induced at the rear side of a thin target the transmitted electrons are redirected back into the target. These refluxing electrons increase the K-α radiation yield, as well as the duration of the X-ray pulse and the size of the radiation emitting area. A model describing the electron refluxing was verified via particle-in-cell simulations for non-relativistic electron energies. Using this model it was confirmed that the effect of the electron refluxing on the generated X-ray radiation depends on the target thickness and the target material. A considarable increase of the number of the emitted K-α photons is observed especially for thin targets made of low-Z materials, and for higher hot electron temperatures.

Key words: electron recirculation • electron refluxing • K-α radiation • laser–plasma interactions • particle-in-cell simulation

V. Horný✉
Faculty of Nuclear Sciences and Physical Engineering,
Czech Technical University in Prague,
115 19 Prague 1, Czech Republic
and Institute of Plasma Physics of the Czech Academy of Sciences,
Za Slovankou 1782/3, 182 00 Prague 8,
Czech Republic,
Tel.: +42026 605 2585, Fax: +42028 658 6142,
E-mail: horny@pals.cas.cz

O. Klimo
Faculty of Nuclear Sciences and Physical Engineering,
Czech Technical University in Prague,
115 19 Prague 1, Czech Republic

Received: 11 July 2014
Accepted: 14 November 2014

Introduction

Fast electrons can be created as a result of laser beam interaction with a solid target [1]. They penetrate into the target material and initialize processes leading to characteristic K-α radiation generation [2]. The collisional stopping range of fast electrons is usually larger than the attenuation length of K-α photons. Thus these electrons may penetrate deep into the target but the photons are absorbed within the target. To increase the conversion efficiency into K-α radiation, the optical path of photons must be decreased, while the length of electron trajectory inside the target should be approximately preserved. This can be done using thin foil targets where fast electron refluxing becomes efficient. Due to the strong electric field induced at the target surface, fast electrons are not allowed to escape but they are turned back and their refluxing increases the K-α radiation yield, as well as the duration of the X-ray pulse and the size of the radiation emitting area. The influence of fast electron refluxing on the K-α radiation is studied here using a simple theoretical model, which is combined with Monte Carlo simulations of the electron transport through the target and of the generation of characteristic radiation. The theoretical refluxing model is based on the theory of isothermal plasma expansion and its reliability is verified here by comparison with a particle-in-cell simulation. Our approach is complementary to the approach presented in Ref. [3], which is based on an analytical model rather than on numerical simulations. Investigations reported in [3] include resistive effects in the stopping power, which is neglected here. On the other hand, in our approach the motion of the electrons and their energy losses outside the target are taken into account.

The simulation models and the obtained results are presented in the next two sections. Section 'Design of experimental setup' contains a proposal for a possible experimental verification of our findings. Our conclusions are summarized in the last section.

Simulations of electron refluxing

In order to validate a model of electron refluxing at the surface of the target numerical PIC simulations were performed using the 1D3V code LPIC++ [4]. A set of electrons was initialized with a Boltzmann–Maxwell distribution in the direction perpendicular to the target surface. Only one temperature of electron was used, which represented the one of hot electrons. Electrons were allowed to expand freely from the target surface while the background (mobile) protons initially had zero temperature. These conditions should approximate the situation in which a bunch of fast electrons penetrates through the target and ionizes its surface contamination layer containing in particular hydrogen atoms. Every electron was accounted for in our simulations. When an electron escaped from the rear side of the target, its energy E_{out} (and time) was recorded and it was compared to the energy E_{rec} (and time) of the same electron when it returned to the same target surface after being decelerated and then accelerated backward by the sheath electric field.

The loss of energy and the time interval were determined for each single electron. The graph in Fig. 1 shows the dependence of the average energy of the refluxing electrons on their initial energy. Several lines represent cases with different electron temperature. In a separate set of simulations it was proven that the average energy loss of refluxing electrons does not depend on the electron density. This is consistent with a 1D theoretical model describing the change of electron energy during the time spent in the potential behind the expanding target during an isothermal expansion of the target [5]. The energy change ΔE of electrons behind the target according to this model is given by

$$\Delta E = \frac{2\sqrt{2}}{3}\sqrt{\frac{Zm_e}{m_i}}\sqrt{\frac{E_{out}}{k_B T_e}}\left(\frac{3}{2}k_B T_e - E_{out}\right) \tag{1}$$

It means that slow electrons ($E < 3/2k_B T_e$) are slightly accelerated, while faster electrons are distinctively decelerated. The energy loss beyond the target plays important role especially for lower plasma temperature relative to the energy of hot electrons, and for lighter ions. An interesting consequence of the relation (1) is that the electron energy loss is independent of the plasma density. The curve given by the theoretical model is included in Fig. 1 for comparison. The simulated dependencies are in good agreement with theoretical expectations for non-relativistic electron energies. Thus, Eq. (1) can be used to describe the electron energy loss behind the target. On the other hand, this simple model has its limitations. It is one-dimensional, it does not take into account the runaway electrons which leave the target before ionization of its rear surface, and the effect of magnetic fields, which may be generated on the surface of the target. Nevertheless, this approximate model should be more accurate than just neglecting the energy loss of refluxing electron like e.g. in [6].

Demonstration of influence of electron refluxing

The transport of hot electrons through the solid target was simulated using the 3D Monte Carlo (MC) code PENELOPE [7]. The target was assumed to be an unstructured slab of a homogeneous material. Simulations discussed here were carried out for different target materials, e.g. aluminum (as a representative of materials with lower Z) and silver (as a representative of materials with higher Z). Simulations were done for three different temperatures of hot electron spectra (50, 100 and 200 keV) and for several target thicknesses (10–500 μm) for both materials. The MC code PENELOPE includes only the collisional and the radiative stopping power, while the resistive stopping power is not taken into account [8]. In an older reference [9] it is claimed that the collisional Monte Carlo modeling of K-α emission experiments can reproduce the measured results, even if the field generation is significant.

One million of electrons with the Boltzmann–Maxwell distribution were placed in the center of the front side of the target at the beginning of each simulation. Direction vectors of all electrons were perpendicular to the target surface and pointed into the target (i.e. pencil beam was assumed initially). A virtual detector was set at the rear side of the target and the positions and direction vectors of the transmitted or secondarily generated electrons and photons were saved when they reached the position of the detector. It was verified that a simulation involving one million electrons is a reasonable compromise between the accuracy of the MC method and the simulation time.

The transmitted electrons were recorded. The energy of each electron was recalculated by subtracting the amount given by Eq. (1) and its direction vector was specular symmetrically transformed. Such a set of electrons was then used as an input for the next step. This means that the simulation of a certain configuration could involve several iteration steps. Iterations were terminated when less than 5% of the original input electrons were recorded in the detector. The total count of the detected K-α photons was evaluated after every iteration. The number of the detected K-α photons in all iterations together was compared with the number of the K-α photons detected in the first iteration. This demonstrates the effect of electron refluxing on the K-α radiation. Typically about 2000 K-α photons were detected per one million initial electrons

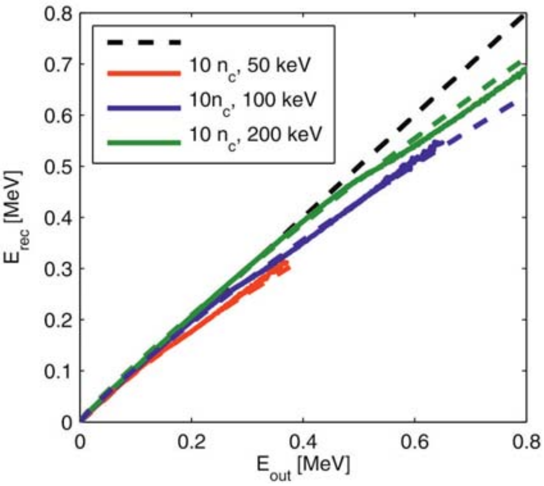

Fig. 1. Numerically simulated dependence of the average returning recirculating electron energy on the energy with which they left the target, for different hot electron temperatures. A model expectation according to Eq. (1) is plotted for comparison.

in the first iteration for a 10 μm thick aluminum target (500 counts for a silver target in this case).

The graphs in Fig. 2 show the relative increase of the count of the detected characteristic K-α photons, characterized by N/N_1, when the hot electron refluxing is taken into account, as a function of the width *d* of the slab target for various hot electron temperatures and for two different materials, aluminum (Fig. 2a) and silver (Fig. 2b).

There are several observations that we want to emphasize:

1. The hot electron refluxing may have significant influence on the K-α radiation. The total photon count may be several times larger when the refluxing is taken into account. The biggest increase (by a factor of ten) was registered for a 10 μm thick aluminum target with the hot electron temperature of 200 keV.
2. The influence of the electron refluxing on the K-α radiation is more significant for higher temperatures of the hot electrons.
3. The influence of the electron refluxing on the K-α radiation is more significant for thinner targets.
4. The effect of refluxing is more important for low-Z materials.

The information about the target composition and thickness and the hot electron temperatures for which it is important to include the influence of the hot electron refluxing on the production of the characteristic K-α radiation is summarized in Table 1.

Refluxing leads also to the enlargement of the radiation spot. The reason is that electrons diverge during the transport through the target. The recirculating electrons do not return back to the center of the target but to the place where they left the target in our refluxing model. It means that the processes leading to the generation of the K-α radiation can take place also at a larger distance from the center of the target. The graphs in Fig. 3 show a remarkable increase in the radiation spot size for 10 μm thick copper target and

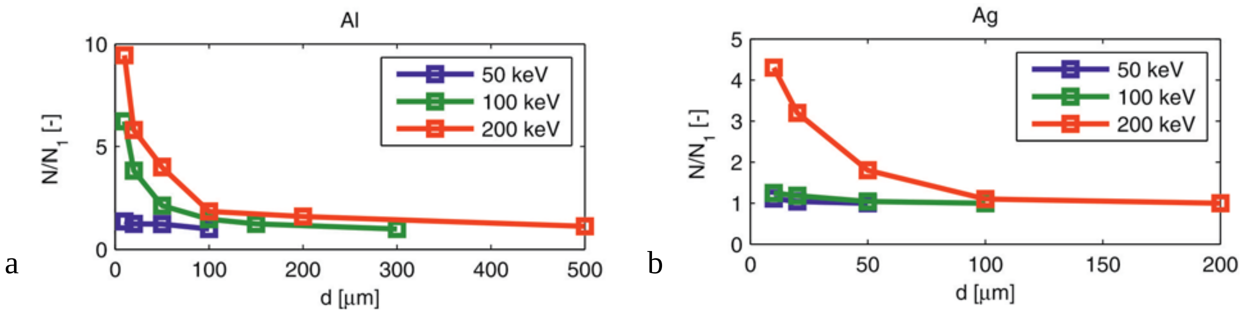

Fig. 2. A relative increase in the count of the detected characteristic K-α photons, represented by N/N_1, when the hot electron refluxing is taken into account, as a function of the width *d* of the slab target, for various hot electron temperatures and for two different materials, aluminum (a) and silver (b).

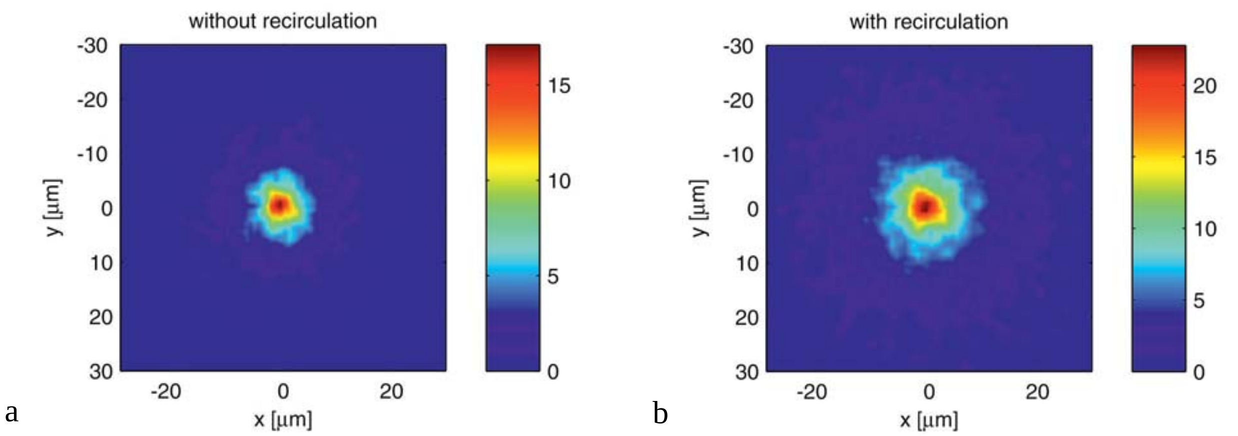

Fig. 3. The total count of K-α photons radiated from the rear side of a 10 μm thick copper slab target, per one million initial hot electrons with the Boltzmann–Maxwell distribution corresponding to the temperature of 200 keV per pixel. The size of the pixel is 0.8 μm × 0.8 μm. (a) The refluxing was not taken into account. (b) The refluxing was taken into account. The colors were smoothed using a convolution mask.

Table 1. The target widths for which the influence of the electron refluxing on the K-α radiation should be taken into account

Target materials	Hot electron temperature		
	50 keV	100 keV	200 keV
Al	not important	<100 μm	<200 μm
Cu	not important	<10 μm	<50 μm
Ag	not important	not important	<20 μm

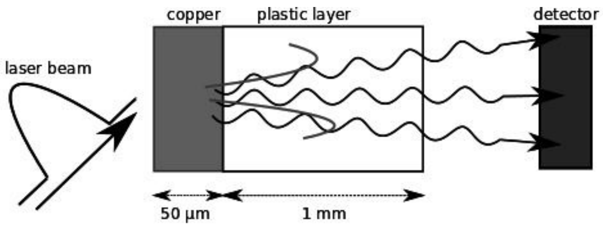

Fig. 4. A simple experimental setup designed to demonstrate the effect of the electron refluxing on the K-α radiation.

hot electron temperature of 200 keV. The full width at half maximum (FWHM) increases from (2.8 ± 0.3) μm to (4.1 ± 0.1) μm in this case.

Design of experimental setup

One of the first clear experimental signals for the electron refluxing effects on the K-α emission was reported in Ref. [10]. A high energy laser (35–40 J) was focused on a multilayer (Al, Cu, Al) target. In this note we propose to demonstrate the influence of hot electrons refluxing on the yield of K-α radiation in a simpler experiment using a less intense laser beam. The scheme of this experiment is shown in Fig. 4; it is similar to the experimental setup described in [6]. A thin slab of some relatively low-Z material is used as a target. The experiment involves two runs, one with a target without a plastic layer, and then with a target including such a layer, which is reasonably transparent to the K-α radiation, but which also absorbs hot electrons. This means that hot electrons do not return into target again and the refluxing effect is suppressed.

The configuration setup shown in Fig. 4 was chosen as a quantitative example. One may expect that the electron refluxing would result in about 80% increase of the K-α photon counts from a 50 micron thick copper target (based on other authors' simulation). On the other hand, the transparency of a 1 mm polyimide layer to the K-α radiation of copper is about 43% [11]. Thus it is possible to reconstruct the intensity of the K-α radiation with and without the electron refluxing being involved and in this way to prove the influence of electron refluxing on the K-α radiation. Such an experiment requires a laser pulse of a limited duration ($\tau < 200$ fs) to restrain the possibility that an electron which left the target could return into the interaction area and be heated once again. The laser intensity should be also moderate ($I < 10^{18}$ W/cm^2), because the refluxing model described above is not relativistic.

Summary and conclusions

A model describing the electron refluxing was verified via a computer particle-in-cell simulation for non-relativistic electron energies. Using this model it was confirmed that the electron refluxing has a distinct influence on the generated X-ray radiation, especially for thin targets made from low-Z materials, and for higher hot electron temperatures. An experimental setup designed to demonstrate this phenomenon was proposed.

Acknowledgments. The support of the Czech Technical University in Prague (grants SGS13/221/OHK4/3T/14 and RVO68407700) and of the Czech Ministry of Education, Youth and Sport (grant LM2010014) is gratefully acknowledged. The access to the computing and storage facilities owned by the parties and the project contributing to the National Grid Infrastructure MetaCentrum, provided under the programme "Projects of large infrastructure for research, development, and innovations" (LM2010005), is greatly appreciated.

References

1. Gahn, C., Tsakiris, G. D., Pukhov, A., Meyer-ter-Vehn, J., Pretzler, G., Thirolf, P., Habs, D., & White, K. J. (1999). Multi-MeV electron beam generation by direct laser acceleration in high-density plasma channels. *Phys. Rev. Lett.*, *83*(23), 4772.
2. Gibbon, P., Mašek, M., Teubner, U., Lu, W., Nicoul, M., Shymanovich, U., Tarasevitch, A., Zhou, P., Sokolowski-Tinten, K., & von der Linde, D. (2009). Modelling and optimisation of fs laser-produced K_α sources. *Appl. Phys. A*, *96*(1), 23–31.
3. Volpe, L., Batani, D., Morace, A., & Santos, J. J. (2013). Collisional and collective effects in two dimensional model for fast-electron transport in refluxing regime. *Phys. Plasmas*, *20*(1), 013104.
4. Lichters, R., Pfund, R. E., & Meyer-ter-Vehn, J. (1997). *LPIC++: A parallel one-dimensional relativistic electromagnetic particle-in-cell code for simulating laser-plasma-interaction*. Garching: Max--Planck-Institut für Quantenoptik. (MPQ 225). www.lichters.net/download.html.
5. Grismayer, T., Mora, P., Adam, J. C., & Héron, A. (2008). Electron kinetic effects in plasma expansion and ion acceleration. *Phys. Rev. E*, *77*(6), 066407.
6. Neumayer, P., Aurand, B., Basko, M., Ecker, B., Gibbon, P., Hochhaus, D. C., Karmakar, A., Kazakov, E., Kuhl, T., Labaune, C., Rosmej, O., Tauschwitz, An., Zielbauer, B., & Zimmer, D. (2010). The role of hot electron refluxing in laser-generated K-alpha sources. *Phys. Plasmas*, *17*, 103103.
7. Salvat, F., Fernández-Varea, J. M., & Sempau, J. (2006, July). PENELOPE-2006: A code system for Monte

Carlo simulation of electron and photon transport. In Workshop Proceedings (Vol. 4, p. 7).

8. Vauzour, B., Debayle, A., Vaisseau, X., Hulin, S., Schlenvoigt, H. P., Batani, D., Baton, S. D., Honrubia, J. J., Nicolai, Ph., Beg, F. N., Benocci, R., Chawla, S., Coury, M., Dorchies, F., Fourment, C., d'Humieres, E., Jarrot, L. C., McKenna, P., Rhee, Y. J., Tikhonchuk, V. T., Volpe, L., Yahia, V., & Santos, J. J. (2014). Unraveling resistive versus collisional contributions to relativistic electron beam stopping power in cold--solid and in warm-dense plasmas. *Phys. Plasmas*, *21*(3), 033101.
9. Davies, J. R. (2002). How wrong is collisional Monte Carlo modeling of fast electron transport in high-intensity laser-solid interactions? *Phys. Rev. E*, *65*(2), 026407.
10. Martinolli, E., Koenig, M., Baton, S. D., Santos, J. J., Amiranoff, F., Batani, D., Perelli-Cippo, E., Scianitti, F., Gremillet, L., Mélizzi, R., Decoster, A., Rousseaux, C., Hall, T. A., Key, M. H., Snavely, R., MacKinnon, A. J., Freeman, R. R., King, J. A., Stephens, R., Neely, D., & Clarke, R. J. (2006). Fast-electron transport and heating of solid targets in high-intensity laser interactions measured by Kα fluorescence. *Phys. Rev. E*, *73*(4), 046402.
11. Henke, B. L., Gullikson, E. M., & Davis, J. C. (1993) X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92. *Atom. Data Nucl. Data Tables*, *54*(2), 181–342.