On the hot electrons and $K_{\alpha}$ x-rays generation in the intense laser interaction with silver targets

O F Kostenko$^1$, N E Andreev$^1$, O N Rosmej$^2$ and A Schönenl$^3$

$^1$ Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
$^2$ GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, Darmstadt 64291, Germany
$^3$ Goethe University Frankfurt am Main, Grüneburgplatz 1, Frankfurt am Main 60323, Germany

E-mail: olegkost@ihed.ras.ru

Abstract. Intensity dependence of the conversion efficiency of laser energy into the energy of hot electrons is determined with the aid of measurements and modeling of $K_{\alpha}$-photon yield from silver targets irradiated by relativistically intense subpicosecond laser pulses. We take into account intensity dependence of the effective hot electron temperature assuming the Wilks’ scaling. The measurements reveal approximately the same values of the $K_{\alpha}$ yield from a silver foil of 10 $\mu$m thickness, attached onto aluminium or plexiglass substrates, at the intensities about $10^{18}$ W/cm$^2$ and $2 \times 10^{19}$ W/cm$^2$. Intensity dependence of the $K_{\alpha}$ yield from the silver foil, calculated using determined conversion efficiency of laser energy into the energy of hot electrons, is in agreement with the measurements.

1. Introduction

Experiments at GSI with use of the high intensity laser system PHELIX [1] have been aimed at investigation of generation of 22.1 keV Ag $K_{\alpha}$ radiation for radiographic applications. High-energy $K_{\alpha}$ x-ray sources produced by high-intensity lasers are under development for use as monochromatic backlighters for high-energy density experiments [2, 3]. Knowledge about laser energy coupling into energy of accelerated relativistic electrons is of paramount importance for understanding of a short pulse laser-matter interaction [4–7] and various prominent applications [8, 9]. Measurements and modeling of the absolute $K_{\alpha}$ yield as a function of the laser intensity permit to determine the conversion efficiency of laser energy into the energy of hot electrons in high-intensity laser interactions with solid targets [10, 11].

In this paper, we use measurements of $K_{\alpha}$-photon yield and a model of $K_{\alpha}$ x-rays generation by laser-produced hot electrons propagating in a silver foil of arbitrary thickness [12] for characterization of the conversion efficiency in intense laser pulses interaction with silver targets at the PHELIX facility.

2. Experiment

The s-polarized laser pulses with wavelength of 1.053 $\mu$m, energy of 80–115 J, average duration (FWHM) of 0.78 ps and the contrast of a nanosecond amplified spontaneous emission of $10^{-6}$ were focused onto Ag targets under an angle of 10° to the target normal. Laser pulse energy at
the targets was equal to approximately 80% of the measured laser pulse energy due to losses in
the compressor and in the focusing off-axis parabola. Laser intensity was varied by displacement
of the targets out of the best focus position.

To determine experimental values of the laser pulse intensity, \( I_{\text{exp}} \), we use the expression
for the peak intensity of the Gaussian laser pulse with the values of the laser pulse energy, the
duration and the area of the spot at the target at half of the maximum intensity, measured
in each laser shot. The total error of the laser intensity determination has been estimated as
±20%.

Measurements of the characteristic K\(_\alpha\) radiation have been performed using a charge-coupled-
device (CCD) camera in the single-photon-counting mode, such that on average much less than
one photon per pixel is detected. The single photon regime allows to reconstruct a measured
spectrum, obtained from the histogram of the CCD exposure. The K\(_\alpha\) yield calculations were
performed by summation of the spectral lines K\(_{\alpha1}\) and K\(_{\alpha2}\) intensities in the energy interval
of 0.65 keV. The CCD single-event efficiency of 1.8% was determined for 22.1 keV photons providing
the absolute calibration. The CCD viewed the target front side at an angle of approximately
35° to the target normal. In order to ensure the single-hit regime, additional Ag filters of 0.1–
0.29 mm thickness were added depending on used target. The number of K\(_\alpha\) photons per unit
laser energy at the target, emitted in the direction of observation per unit solid angle, \( N_{k}^{\text{exp}} \), has
been determined taking into account filter transmission.

In order to exclude the process of hot electron refluxing [13, 14] from the analysis, the bulk
silver target of 3 mm thickness and silver foils of 10 and 100 \( \mu \)m thickness, attached onto
mm thick aluminium or plexiglass substrates, were used. Application of the thin silver foils,
attached onto low-Z substrates, led to strong reduction of bremsstrahlung radiation level, what
was important to ensure the single-hit regime.

The most reliable and comprehensive data on the K\(_\alpha\)-photon yield have been obtained with
the 10 \( \mu \)m thick silver foil. The measurements reveal approximately the same values of the K\(_\alpha\)
yield at the intensities about \( 10^{18} \) W/cm\(^2\) and about \( 2 \times 10^{19} \) W/cm\(^2\) (figure 1).

3. Modeling
We assume that a spectrum of laser-generated hot electrons incident on the silver targets is
described by the exponential energy distribution [10, 11]
\[
f(E_0) = N_h \exp \left( -E_0/T_h \right) / T_h
\]
with the average energy $T_h (I_L)$ determined by the Wilks’ scaling [15]

$$T_h \ [\text{MeV}] = 0.511 \left( \sqrt{1 + I_{18} \lambda_\mu^2/1.37} - 1 \right).$$

(2)

Here, $I_{18}$ is the laser intensity $I_L$ in units of $10^{18} \ \text{W/cm}^2$ and $\lambda_\mu$ the wavelength in microns. If $\eta (I_L)$ is a fraction of incident laser energy $E_L$, transmitted to hot electrons, then the total number of hot electrons $N_h$ follows from the energy conservation law

$$N_h T_h = \eta E_L.$$

(3)

The number of $K_\alpha$ photons generated by the hot electrons per unit laser energy in given direction per unit solid angle can be expressed as follows

$$N_k (I_L) = \frac{\eta (I_L)}{T_h^2 (I_L)} \int_0^\infty dE_0 \exp \left[ \frac{-E_0}{T_h (I_L)} \right] N_{em} (E_0).$$

(4)

Here, $N_{em} (E_0)$ is the total number of photons per unit solid angle emitted by an electron with initial energy $E_0 > E_k$, incident on a silver foil of given thickness; $E_k$ is the ionization potential of the K-shell. When calculating the relation $N_{em} (E_0)$ according to the model described in reference [12], we suppose that electron refluxing in the thin foils is suppressed by use of the substrates. The model takes into consideration energy losses of the electrons, energy dependence of the cross-section of target atom K-shell ionization by electron impact, the foil thickness, as well as absorption of the x-rays.

To determine dependence of the conversion efficiency of laser energy into the energy of hot electrons on the intensity, we use the approximation

$$\eta (I_L) = a + b \log (I_{18}),$$

(5)

suggested in the paper [12] to describe results of the modeling of the conversion efficiency in the interaction of the PHELIX laser pulses with a metal target in the intensity range of $10^{17} - 1.5 \times 10^{19} \ \text{W/cm}^2$ as described in the reference [13].

Dependence (5) contains only two free parameters, $a$ and $b$. To determine them it would be sufficient two measurements. In reality, we use six measurements in the intensity range of $(1-2) \times 10^{18} \ \text{W/cm}^2$ and three measurements at the intensities above $10^{19} \ \text{W/cm}^2$ to determine the coefficients $a$ and $b$, and, consequently, the intensity dependence of the conversion efficiency (5).

We calculate the laser energy conversion efficiency $\eta^{\exp}$ from equation (4) for each laser shot, using the $K_\alpha$ yield $N^{\exp}_k$ and the laser pulse intensity $I^{\exp}_L$, determined from the experimental data. Obtained values of $\eta^{\exp} (I^{\exp}_L)$ have been approximated by the logarithmic dependence on the laser intensity (5). The values of $a = 1\%$ and $b = 7\%$ have been found by the least-squares regression. These parameter values correspond to the strong intensity dependence of the conversion efficiency of laser energy into the energy of hot electrons (5): $\eta = 1\%$ and $10\%$ at the intensities of $10^{18} \ \text{W/cm}^2$ and $2 \times 10^{19} \ \text{W/cm}^2$, respectively.

The $K_\alpha$ yield from the silver foil of $10 \ \mu\text{m}$ thickness, calculated according to formula (4) using the conversion efficiency $\eta (I_L)$ (5), increases sharply at the intensities above $10^{18} \ \text{W/cm}^2$ and then decreases relatively slowly with growth of the intensity up to $3 \times 10^{19} \ \text{W/cm}^2$, despite strong intensity dependence of the average electron energy (2). As a result, the $K_\alpha$ yields calculated at the intensities about $10^{18} \ \text{W/cm}^2$ and about $2 \times 10^{19} \ \text{W/cm}^2$ are close in accordance with the measurements (figure 1).

In conclusion, we have determined the intensity dependence of the conversion efficiency of the laser energy into the energy of hot electrons (5) by means of measurements and modeling of
the Kα-photon yield from silver targets irradiated by relativistically intense subpicosecond laser pulses, assuming the Wilks’ scaling of the hot electron temperature. The conversion efficiency (5) at the intensities above $10^{19}$ W/cm² is comparable with the value of 10% deduced from measurements of Kα production efficiency from a mass-limited copper foil over wide range of intensities of $2.5 \times 10^{18}$–$10^{20}$ W/cm² in papers [10, 11], where the Wilks’ scaling also was assumed. At the same time, obtained conversion efficiency in silver targets drops about twofold at the intensity of $2.5 \times 10^{18}$ W/cm². A more comprehensive analysis of experimental data and results of modeling is the subject of the following paper.

Acknowledgments
Theoretical part of the work performed by the team of the Joint Institute for High Temperatures RAS was supported by the Russian Science Foundation (grant No. 14-50-00124).

References
[1] Bagnoud V, Aurand B, Blazevic A, Borneis S, Bruske C, Ecker B, Eisenbarth U, Fils J, Frank A, Gaul E et al 2010 Appl. Phys. B 100 137–50
[2] Park H S, Chambers D M, Chung H K, Clarke R J, Eagleton R, Giraldez E, Goldsack T, Heathcote R, Izumi N, Key M H et al 2006 Phys. Plasmas 13 056309
[3] Park H S, Maddox B R, Giraldez E, Hatchett S P, Hudson L T, Izumi N, Key M H, Le Pape S, MacKinnon A J, MacPhee A G et al 2008 Phys. Plasmas 15 072705
[4] Gibbon P 2005 Short Pulse Laser Interactions with Matter: An Introduction (London: Imperial College Press)
[5] Belyaev V S, Kostenko O F and Lisitsa V S 2003 JETP Letters 77 653–56
[6] Andreev N E, Pugachev L P, Povarnitsyn M E and Levashov P R 2016 Laser Part. Beams 34 115–22
[7] Pugachev L P, Andreev N E, Levashov P R and Rosmej O N 2016 Nucl. Instrum. Methods Phys. Res. A 829 88–93
[8] Yasuike K, Key M H, Hatchett S P, Snively R A and Wharton K B 2001 Rev. Sci. Instrum. 72 1236–40
[9] Chen C D, Patel P K, Hey D S, Mackinnon A J, Key M H, Akli K U, Bartal T, Beg F N, Chawla S, Chen H et al 2009 Phys. Plasmas 16 082705
[10] Theobald W, Akli K, Clarke R, Delettrez J A, Freeman R R, Glenzer S, Green J, Gregori G, Heathcote R, Izumi N et al 2006 Phys. Plasmas 13 043102
[11] Myatt J, Theobald W, Delettrez J A, Stoeckl C, Storm M, Sangster T C, Maximov A V and Short R W 2007 Phys. Plasmas 14 056301
[12] Kostenko O F and Andreev N E 2013 Quantum Electron. 43 237–41
[13] Neumayer F, Aurand B, Basko M, Ecker B, Gibbon P, Hochhaus D C, Karmakar A, Kazakov E, Kühl T, Labaune C, Rosmej O, Tauschwitz A, Zielbauer B and Zimmer D 2010 Phys. Plasmas 17 103403
[14] Quinn M N, Yuan X H, Lin X X, Carroll D C, Tresca O, Gray R J, Coury M, Li C, Li Y T, Brenner C M et al 2011 Plasma Phys. Control. Fusion 53 025007
[15] Wilks S C, Kruei W L, Tabak M and Langdon A B 1992 Phys. Rev. Lett. 69 1383–6