

On the hot electrons and K_α x-rays generation in the intense laser interaction with silver targets

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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_α -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_α yield from a silver foil of 10 μm thickness, attached onto aluminium or plexiglass substrates, at the intensities about 10^{18} W/cm² and 2×10^{19} W/cm². Intensity dependence of the K_α 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_α radiation for radiographic applications. High-energy K_α 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_α 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_α -photon yield and a model of K_α 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 μm , 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



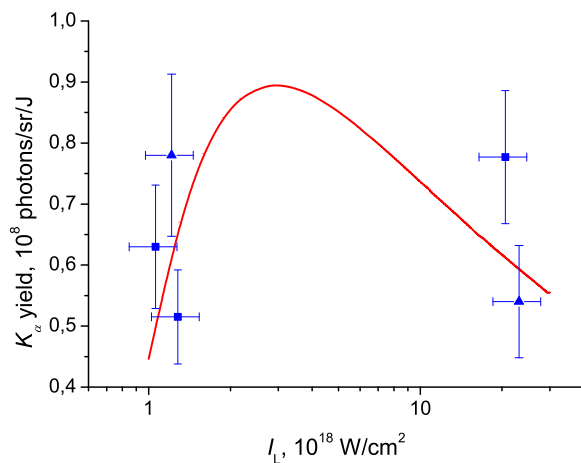


Figure 1. Intensity dependence of the K_α photons number per unit laser energy at the target, emitted in the direction of observation per unit solid angle, from the silver foil of $10\ \mu\text{m}$ thickness backed by aluminium (triangles) or plexiglass (squares) substrates. Points correspond to the values of I_L^{exp} and N_k^{exp} , determined from the experimental data for each laser shot. Solid curve—calculation according to formula (4) with the approximate conversion efficiency (5).

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_L^{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 $\pm 20\%$.

Measurements of the characteristic K_α 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_α yield calculations were performed by summation of the spectral lines $K_{\alpha 1}$ and $K_{\alpha 2}$ 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_α photons per unit laser energy at the target, emitted in the direction of observation per unit solid angle, N_k^{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 $100\ \mu\text{m}$ 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_α -photon yield have been obtained with the $10\ \mu\text{m}$ thick silver foil. The measurements reveal approximately the same values of the K_α yield at the intensities about $10^{18}\ \text{W}/\text{cm}^2$ and about $2 \times 10^{19}\ \text{W}/\text{cm}^2$ (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]

$$f(E_0) = N_h \exp(-E_0/T_h) / T_h \quad (1)$$

with the average energy $T_h(I_L)$ determined by the Wilks' scaling [15]

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

Here, I_{18} is the laser intensity I_L in units of 10^{18} W/cm² and λ_μ 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

$$N_h T_h = \eta E_L. \quad (3)$$

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

$$N_k(I_L) = \frac{\eta(I_L)}{T_h^2(I_L)} \int_{E_k}^{\infty} dE_0 \exp[-E_0/T_h(I_L)] N_{\text{em}}(E_0). \quad (4)$$

Here, $N_{\text{em}}(E_0)$ 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 $N_{\text{em}}(E_0)$ 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

$$\eta(I_L) = a + k \lg(I_{18}), \quad (5)$$

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} – 1.5×10^{19} W/cm² 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 $(1-2) \times 10^{18}$ W/cm² and three measurements at the intensities above 10^{19} W/cm² to determine the coefficients a and b , and, consequently, the intensity dependence of the conversion efficiency (5).

We calculate the laser energy conversion efficiency η^{exp} from equation (4) for each laser shot, using the K_α yield N_k^{exp} and the laser pulse intensity I_L^{exp} , determined from the experimental data. Obtained values of $\eta^{\text{exp}}(I_L^{\text{exp}})$ have been approximated by the logarithmic dependence on the laser intensity (5). The values of $a = 1\%$ and $k = 7\%$ 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} W/cm² and 2×10^{19} W/cm², respectively.

The K_α 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} W/cm² and then decreases relatively slowly with growth of the intensity up to 3×10^{19} W/cm², despite strong intensity dependence of the average electron energy (2). As a result, the K_α yields calculated at the intensities about 10^{18} W/cm² and about 2×10^{19} W/cm² 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 K_α -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 K_α production efficiency from a mass-limited copper foil over wide range of intensities of 2.5×10^{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 2.5×10^{18} W/cm². A more comprehensive analysis of experimental data and results of modeling is the subject of the following paper.

Acknowledgments

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