Laser and Particle Beams (2001), *19*, 147–150. Printed in the USA.

Numerical studies on the properties of femtosecond laser plasma $K\alpha$ sources

CH. REICH, P. GIBBON, I. USCHMANN, AND E. FÖRSTER
Abteilung Röntgenoptik, Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany

(Received 4 December 2000; Accepted 5 February 2001)

Abstract

One of the features of ultra high intensity (UHI) short pulse laser–matter interactions is the prospect of *creating* a cheap, compact source of hard X rays with femtosecond pulse duration. The properties of such $K\alpha$ sources are studied using analytical and numerical models of hot electron generation and subsequent transport in a range of materials (Reich *et al.*, 2000). First, we find that there is an optimum laser intensity for $K\alpha$ generation from bulk targets, which scales as $Z^{4.4}$. Second, we show that efficient hard X-ray pulses with durations below 100 fs can be generated at intensities of $\sim 10^{16}$ W/cm^2.

1. INTRODUCTION

The X-ray bursts which originate from $K\alpha$ transitions in ultra high intensity (UHI) laser-irradiated solids present an interesting alternative to synchrotron radiation in medical imaging applications (Svanberg *et al.*, 1994) as well as opening up completely new possibilities in time-resolved measurements of phase transitions, chemical reactions, and thermal transport (Rischel *et al.*, 1997). In this article, we address two important aspects of the $K\alpha$ emission: first, we show that the dependence of $K\alpha$ emission on the target element is self-similar, leading to a universal value for the optimal hot electron temperature. Using this result, a simple scaling of the laser intensity giving maximum $K\alpha$ yield can be derived. These analytical predictions are then verified by numerical simulations for a wide range of laser intensities and target materials. Second, we consider how the stopping times of the hot electrons in the solid influence the temporal development of the X-ray emission and propose formulae for the design of foil targets to produce high-yield hard X-ray pulses of a specific duration.

2. NUMERICAL MODEL

For the numerical modeling, a two-step approach was applied to determine the $K\alpha$ emission. First, 1-D, oblique incidence Particle-in-Cell (PIC) simulations (Gibbon *et al.*, 1999) were performed to obtain hot electron distributions $f_{hot}(E)$ for density profiles appropriate to interactions where a laser prepulse or pedestal generates a small amount of preformed plasma (Bastiani *et al.*, 1997). Second, a Monte Carlo (MC) transport code (Joy, 1995) extended for the calculation of $K\alpha$ emission was used to compute electron trajectories in the solid. *K*-shell ionization cross sections from Casnati *et al.* (1982) and fluorescence yields, relative line intensities, and absorption lengths for self-emitted $K\alpha$ radiation given by Zschornack (1989) were applied. Temporal information on electrons and photons was calculated taking into account the electron entry time into the solid (PIC code), the photon generation time and the time of flight of the photon to the detector (MC code). All calculations were performed for a p-polarized, high-contrast 60-fs Ti:Sa laser with an incidence angle of 45°, delivering a *constant energy* of 100 mJ on the target. An exponential plasma density profile with scale length $L = 0.3\lambda$, $n_e(\max) = 10 n_c$ was used, n_c being the critical density. The $K\alpha$ radiation was observed normal to the target frontside.

3. OPTIMUM $K\alpha$ YIELD

Analytically, the $K\alpha$ yield from a hot electron distribution can be expressed as an energy integral over the properties of monoenergetic electrons:

$$N = \int n_{hot}\, f_{hot}(E) N_{gen}(E) f_{em}(E)\, dE, \qquad (1)$$

Address correspondence and reprint requests to Christian Reich, Institut für Optik und Quantenelektronik, Max-Wien-Platz 1, 07743 Jena, Germany. E-mail: reich@roentgen.physik.uni-jena.de

where N is the number of emitted photons, n_{hot} is the total number of hot electrons and $f_{hot}(E)$ their energy distribution, $N_{gen}(E)$ is the number of $K\alpha$ photons generated by an electron of incidence energy E, and $f_{em}(E)$ is the fraction of these photons that escapes from the solid—the "emission factor."

The emission factor shows a *universal behavior* with respect to the incident electron energy normalized to the K-shell ionization energy of the target: $U = E/E_k$ (Fig. 1a). At $U = 20$, the mean depth of $K\alpha$ generation in the target is comparable to the absorption length for self-emitted $K\alpha$ radiation (Fig. 1b), so that for $U < 20$, most of the generated photons can escape from the target. For $U > 20$, the electron penetration depth and reabsorption both increase, so that f_{em} falls off rapidly as $\sim U^{-5/3}$. To facilitate the integration of Eq. (1), the emission factor was approximated by a step function:

$$f_{em} = \begin{cases} 1 & \text{if } U \leq 20 \\ 0 & \text{if } U > 20. \end{cases} \tag{2}$$

Applying a fit of the ionization energies, we can approximate $U \approx E/0.0054\, Z^{2.2}$.

Substituting the factors in Eq. (1) with the results of PIC or MC simulations respectively, the total $K\alpha$ yield in the interval $1 \leq U \leq 20$ is

$$N_{I,Z} \propto \frac{Z^{2.73}}{I^{3/4}} \int_1^{20} U \exp\left(-\frac{U}{U_{kT}}\right) dU, \tag{3}$$

with $U_{kT} = kT/E_k$ being the normalized hot electron temperature. It is highest for an optimal electron temperature U_{opt}. This implies an optimal laser intensity I_{opt} (which produces this optimal electron temperature) for a given Z. Setting $\partial N/\partial I = 0$ gives

$$I_{opt} = 7 \times 10^9\, Z^{4.4}, \tag{4}$$

which corresponds to an electron temperature $U_{opt} = 6.4$.

The scaling of I_{opt} results from the combination of two scaling laws. The reference value for $K\alpha$ production *and* reabsorption is the ionization energy of the K-shell, which gives a scaling of the appropriate hot electron energy as $E \propto Z^{2.2}$. The laser intensity scales with the hot electron energy as $I \propto (kT)^2$, giving $I_{opt} \propto Z^{4.4}$. A weaker temperature scaling, for example, $kT \propto (I\lambda^2)^{1/3}$, would lead to a correspondingly stronger scaling of I_{opt} with Z.

To check the result in (3), combined PIC-MC calculations were used to derive $K\alpha$ yields without the approximations included in the analytical model (Fig. 2a). Photon numbers in Figure 2a agree within a factor of 3 with those predicted by Eq. (3). For all elements, the $K\alpha$ yield shows a distinct maximum at an optimal laser intensity I_{opt}, which follows the predicted $Z^{4.4}$ dependence of Eq. (4) (Fig. 2b). The simulated values are generally in good agreement with experimental data (Eder *et al.*, 2000; Schlegel *et al.*, 1999; Yu *et al.*, 1999), although slightly higher.

4. DURATION OF THE $K\alpha$ EMISSION

After the laser pulse has gone, $K\alpha$ emission continues until the energy of the last hot electron in the solid has dropped below the K-shell ionization energy. Depending on the laser intensity, a small fraction of super-hot electrons can produce a long-lasting $K\alpha$ afterglow with low intensity. For example, the $K\alpha$ emission from Cu, irradiated for 60 fs at $I = 3 \times 10^{16}$ W/cm^2, continues for more than 1.6 ps,

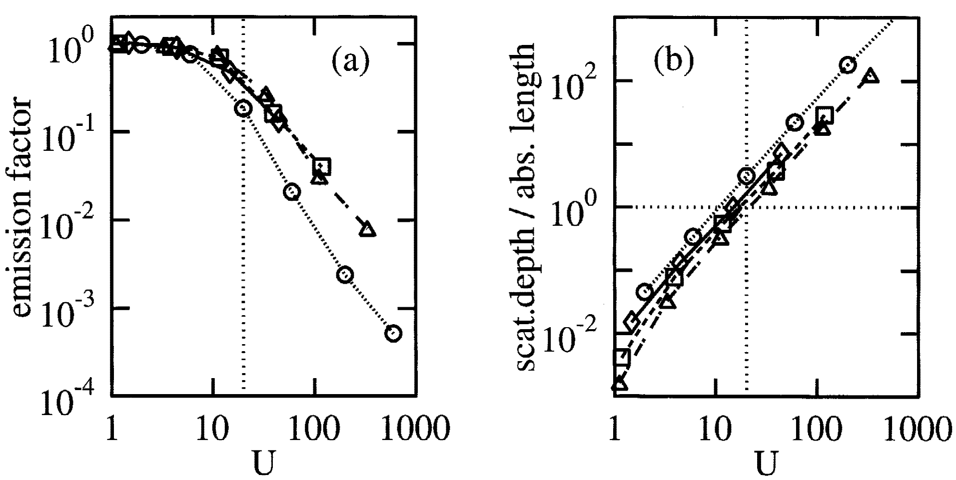

Fig. 1. (a) The emission factor f_{em} of monoenergetic electrons and (b) ratio of mean depth of $K\alpha$ generation to absorption length versus $U = E/E_k$. ○: Ti; △: Cu; □: Ag; ◇: Ta. Dotted lines: $U = 20$.

https://doi.org/10.1017/S0263034601191238 Published online by Cambridge University Press

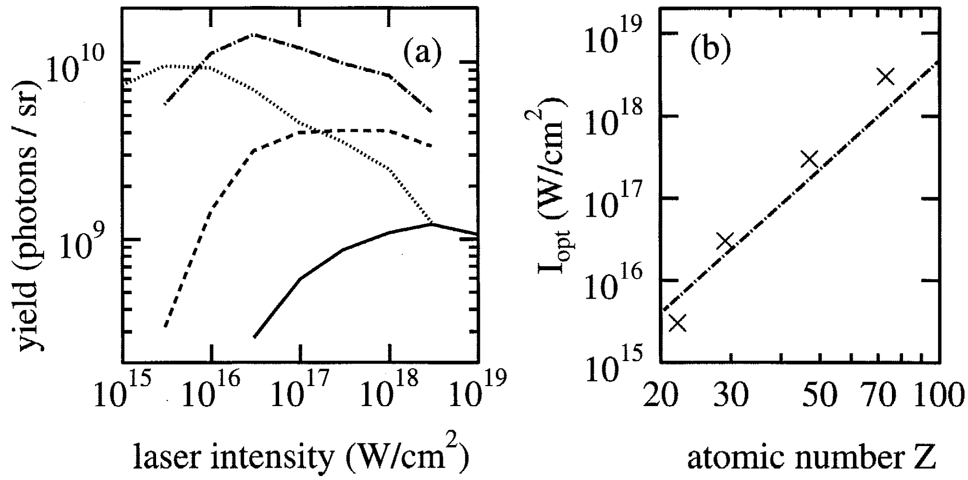

Fig. 2. (a) Simulated $K\alpha$ yields from bulk targets for a laser energy of 100 mJ: Ti (dotted), Cu (dash-dotted), Ag (dashed), and Ta (solid). (b) Dependence of the optimum laser intensity on the target material. Points are from simulations (a), the line is from the analytical model—Eq. (4).

though 90% of the emission occurs within 400 fs. Henceforth we define the time of the first 90% of emission as the temporal figure of merit of the $K\alpha$ pulses, this duration being of much more relevance for experimental applications than the total emission time.

To achieve a $K\alpha$ pulse duration of less than 100 fs suitable for ultrafast diagnostic applications, *foil* targets can be used, which are quickly traversed by super-hot electrons, limiting the time they can produce X rays. The number of photons which an electron can produce depends on the length of its scattering path and therefore on the time it spends inside the target. To determine how the optimal electron energy E_{max}—which gives maximum mean time inside the target τ_{max} and maximum number of $K\alpha$ photons per incidence electron energy—depends on target material and target thickness l, numerical simulations using monoenergetic electrons were applied, giving $E_{max} = 1.1\, Z^{0.95} l^{0.5}$ and $\tau_{max} = 100\, Z^{-0.4} l^{0.8}$. The electrons with this energy give an afterglow emission $\tau_a \approx \tau_{max}$ which is related to the laser pulse duration τ_l and the desired duration of the X-ray pulse τ_x by $\tau_{max} \approx \tau_a \approx \tau_x - \tau_l$.

Table 1. *Calculated parameters of foil targets for the generation of 100 fs Kα pulses; simulated Kα pulse duration τ_x (first 90% of emission) and Kα yield for calculated l and I_{opt}.*

Element	Z	l (μm)	I_{opt} (W/cm^2)	τ_x (fs)	Yield (photons/sr)
Ti	22	1.5	4×10^{15}	90	5×10^9
Cu	29	1.7	7×10^{15}	90	5×10^9
Ag	47	2.2	3×10^{16}	95	6×10^8
Ta	73	2.8	7×10^{16}	95	7×10^7

Solving for the foil thickness needed and the optimal laser intensity for producing electrons with energy E_{max} gives:

$$l = 0.0032\, Z^{0.5} (\tau_x - \tau_l)^{1.25}, \quad (5)$$

$$I_{opt} = 2.3 \times 10^{10}\, Z^{2.4} (\tau_x - \tau_1)^{1.25}. \quad (6)$$

Table 1 gives an overview over the parameters predicted by Eqs. (5) and (6) for a desired X-ray pulse duration of 100 fs, taking into account the 60 fs-laser pulse. Simulations using realistic hot electron distributions show that application of the calculated parameters yields 90%-pulse durations a little lower than 100 fs.

The pulse duration increases slowly with increasing either foil thickness (Fig. 3a) or laser intensity (Fig. 3b). The $K\alpha$ yield increases with the foil thickness due to the higher number of scattering events in thicker foils. It falls slowly for laser intensities above the optimum value. A laser intensity smaller than I_{opt} gives a quick decrease in X-ray radiation because the hot electron temperature is no longer high enough to produce significant K-shell ionization.

5. CONCLUSIONS

In summary, we have presented a systematic study of femtosecond $K\alpha$ sources, giving formulae for the optimal photon yield and pulse duration which agree well with the results of PIC–MC simulations. In biomedical imaging applications, the maximum achievable magnification will be limited by source broadening—whether caused by lateral transport, in both plasma and solid, or by deliberate defocusing. A more complete model is therefore planned, to deal with lateral transport effects including self-induced E- and B-fields.

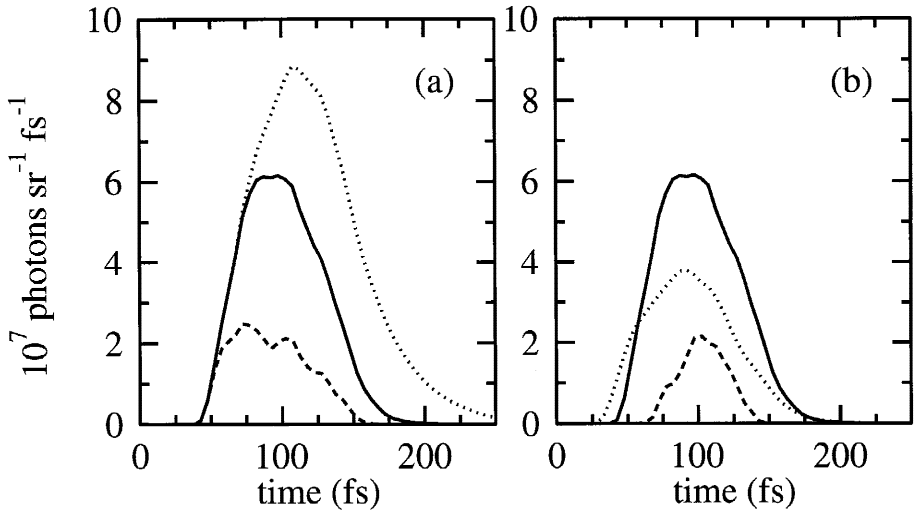

Fig. 3. *Kα* emission from Cu foils: (a) Irradiated at $I = 7 \times 10^{15}$ W/cm^2, for thicknesses: 0.5 μm (dashed), 1.7 μm (solid), and 5 μm (dotted). (b) For constant thickness: 1.7 μm, irradiated 10^{15} W/cm^2 (dashed), 7×10^{15} W/cm^2 (solid), and 3×10^{16} W/cm^2 (dotted).

ACKNOWLEDGMENTS

This work was supported by the German Science Council (DFG), the Max-Planck-Society and the European TMR Programme (Contract ERB FMRX-CT96-0080).

REFERENCES

Bastiani *et al.* (1997). *Phys. Rev. E* **56**, 7179.
Casnati *et al.* (1982). *J. Phys. B* **15**, 155.
Eder, D.C. *et al.* (2000). *Appl. Phys. B* **70**, 211.
Gibbon, P. *et al.* (1999). *Phys. Plasmas* **6**, 947.
Joy, D.C. (1995). *Monte Carlo modeling for electron microscopy and microanalysis* (Oxford University Press, Oxford).
Reich, Ch. *et al.* (2000). *Phys. Rev. Lett.* **84**, 4846.
Rischel, C. *et al.* (1997). *Nature* **390**, 490.
Schlegel, T. *et al.* (1999). *Phys. Rev. E* **60**, 2209.
Svanberg, S. *et al.* (1994). *Phys. Scr.* **49**, 187.
Yu. J. *et al.* (1999). *Phys. Plasmas* **6**, 1318.
Zschornack, G. (1989). *Atomdaten für die Röntgenspektralanalyse* (Deutscher Verlag für Grundstoffindustrie, Leipzig).