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Characteristics of ultrafast K line hard x-ray source from femtosecond terawatt laser-produced plasma*

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Theoretical studies and analytical scalings were carried out to find the optimized laser parameters and target conditions so that ultrashort hard x-ray pulses and high x-ray power could be achieved. The dependence of laser intensity and wavelength on the yield of K-shell x-ray emission was studied. We propose an optimal design for a foil target for producing high-yield hard x-ray pulses of customizing duration.

Keywords: ultrafast K line x-ray source, femtosecond laser-produced plasma
PACC: 4280W, 4255V, 7847

1. Introduction

A recent breakthrough in laser amplification technique has permitted the generation of small-scale laser systems with peak powers well into the terawatt regime.[1] The advance of the development and technology of femtosecond laser now provides the opportunity of generation of sub-picosecond length at moderate and high repetition rates. These pulses can be focused to intensities $\geq 10^{15}\,\mathrm{W\,cm^{-2}}$ on to a solid target and thus lead to the generation of a high-temperature and high-density plasma. When these hot electrons enter a solid material, bremsstrahlung and characteristic x-ray radiation are produced.[2] With the femtosecond driving lasers, hard x-ray pulses with durations of ~ps have been demonstrated.[3,4] Because of its intrinsic short pulse duration and significantly higher-energy x-ray production, this type of x-ray emission can be applied to different disciplines, such as chemistry, biology and imaging science,[5−11] including, for example, the investigation of time-resolved x-ray diffraction,[5,6] extended x-ray absorption fine structure[7−9] and probing of molecular dynamics.[10−12] The spectra of x-ray emission produced by ultrafast laser pulses have been measured in many laboratories. In particular, the generation of K_α photons is of interest for mid-Z materials. Prior to designing an experiment of ultrafast x-ray diffraction based on this source, it is necessary to understand the emission of K_α as a function of the laser condition. For numerical simulations of the laser pulse absorption, the plasma parameters and the plasma emission, a hydrodynamical computer code has been coupled to a x-ray line, and a continuum emission calculation including radiation transport[13] has been applied to study the interaction and emission of the x-rays. Also, Eder *et al*[4] have recently reported on the observation of a maximum in K_α emission, when the target is placed away from the best focus. Eder *et al* explained qualitatively the existence of an optimal laser intensity with the re-absorption of photons produced inside the target: higher laser intensities would lead to electrons with higher energies and smaller cross sections, producing K_α photons deeper inside the target. More photons would be re-absorbed on their way to the target surface, so the observed radiation drops. In this paper, we show theoretically the dependence of K_α emission on the target, with the high contrast Terawatt femtosecond Ti:sapphire laser in our laboratory as a driving source. It can provide a high intensity ($10^{14} - 10^{18}\,\mathrm{W\,cm^{-2}}$), and we propose an optimal design of foil target to produce high-yield hard x-ray pulses of a specific duration.

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2. Modelling K line production by hot electrons

Ultrashort intense laser pulses focused on solid targets are able to transform a thin surface layer to a hot and dense plasma. Due to the enormously high magnetic and electric fields, particles are accelerated to high energies. For instance, fast electrons are produced during a certain interaction time with an average energy on the order of a few tens of keV at intensities ranging from 10^{16} to $10^{18}\,\mathrm{W\,cm^{-2}}$. Since the interaction time is limited to the laser pulse width, it is expected that the temporal duration of the electron burst is on the order of the pulse duration.

It is well known that for s-polarized laser light the only important absorption process is collisional absorption. For p-polarized light the situation is partly different. In the present case, all calculations are performed for a p-polarized high-contrast femtosecond laser with an incidence angle of 45°, delivering a constant energy of 100 mJ on the target. An exponential plasma-density profile with a scale length of L=0.3λ, n_{emax}=10n_{c} is used, n_{c} being the critical density.[14]

Analytically, the K_α yield from a hot electron distribution can be expressed as an energy integral over the properties of monoenergetic electrons

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

where N is the number of emitted photons, n_{hot} is the total number of hot electrons, and $f_{\mathrm{hot}}(E)$ is their energy distribution, $N_{\mathrm{gen}}(E)$ is the number of K_α photons generated by an electron of incidence energy E in unit of keV, and $f_{\mathrm{em}}(E)$ is the fraction of these photons that escapes from the solid.

To simplify the following analysis we employ a modified formula

$$N_{\mathrm{gen}}(E) = 4\times10^{-3} Z^{-1.67} E^{3/2}, \qquad (2)$$

where Z is the atomic number. Let $U = E/E_k$ be the ratio of the normalized energy to the K-shell ionization energy of the target. Reich *et al*'s simulation[14] demonstrated that the emission factor shows a universal behaviour of the normalized energy U. To facilitate the integration of Eq.(1), the emission factor is approximated by a step function

$$f_{\mathrm{em}} = \begin{cases} 1 & : \quad U \le 20, \\ 0 & : \quad U > 20. \end{cases} \qquad (3)$$

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

The energy spectrum of hot electrons generated by an ultrafast laser is usually fitted by an one-dimensional Maxwellian energy distribution with an effective temperature denoted as T_{hot}: $f_{\mathrm{hot}}(E)\mathrm{d}E = 1/\sqrt{ET_{\mathrm{hot}}}\exp(-E/T_{\mathrm{hot}})\mathrm{d}E$. For the fast electron temperature, most current experiments and simulations have a scaling closer to $T_{\mathrm{hot}} \propto (I\lambda^2)^{1/3}$. In this paper we use the result given by Beg *et al*[15] obtained from K_α and bremsstrahlung emission measurement from the solid experiments.

$$T_{\mathrm{hot}} \approx 100\left(\frac{I\lambda^2}{10^{17}\,\mathrm{W\,cm^{-2}}}\right)^{1/3}(\mathrm{keV}), \qquad (4)$$

where we have included the usual wavelength scaling, I is the incident laser intensity and λ is the laser wavelength. While the number of generated electrons scales is

$$n_{\mathrm{hot}} \approx 1.9\times10^{20} I^{-1/2}. \qquad (5)$$

From these parameters we can make estimates for the yield of the emitted photons. The total K_α yield of Eq.(1) in the interval $1 \le U \le 20$ is

$$N_{I,Z} = 1.5\times10^{15}\frac{Z^{2.73}}{I^{2/3}\lambda^{1/3}}\int_1^{20} U\exp\left(-\frac{U}{U_k}\right)\mathrm{d}U, \qquad (6)$$

with the shape of the integrand being determined by the normalized electron temperature

$$U_k = \frac{T_{\mathrm{hot}}}{E_k} = 4\times10^{-2}\frac{(I\lambda^2)^{1/3}}{Z^{2.2}}. \qquad (7)$$

Here U_k is also the electron energy at which most K_α photons are produced.

3. Results

3.1. Intensity dependence of the K_α yield

First, we study the x-ray yield as a function of the laser intensity. Figure 1 shows the dependence of the laser intensity on the photon yield for several typical targets. It is shown that all the elements have a distinct maximum yield on increasing the laser intensity. For light elements, for example, Cu, the yield reaches its maximum at an intensity of $I \sim 3.4\times10^{15}\,\mathrm{W\,cm^{-2}}$, the maximum yield is $\sim 6.6\times10^9$ photons/sr (for laser wavelength λ=0.8 μm, also see Fig.2), while the electron temperature is close to 28 keV which is approximately in agreement with the experimental result in Ref.[4]. For the elements with a larger atomic number, to achieve the maximum yield, a higher intensity

is required if the different experimental condition is only the laser intensity.

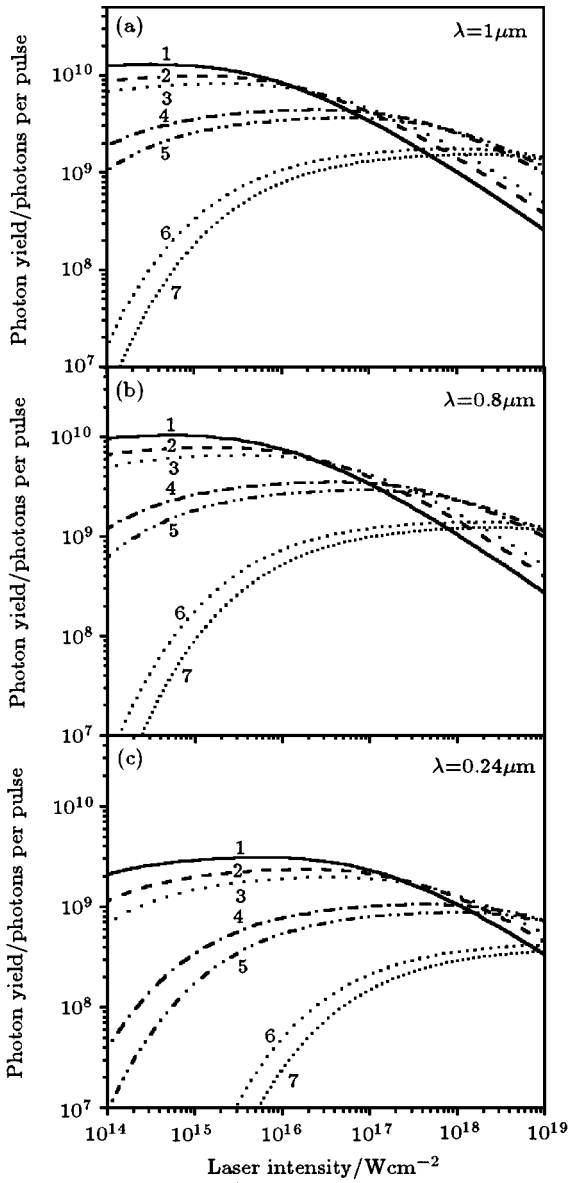


Fig.1. Calculated K-shell x-ray yield as a function of incident laser intensity. Curves 1–7 denote Ti, Fe, Cu, Mo, Ag, Ta and Au, respectively.

3.2. The wavelength dependence of the K_α yield

Because the energy spectrum of hot electrons is mainly determined by $I\lambda^2$, the fast electrons remain to dominate even at a lower intensity for a large wavelength. For example, for Cu target, the optimal intensities are 2.3×10^{15}, 3.4×10^{15} and 3.7×10^{16} W cm^{-2} at wavelengths 1, 0.8 and 0.24 μm, and the related maximum yields are 8.2×10^{9}, 6.6×10^{9} and 2×10^{9} photons/sr per pulse, respectively. The calculated x-ray yield is in good agreement with the results in Ref.[16].

Figure 2 depicts the K-shell x-ray yield as a function of laser intensity at different wavelengths for a copper target. The yield at λ=1 μm is about four times of that at λ=0.24 μm. In addition, the optimal intensity for different targets is shown in Fig.3. In Fig.3 we can see that to achieve the maximum yield, a lower intensity is desired for a large wavelength, and *vice versa*.

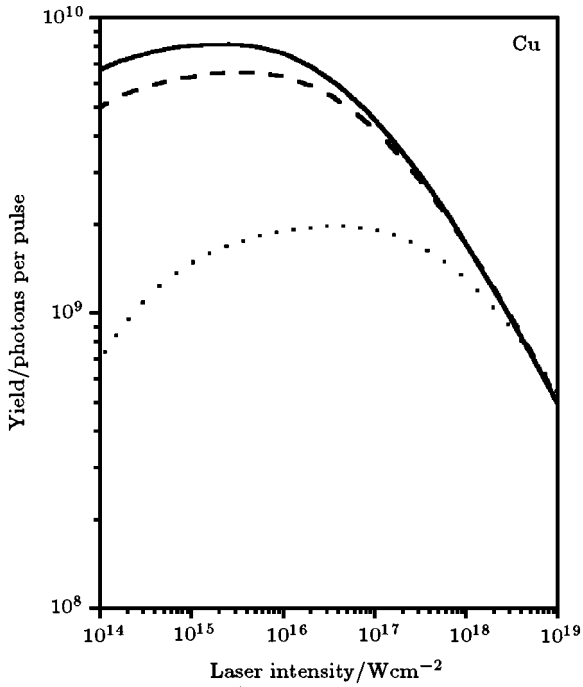


Fig.2. K-shell x-ray yield as a function of laser intensity at different wavelengths for a copper target. Solid: λ=1 μm, dashed: λ=0.8 μm and dotted: λ=0.24 μm.

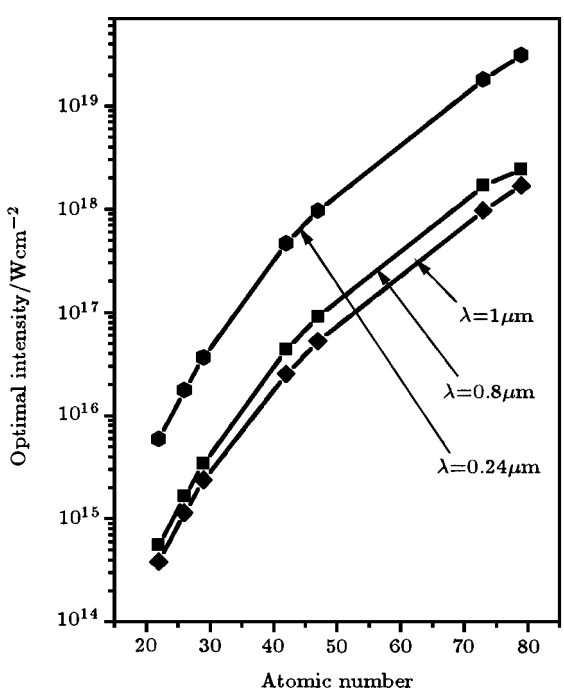


Fig.3. Calculated optimal intensities for typical targets at different wavelengths.

3.3. X-ray emission from a foil target

The extension of the hot plasma is of great importance, and thus the optimum target thickness is given by the thickness of the target. When the target is very thin, for example 100 nm, the whole–target would be strongly heated. This leads to a strong ionization and fast two-sided expansion of the target material. For too thick or massive targets, they will be heated up to regions far behind the original target surface, this leads to ionization deep in the target bulk as well, but the temperature is not high enough to reach the highest ionization stages. In this case a large fraction of the absorbed laser energy is spent on inefficient heating of the bulk material. Besides, the spectral shape of the x-ray line emission is also influenced by the target thickness. By using foil targets, afterglow emission can be restricted which are quickly traversed by superhot electrons, thus limiting the time they can produce x-rays. To determine the optimal thickness of the targets and related intensity, the scaling expressions can be used[14] at λ=0.8 μm:

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

$$I_{\rm opt} = 2.3 \times 10^{10} Z^{2.4}(\tau_x - \tau_l)^{1.25}, \qquad (8)$$

where the units are μm, fs and W cm^{-2} for l, τ and I, respectively. τ_l is the duration of the laser pulse and $\tau_x = \tau_a + \tau_l$ is the time of the first 90% of x-ray emission which is large than its full width at half maximum, τ_a is the duration of afterglow emission. Table 1 gives the parameters of the seven elements in Fig.1

Table 1. Calculated parameters of foil targets for the generation of 100 fs K line pulses and K line yield for calculated l and $I_{\rm opt}$ at wavelength 0.8 μm.

Element	Z	l/μm	$I_{\rm opt}$	Yield/(photons/sr)
Ti	22	1.5	3.9×10^{15}	9.2×10^{9}
Fe	26	1.6	5.8×10^{15}	7.6×10^{9}
Cu	29	1.7	7.5×10^{15}	6.5×10^{9}
Mo	42	2.1	1.8×10^{16}	3.5×10^{9}
Ag	47	2.2	2.4×10^{16}	2.8×10^{9}
Ta	73	2.8	6.9×10^{16}	1.2×10^{9}
Au	79	2.9	8.3×10^{16}	9.6×10^{8}

predicted by Eq.(8) for a desired x-ray pulse duration of 100 fs, taking into account the 60 fs laser pulse.

4. Conclusion

It has been shown that the sub-picosecond x-ray emission on several targets can be produced from a femtosecond laser-produced plasma. Theoretical studies and analytical scalings are carried out to find the optimized laser parameters and target conditions, so that the short x-ray pulses and high x-ray power can be achieved.

Firstly, it has been shown that for the laser intensity of $I < 10^{18}$ W cm^{-2}, the light element target is most suitable to produce higher yield of x-ray emission. In our present experimental condition, the copper target is of interest, and the K_α wavelength of 0.154 nm is suitable for many applications, for example, the time-resolved x-ray diffraction in solid dynamics.

Secondly, to obtain the maximum yield, the optimal intensity can be decreased when a long-wavelength of the laser is chosen. In the present condition, the intensity 4×10^{15} W cm^{-2} can be available to obtain a maximum yield of 7×10^{9} photons/sr per pulse for copper target at a wavelength of 800 nm. This yield of x-ray photons is sufficient for the application of solid state physics. But for the biological application, such as the time-resolved diffraction of protein, which needs a flux of about 10^{11}–10^{12} photons per pulse, further optimization should be made. In addition, a high repetition-rate laser system is also desired to yield high intensity in a single shot.

Thirdly, the laser pulse duration should be several tens or hundreds femtoseconds to achieve a short pulse duration for the x-ray emission. The thickness of the target and the laser intensity should be well-chosen to achieve a desired duration of x-rays. Although more detailed calculations are needed to accurately determine the duration of x-rays, our estimate shows that the sub-picosecond x-ray pulse should be available for foil target. Further studies will include the effects of other conditions, such as the incident angle of laser, re-absorption of produced photons, etc.

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