K-shell x-ray emission enhancement via self-guided propagation of intense laser pulses in Ar clusters

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Abstract: K-shell x-ray at about 3 keV emitted from Ar clusters irradiated by 110mJ 55 fs intense laser pulses is studied. The x-ray flux is optimized by moving the nozzle away from the focus of the laser pulse. The total flux of K-shell x-ray photons in 4π reaches a maximum of 4.5×109 photons/shot when the nozzle displacement is 2 mm and a long plasma channel is observed by a probe beam.

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References and links
1. Introduction

The intense laser interactions with clusters have been extensively studied because of potential applications including hot electrons ejection [1, 2], MeV ions generation [3], x-ray emission [4, 5], and table top laser driven nuclear fusion [6]. Compared to solid target, the x-ray sources from laser driven clusters have the advantage of debris-free and high coupling efficiency of laser energy to the plasmas [7].

It is important to improve the brightness of x-ray source for time resolved diagnostic applications requiring single shot imaging. Laser and cluster parameters have been investigated to enhance the x-ray yields in several experiments [8]. It is shown that soft x-ray emission is enhanced by cooling the gas resulting in efficient collisional heating and ionization of larger clusters [9]. Doped Ar clusters are also used to change the ionization dynamics with easily ionizable H₂O molecules to increase K-shell x-ray emission [10]. Most of these experiments explore optimization of x-ray emission by altering the interaction dynamics of laser pulses with individual cluster, while only a few results concern on macroscopic effect of laser propagation in clusters [11].

The guided propagation of intense laser pulses in plasma channels is a popular method to increase the conversion efficiency in high order harmonics [12] and soft x-ray [13] generation by extension of the interaction length. Up to now, it is rarely used in hard x-ray generation by laser cluster interaction. Moreover, the correlation between hard x-ray generation and plasma channel in clustering gas is more complicated. Clustering gas has been demonstrated as an efficient medium for self-guided propagation of laser pulses [14, 15]. However, it is observed that x-ray emission decreases when plasma channels are created due to the maximum laser intensity available limited by ionization induced refraction [11].

In this paper, we report the experimental results of K-shell x-ray emission enhancement by self-guided propagation of intense laser pulses in Ar clusters. The total flux of K-shell photons is optimized when plasma channels are created by moving the cluster jet away from the focus of pulses.
2. Experimental setup

The experiment was performed at Institute of Physics, Chinese Academy of Sciences, with the Xtreme Light II (XL-II) Laser system [16]. Laser energy of 110mJ with duration of 55fs was used to carry out the experiment. The linearly polarized 2TW laser beam at 800 nm is focused on the target by an f/3.5 off-axis parabolic mirror (OAP) to a focal spot with size of 5 \( \mu \text{m} \) in FWHM, corresponding to a vacuum peak intensity of \( 6.6 \times 10^{18} \text{W/cm}^2 \).

Figure 1 shows a sketch of the experimental setup. The main laser pulse propagates along \( x \) direction and is focused by the OAP onto the Ar clustering gas jet with back pressure of 4 MPa at \( z=2 \text{mm} \). The origin of coordinates is defined as when the focus spot of the laser pulse is on the axis of the jet at the output of the nozzle. The spectrum of the x-ray emitted in \( x \) direction was measured with a 16 bit single photon counting charge coupled device (LCX CCD, Roper Scientific) [17]. A 30\( \mu \text{m} \) thick Be filter in front of the LCX CCD is used to block the x-ray with energy lower than 0.7 keV and the laser light. The energetic electrons accelerated forward are deflected by a magnet to reduce the background x-rays generated by the bremsstrahlung radiation. A probe beam propagates through the plasma in the \( y \) direction to get the shadowgraph of the plasma profile.

The clustering gas jet is produced by expanding of high pressure Ar gas out of a conical nozzle with a 3 mm diameter orifice and 1 mm diameter throat. We have characterized the atom density profile of the gas jet with an interferometer. The gas jet density profile at \( z=2 \text{mm} \) with 4 MPa stagnation pressure is presented in the inset of Fig. 3. The mean size of clusters can be characterized by a parameter \( \Gamma^* \) introduced by Hegena [18]: \( \Gamma^*=k/d\tan \alpha_0^{0.85}P/T^{2.29} \), where \( k \) is a constant depends on the atom species (\( k=1650 \) for Ar), \( d \) is the throat diameter in \( \mu \text{m} \), \( \alpha \) is the half opening angle of the nozzle (\( \alpha=8^\circ \)), \( P \) and \( T \) is the initial pressure and temperature of the gas before expansion. The mean number of atoms per cluster \( N_{\text{cl}} \) scales as: \( N_{\text{cl}}=100(\Gamma^*/100)^{1.8} \) [19]. \( N_{\text{cl}} \) is estimated to be \( 2.3 \times 10^6 \) and cluster radius is 270 \( \AA \) for our experimental parameter. The formation of Ar clusters is verified experimentally by Rayleigh scattering as shown in the inset of Fig. 1. The scaling law, \( S \propto P^{2.44} \), indicates a gas cluster mixed target.

![Fig. 1. Sketch of the experimental setup. The inset shows the dependence of Rayleigh scattered signal \( S \) on the gas jet back pressure \( P \). The experimental data is fitted by \( S \propto P^{2.44} \).](image)

3. Experimental results and discussion

Figure 2 shows a typical spectrum obtained in experiment. The peak at about 3 keV is identified as K-shell emission and the background x-ray with energy < 3 keV is from low charge state ions and bremsstrahlung. The width of the peak is 163 eV in FWHM, comparable to the resolving limit of the detector (150 eV at 3 keV). It is worthy to mention that the intensity contrast of peak to background is about 40 which is much higher than the previous results of x-ray sources from solid targets [20, 21] and clusters [22]. This high contrast k-shell
x-ray source with much less energetic tail may have applications in imaging to improve the imaging figure of merit. The dependence of K-shell photons emitted into 4π on the laser peak intensity measured in vacuum is shown in the inset of Fig. 2. The x-ray flux is just above the detection threshold of the LCX CCD when the laser intensity is very low. The x-ray yield begins to increase quickly when the vacuum laser intensity increases to be above 1×10^{18} W/cm^2.

![Fig. 2. X-ray spectrum emitted from Ar clusters. The inset shows the dependence of K-shell photons emitted into 4π on the laser peak intensity measured in vacuum.](image)

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![Fig. 3. Dependence of the total flux of K-shell photons emitted into 4π on the nozzle position relative to the focus point of laser pulses. The dots are experimental data averaged by 5 shots, and the error bars are standard deviation errors. The inset shows the atom density profile at z=2mm and 4 MPa stagnation pressure.](image)

Fig. 3. Dependence of the total flux of K-shell photons emitted into 4π on the nozzle position relative to the focus point of laser pulses. The dots are experimental data averaged by 5 shots, and the error bars are standard deviation errors. The inset shows the atom density profile at z=2mm and 4 MPa stagnation pressure.

In order to optimize the x-ray flux, we moved the nozzle away from the focus spot along x direction. The dependence of the total flux of K-shell photons in 4π on the nozzle displacement is shown in Fig. 3. The x-ray flux is low when the laser pulses are focused on the gas jet axis. As the nozzle moves away from the laser focus spot, the x-ray yield is enhanced and reaches its maximum of 4.5×10^9 photons/shot when the displacement is 2 mm. The conversion efficiency of laser pulse energy to K-shell x-ray is about 2.5×10^{-5}. Our results are comparable to that obtained with a much higher laser power of 100TW [23]. The x-ray flux will decrease when the distance is increased further.
Transverse shadowgraphs of the plasma when the nozzle is 0, 2.5, and 4 mm away from the laser focus are presented in Fig. 4. When the laser is focused on the gas jet axis, a uniform plasma column with diameter of about 360 µm is observed as shown in Fig. 4(a). The intensity of the laser beam is estimated to be $2 \times 10^{15}$ W/cm$^2$ corresponding to this diameter. When the displacement is 2.5 mm, a 1.5 mm long plasma channel with diameter of 68 µm is created in Fig. 4(b). The channel length is about $14Z_R$, where $Z_R = \pi w_0^2/\lambda$ is the Rayleigh length of the laser pulses in vacuum, $w_0$ is the beam waist at the focus obtained in vacuum, $\lambda$ is the wavelength of the laser beam. The intensity of the laser beam inside the channel is estimated to be $5.5 \times 10^{16}$ W/cm$^2$. The quivering energy of electrons in this laser fields $\varepsilon = e^2 E^2/(2 m_e \omega_0^2)$ is 6.5 keV, where $e$ and $m_e$ is the electron charge and mass, $E$ is laser electric field, and $\omega_0$ is the laser angular frequency. This energy is enough to efficiently create inner-shell vacancies by collisions with Ar atoms and ions for the generation of K-shell x-ray [24].

![Image of shadowgraphs](image)

Fig. 4. Transverse shadowgraphs of the plasma profile when the nozzle is 0 (a), 2.5 mm (b) and 4 mm (c) away from the laser focus. The laser propagates from the right to the left. The focusing cone of the laser pulse in vacuum is marked with white lines in (b) and (c). The position of laser focus is indicated by the arrows. The plasma column and channel is marked by red lines in (a) and (b).

We believe that the enhancement of the K-shell x-ray emission is due to the self-guided propagation of laser pluses in the long plasma channel. As described by the Hydrodynamic model of the intense laser-cluster interaction proposed by Milchberg et al [25], Electrons are ionized and heated by the rising edge of the intense laser pulse. The local electron density inside the cluster increases to supercritical and then decreases to subcritical during the expanding of the nanoplasma. The refractive index of the plasma will increase from 1 to >1 and then decrease to <1 during the cluster pre-heating procedure. So the plasma acts as a convex lens to focus the laser beam and then a concave lens to defocus the laser beam. For low energy laser pulses, long pulse duration [14] or a prepulse [15] is needed to heat the clusters for self-focusing and guided propagation.

In our experiment, we alternatively optimize the laser propagation in clusters by moving the cluster jet away from the laser pulse focus. When the laser is focused inside the clustering jet, the plasma created by the leading edge of the laser pulse has already expanded to subcritical and then the laser beam is defocused to a large size. This phenomenon rules out the possibility that the relativistic self-focusing leads to the self-guiding of the laser pulse, because in that case, a high intensity is preferable. When the nozzle is moved away from the laser focus, the laser pulses incidence on the clusters have a larger beam size and lower intensity, which delays the time when the laser rising edge can ionize and heat the clusters. The electron density in the cluster will still be supercritical when the laser peak arrives. A distance of 2-2.5 mm is optimal for x-ray generation in our case. The balance between the convex lens effect and the refractive effect leads to the laser self-guided propagate in the
clusters at a high intensity for a long distance, as shown in Fig. 4(b). When we decrease the laser pulse energy to about 15 mJ, pulse duration of about 500 fs is needed to optimize the x-ray flux. This observation is consistent with the previous results [26]. When the nozzle is moved further away from the focus of the laser, the laser beam becomes divergent as shown in Fig. 4(c) and the laser intensity is too low to heat the cluster sufficiently.

3. Conclusions

In conclusion, we have presented K-shell x-ray emission from Ar clusters irradiated by 110mJ 55 fs laser pulses. Emission of K-shell x-ray photons with energy peaked at about 3 keV without a Maxwellian distributed background is obtained. The x-ray flux is optimized by moving the nozzle away from the focal point of the laser pulses. The total flux of K-shell photons emitted into 4π reaches up to 4.5×10⁹ photons/shot and the corresponding conversion efficiency is 2.5×10⁻⁵ when the nozzle displacement is 2 mm. The x-ray emission enhancement is correlated with self-guided propagation of intense laser pulses in Ar clusters and a long plasma channel is observed.

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