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A K-alpha x-ray source using high energy and high repetition rate laser system for phase contrast imaging

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Abstract

K-alpha x-ray sources from laser produced plasmas provide completely new possibilities for x-ray phase-contrast imaging applications. By tightly focusing intense femtosecond laser pulses onto a solid target K-alpha x-ray pulses are generated through the interaction of energetic electrons created in the plasma with the bulk target. In this paper, we present a continuous and efficient Mo K-alpha x-ray source produced by a femtosecond laser system operating at 100 Hz repetition rate with maximum pulse energy of 110 mJ before compression. The source has an x-ray conversion efficiency of greater than 10^{-5} into K-alpha line emission. In preparation for phase contrast imaging applications, the size of the resultant K-alpha x-ray emission spot has been also characterized. The source exhibits sufficient spatial coherence to observe phase contrast. We observe a relatively small broadening of the K-alpha source size compared to the size of the laser beam itself. Detailed characterization of the source including the x-ray spectrum and the x-ray average yield along with phase contrast images of test objects will be presented.

Keywords

hard x-rays; laser-produced plasmas; x-ray source; x-ray phase-contrast imaging

1. INTRODUCTION

Recent developments of the high-intensity and high-repetition ultrafast lasers have lead to the production of high mean fluxes of quasi-monochromatic K_{α} x-rays. In general, efficient K_{α} radiation is generated by tightly focusing femtosecond laser pulses onto a solid target with peak intensities in the range of $10^{15} - 10^{18}$ W/cm². Solid density plasma is produced at the metal surface where hot electrons are generated during the laser irradiation. Some electrons penetrate inside the target emitting bremsstrahlung and characteristic radiation. Such ultrafast laser-based K_{α} x-ray sources are of high interest for biomedical imaging applications, which depend strongly on the emission source size to achieve high spatial resolution and contrast. K_{α} x-ray sources with sizes similar to the laser focus ones can be in

principal realized. Moreover, laser-produced K_{α} x-ray sources offer energy tunability as their energy can be easily selected by changing the target material. In this work, we report an x-ray source size below $10\text{ }\mu\text{m}$ allowing imaging with high spatial resolution. With such a small x-ray source size, phase contrast imaging can be achieved. This imaging technique takes advantage of partially-coherent x-rays to enable visualization of internal soft tissue that cannot be observed via conventional absorption radiography. Traditionally, the x-ray imaging provides a map of the absorptive properties of the sample. Consequently, for samples with minimum absorption such as soft tissue, the differences in sample absorption yield to poor image contrast. Since the x-ray phase-contrast imaging uses spatially coherent x-ray photons, they create constructive and destructive interference patterns as they cross regions of differing indices of x-ray refraction in a sample. These patterns enable high-contrast imaging of interfaces within the sample.

These sources are very interesting for *in vivo* phase contrast micro Computed Tomography (micro-CT) of small animals' soft tissue cancer models. However, during the *in vivo* scan, for which the duration should be no longer than 1 hour, it is necessary to reach a sufficiently high and stable average x-ray flux while keeping the x-ray source size small. This can be achieved by either increasing the energy and/or the repetition rate of a femtosecond laser system with high-contrast laser pulses. From this prospective, it has been proposed to build a laser for biomedical imaging with 100 TW of instantaneous power, 100 Hz repetition rate and 400 W of average power (ASUR project)¹. Consequently, after indicating the potential for phase contrast imaging with a 10 Hz laser system and 9 W power before compression², we decided to test the prospective of a laser system with higher repetition rate of 100 Hz and 11W. Besides the challenge to develop a new x-ray source of high-energy K-alpha x-rays with sufficient x-ray flux, also a constant x-ray yield has to be attained with such a high thermal load on the optical components. Using high energy and high repetition rate femtosecond laser pulses, we report an efficient K-alpha line emission and a small x-ray source size (compared to the laser spot size) resulting in a high x-ray source brightness from material targets with higher atomic number Z (i.e. Mo), appropriate for biomedical x-ray imaging.

The K-alpha x-ray production depends on the target geometry and the laser beam parameters in a relatively complex way. Many groups have recently embarked on optimization of hard x-ray sources by using different laser-target configuration, i.e. laser intensity, polarization, prepulse contrast ratio, target material, and target thickness. The first studies on the hard x-ray emission from femtosecond laser-produced plasmas have been done using low-repetition-rate lasers systems with pulse energies in the range of hundreds of millijoules to joules per pulse that can emit a large number of x-ray photons per pulse^{3–8}. With the recent development of the laser technology, K_{α} x-ray sources have been extensively studied with various femtosecond laser systems operating from single shot mode up to 10 kHz repetition rate^{9–14}. The most efficient K_{α} generation with ultrashort laser pulses is reported from laser systems with low repetition rate ($< 10\text{ Hz}$). Rousse et al.³ have realized the first characterization of the K-alpha x-ray emission with a femtosecond laser system at 10 Hz obtaining a conversion efficiency of 3.4×10^{-5} for the 6.4 keV Fe K-alpha line emission at a laser intensity of $3 \times 10^{16}\text{ W/cm}^2$, with an optimized prepulse, much above the present values

obtained for the Mo K-alpha line. The conversion efficiencies into K_{α} line radiation from these laser systems are in the range of 10^{-5} – 10^{-4} . For instance, Eder et al. 4 reported a very high conversion efficiency of 4×10^{-4} Cu K_{α} using large energy laser pulses of 200 mJ and laser intensity of nearly 10^{17} W/cm² with a large contrast ratios of 10^{-4} and 10^{-6} . However, it is expected that the extended preplasma may affect the size of the x-ray emission spot as shown by measurements. Many K_{α} x-ray sources have been developed using low-medium atomic number Z target materials such as Cu, Fe, Cr or Ga. However, the relatively low energy of the K_{α} lines from these elements makes these sources to be suited for x-ray diffraction measurements but not optimized for biomedical imaging. Only few experimental studies have been reported on the realization of K_{α} x-ray sources with higher energy x-ray photons from heavy metals such as Ag or Mo. Yu et al. 7 produced K_{α} x-ray radiation with frequency doubled high-contrast laser using Ag target. The x-ray energy and the x-ray source size were of interest for biomedical imaging but the repetition rate was too low for such applications. High-energy 600 mJ and high-intensity 4×10^{18} W/cm² K_{α} x-ray radiation has been produced using Ag target resulting in 2×10^{-5} conversion efficiency but, due to the large laser prepulse, the x-ray source size was 5 times larger, as compared to the 10 μ m optical focal spot size 5. Adjusting the prepulse contrast ratio, the previously reported results have used varied degrees of preplasma and clearly, the level of preplasma is an important parameter in the efficiency of the K_{α} production.

Apart from focusing intense femtosecond laser pulses onto solid targets, hard X-ray pulses can be also produced by synchrotron sources. Their average X-ray flux is very large and provides good coherent radiation, but they are expensive and require a large facility. In comparison, laser produced plasma X-ray sources are relatively small facilities. Because of their small size and low facility cost, laser-produced plasma x-ray sources offer an alternative for economical and compact sources of hard x-rays.

The objective of this work is to investigate the K_{α} x-ray production from a laser-produced plasma x-ray source by using a femtosecond laser system with high energy (110 mJ per pulse before compression) and high repetition rate (100 Hz). In this study, we use frequency-doubled laser pulses in order to enhance the laser pulse contrast ratio and to keep the x-ray source size close to the laser spot size. We demonstrate long-term stability of the x-ray yield (hence the long-term stability of the x-ray flux), conversion efficiency higher than 1.5×10^{-5} with a high Z Mo target, and the x-ray spot size close to the optical focal spot.

2. EXPERIMENTAL SETUP

This experiment was carried out at the Advanced Laser Light Source (ALLS) Canadian facility 15 with the 100 Hz commercial prototype laser system 16 built by Thalès Laser. It is based on Ti:Sapphire amplification crystals and the chirp pulse amplification (CPA) technique. This system produces laser pulses at 800 nm fundamental frequency with 100 Hz repetition rate, 35 fs pulse duration and a maximum 80 mJ energy after compression. The incident average power on the compressor grating is 11 W. For 800 nm, a fast photodiode using calibrated neutral density filters and a third order autocorrelator have been employed to measure the nanosecond and picosecond prepulses, respectively. The laser pulse contrast ratio is better than 10^{-5} both in the nanosecond time range and in the picosecond time range

for a delay higher than 5 ps prior to the main pulse. About one picosecond prior to the main pulse the laser pulse contrast is 4×10^{-5} . The nanosecond prepulses are produced in the regenerative amplifier as leakage through the Pockels cell before the final pulse is switched out. Because the main pulse is focused to peak intensities higher than $5 \times 10^{17} \text{ W/cm}^2$, the nanosecond prepulses originated from the regenerative amplifier may be focused to intensities of about $5 \times 10^{12} \text{ W/cm}^2$. Laser ablation for metals requires intensities in the range of 10^{12} – 10^{14} W/cm^2 for ultrashort pulse laser-matter interaction mode¹⁷ and thus, the existing prepulses at fundamental frequency will create a small preplasma at the surface of the target. To improve the laser pulse contrast ratio, the pulses were frequency-doubled by a Type I, 1-mm thick KDP crystal. The measured conversion efficiency was 20 % that reduced the average laser power down to 1.5 W on the target. The laser pulse contrast ratio for the frequency-doubled pulses were estimated it to be better than 10^{-9} at 400 nm^{7,18–20}.

Using a f/3 off-axis parabola the 400 nm beam is focused onto a molybdenum solid target into a 7.5 μm diameter (FWHM) focal spot resulting in a peak intensity of $8 \times 10^{17} \text{ W/cm}^2$ on target. Thus, for the same focusing conditions, the prepulses at 400 nm are focused to intensities lower than 10^9 W/cm^2 that is much below the ablation threshold for metals. The size of the laser spot in the focus position was monitor by a high magnification imaging system consisting of a lens with 10-cm focal length and a CCD camera located 2.5 m away with a 10 $\times$ microscope objective. The target was moved continuously to ensure that the beam is interacting with a fresh surface for each laser shot. Over one rotation, the target was kept in focus within 10 μm from the focal spot along the laser axis. The target holder is translated under vacuum to allow beam propagation at maximum energy into the imaging system or to set the target in position during the measurements. Protective thin plate of fused silica was used in front of the off-axis parabola mirror to avoid any coating that may result in its deterioration and consequently, in the decrease of the x-ray yield. The laser is not fully *p*-polarized due to geometric constraints. The experimental setup is depicted in figure 1.

The X-ray emission was measured with two identical scintillator-photomultiplier detectors (PMT) filtered by a beryllium (Be), symmetrically positioned outside of the vacuum chamber as shown in figure 1. A pulse height X-ray spectrometer has also been used to measure the x-ray spectra. First of all, focal scan measurements have been carried out with the PMT detectors to ensure the location for the maximum x-ray signal. Once the location of the x-ray signal was determined, the x-ray spectra were measured with a CZT detector (Amptek) positioned at 60 cm distance from the target (35 cm in air). This detector had a light-tight vacuum Be window with 10 mil thickness.

The signal from the CZT detector was amplified in a preamplifier (Amptek) and finally fed into a multi-channel analyser MCA (micro-ACE, Ortec). The whole detection system was calibrated with Am-241 radiation source at 13.95 keV and 59.54 keV. The detector was located at a large distance from the plasma source outside the vacuum chamber and a small aperture of $\sim 100 \mu\text{m}$ diameter of tungsten (thickness 2 mm) was placed at the detector head to reduce the x-ray flux in order to operate in single photon counting mode. The $K\alpha$ x-ray source size is measured by the knife-edge technique using a 1mm-thick tungsten sheet and a cooled PI-SCX4300 (Roper Scientific) Charge-Coupled Device (CCD) camera coupled to a Gd_2SO_4 scintillator. For convenient coupling of scintillator screens to the CCD, a 1:1 fiber-

optic faceplate is permanently bonded to the chip. This faceplate isolates the CCD, which is placed under vacuum. This CCD has a 50×50 mm field-of-view and 2084×2084 pixel CCD chip. It offers 16 bits of digitization.

3. RESULTS AND DISCUSSION

A mechanical shutter situated at the entrance of the compressor vacuum chamber was utilized to introduce the laser beam into the experimental system. Because we observed a decrease of the x-ray flux occurring shortly after the beam was inserted in the experimental setup, such that after about 2 minutes the PMT signal has decreased by 80%, we embarked in a characterization of the laser beam focal spot. We noticed a beam focal spot distortion after 10 sec when using the 100 Hz laser repetition rate. The distortion evolved for about 2 minutes before stabilization. This behavior of the focal spot of the laser beam is depicted in Figure 2. Using 10% energy, the laser spot size was measured to be $7.5 \times 7.4 \mu\text{m}$ FWHM (Fig. 2a). When the laser pulse energy was increased up to its maximum value we observed a laser beam distortion due to 11 W thermal loading of the compressor grating under vacuum (Fig. 2b)²¹. Because this distortion was mainly defocusing resulting in a 500 μm displacement of the focal spot position, the beam focusing was easily corrected under vacuum and the resulting corrected spot size was $6.9 \times 7.4 \mu\text{m}$ FWHM (Fig. 2c).

X-ray spectra had been acquired for 300 s and they are presented in Fig. 3. The laser system was operated in two modes: either using 110 mJ maximal energy before compression, resulting in 15 mJ at 400 nm incident on target or using 90 mJ maximal energy before compression resulting in 9 mJ at 400 nm incident on target. A typical x-ray spectrum obtained with 110 mJ before compression and no correction for the thermally induced effects is display in Figure 3 (a).

We measured conversion efficiency of 1.5×10^{-5} into K_{α} x-rays (using 110 mJ energy) with 28 % of the detected photons in the K_{α} lines, while using 90 mJ energy, we measured 5×10^{-6} conversion efficiency into K_{α} x-rays. The laser peak intensities were $8 \times 10^{17} \text{ W/cm}^2$ and $5 \times 10^{17} \text{ W/cm}^2$, respectively. During the acquisition time of the x-ray spectrum, we noticed an increase of the soft x-rays counts, as compared to the hard x-rays counts after 90 s of acquisition. This was consistent with the decrease in the laser intensity due to laser focal spot distortion. After 30 s of operation, we also observed a decrease in the signal values of the two PMT detectors and after 90 s, their values became 25% of their initial values. As deduced from the x-ray spectra, the K_{α} x-ray source flux was $1.2 \times 10^9 \text{ ph/(sr.s)}$ and $2.8 \times 10^8 \text{ ph/(sr.s)}$ using laser energy (at the compressor entrance) of 110 mJ and 90 mJ, respectively.

The size of the resultant emission spot source has been also characterized for potential applications. Figure 4 displays the horizontal and vertical intensity profiles measured using the standard knife-edge method after 5 minutes of acquisition time. The x-ray source size was $8.5 \mu\text{m} \times 16 \mu\text{m}$ FWHM. Due to the experimental geometry the laser focal spot was projected onto the target resulting in $6.9 \mu\text{m} \times 8.8 \mu\text{m}$ at FWHM. Thus, the x-ray source size was only 1.2×1.8 times greater than the laser focal spot size. Such an x-ray source size, confirms the high applicability for phase contrast x-ray imaging applications.

The images in figure 5 show the results of x-ray phase-contrast imaging of a silicon edge and a nylon wire using this K_{α} x-ray source. Both the object and the detector have been positioned in air with the source-to-object distance of 25 cm and the object-to-detector of 150 cm. The raw images display a honeycomb background pattern due to fiber optic taper of the detector. This was subtracted when plotting the intensity profiles for each sample. The resultant intensity profiles are specific to the phase-contrast interference pattern demonstrating the potential of the source for biomedical imaging applications.

We note that the high contrast of the driving pulses is a major point of this work to be able to get a small x-ray source size to achieve high resolution phase-contrast imaging. Preliminary experimental studies have been carried out at fundamental frequency for which the prepulse is high enough to create small plasma on the surface of the target material prior to the arrival of the main pulse. The x-ray source size is observed to be at least twice as large as compared to the case of no prepulse. Observing the influence of the prepulse on the x-ray source size will be the subject for the future investigations. The increase of the incident energy on target by a factor of five while keeping high contrast ultrashort laser pulses can be realized by using either cross-polarised wave (XPW) generation²² and booster amplifier²³.

4. CONCLUSIONS

The emission of keV X-rays from laser-produced plasmas using a high-energy high-power femtosecond laser system was studied in order to develop a K_{α} X-ray source to be operated for x-ray imaging applications. Emphasis was set for ensuring high contrast laser pulses in order to reduce the x-ray source size close to the laser focal spot, thus achieving good spatial resolution and contrast for biomedical applications. We obtained a peak conversion efficiency of 1.5×10^{-5} into K_{α} line using high Z target material necessary for imaging applications.

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Fig.1.

Schematic experimental setup. The 400 nm laser beam is represented by the blue lines. OAP, off-axis parabola. The x-ray diagnostics were located outside the vacuum chamber and filtered by a Be window: two symmetrically positioned photomultiplier (PMT) detectors, a CZT X-ray detector and a X-ray CCD camera for source size measurement. The imaging system consists of a lens with focal length $f=+10$ cm lens and $\times 10$ microscope objective connected to CCD placed outside the vacuum chamber.

Fig.2.

Two dimensional laser beam profile measured with the imaging system. The lens images the plane corresponding to the center of the vacuum chamber: (a) focal spot under vacuum and 10% energy; (b) beam shape profile after stabilization (about 2 minutes) at 100% energy and (c) focal spot obtained after moving the off axis parabola along the laser axis to compensate for the thermal induced distortion.

Fig.3.

X-ray spectra obtained with the CZT detector: (a) using 110 mJ laser pulse energy before compression and no correction for the thermally induced effects (laser beam focal spot is align at air and low energy), (b) using 90 mJ laser pulse energy before compression and no correction for the thermally induced effect and (c) using the same energy as in the previous case but with compensation for the thermally induced effect. The laser beam is propagated through the experimental system until a steady state for the thermal loading is reached, and then, the focal spot is corrected by moving the off axis parabola.

Fig.4.

Intensity profile of the Mo K α spot size measured by the knife-edge technique (red line) and Gaussian fit (black line): (a) horizontal profile and (b) vertical profile. The knife-edge was a tantalum edge.

Fig.5.

X-ray imaging of a silicon edge and a nylon wire using the 17.5 keV K-alpha line from Mo target. The test objects are positioned at 25 cm from the x-ray and the object-to-detector distance is 150 cm: (a) raw image, (b) image with background subtracted, (c) the intensity profile of the silicon edge and (d) the intensity profile of the nylon wire.