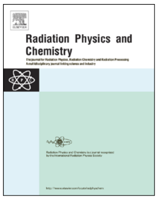
Radiation Physics and Chemistry ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem



Laser-driven powerful kHz hard x-ray source

Minghua Li [a,1], Kai Huang [a,1], Liming Chen [a,*,1], Wenchao Yan [a,1], Mengze Tao [a,1], Jiarui Zhao [a,1], Yong Ma [a,1], Yifei Li [a,1], Jie Zhang [b,c,2]

[a] *Beijing National Laboratory of Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[b] *Key Laboratory for Laser Plasmas (MOE) and Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[c] *IFSA Collaborative Innovation Center, Shanghai Jiao Tong University, Shanghai 200240, China*

HIGHLIGHTS

- The most powerful laser plasma Kα hard x-ray source with high spatial coherence.
- The first time to stimulate Vacuum Heating with a KHz laser system.
- Absorption mechanism varies with different laser intensity.

ARTICLE INFO

Article history:
Received 3 November 2015
Received in revised form
27 January 2016
Accepted 29 January 2016

Keywords:
laser plasma
high repetition rate
K_α
x-ray source
imaging

ABSTRACT

A powerful hard x-ray source based on laser plasma interaction is developed. By introducing the kHz, 800 nm pulses onto a rotating molybdenum (Mo) disk target, intense Mo K_α x-rays are emitted with suppressed bremsstrahlung background. Results obtained with different laser intensities suggest that the dominant absorption mechanism responsible for the high conversion efficiency is vacuum heating (VH). The high degree of spatial coherence is verified. With the high average flux and a source size comparable to the laser focus spot, absorption contrast imaging and phase contrast imaging are carried out to test the imaging capability of the source. Not only useful for imaging application, this compact x-ray source is also holding great potential for ultrafast x-ray diffraction (XRD) due to the intrinsic merits such as femtosecond pulse duration and natural synchronization with the driving laser pulses.

1. Introduction

It was just after the discovery in 1895 by W.K. Röntgen, X-ray became an invaluable tool for probing the structure of matter due to the short wavelength and strong ability to penetrate. X-ray was utilized throughout the most important discoveries in modern science history. After research and development over one century, the quality of these radiation sources have been greatly improved, either the portable x-ray tubes or the sophisticated km sized synchrotron facilities and x-ray free electron lasers (XFEL). Thanks to the rapid development of the ultra intense femtosecond lasers, the innovative laser-based radiation sources have gone through a worldwide study and progress during the last few decades. Among different schemes of laser-based x-ray sources, one can use the high-order harmonic generation (HHG) method to up-convert the laser to extreme ultraviolet (EUV) or soft x-ray regime (Ding et al., 2014), however, this method suffers the low conversion efficiency and application limitation (very thin samples). Hard x-rays produced by inverse Compton scattering (ICS) of laser and electron beam from compact storage ring (Bulyak et al., 2002; Eggl et al., 2015) and linear accelerator facility (Jochmann et al., 2013) could be tunable and quasi monochromatic, but the relatively long duration of the electron bunch (several picoseconds) makes these sources unsuitable for probing sub picosecond phenomena, they also suffer the low flux due to the small colliding cross section of electron bunch and laser beam. Though the compact storage ring based ICS sources are smaller and cheaper than synchrotron facilities, still they are not table-top and not affordable for many clients.

Laser-driven plasma x-ray sources (Chen et al., 2010; Corde et al., 2013) have compact size (table-top), high brightness (comparable to the 3rd generation synchrotrons), ultra short bursts (femtoseconds), and high spatial resolution (source size sub-10 um). These merits make this kind of source not only promising for ultrafast x-ray science, e.g., time resolved x-ray diffraction, transient physics etc. (Rousse et al., 2001; Vrakking and Elsaesser, 2012), but also affordable for users from universities and industrial

---

[*] Corresponding author.
E-mail address: lmchen@iphy.ac.cn (L. Chen).
[1] Address: P. O. Box 603 (33), Beijing 100190, China.
[2] Address: 800 Dongchuan Road, Minhang District, Shanghai 200240, China.

http://dx.doi.org/10.1016/j.radphyschem.2016.01.042
0969-806X/© 2016 Elsevier Ltd. All rights reserved.

Please cite this article as: Li, M., et al., Laser-driven powerful kHz hard x-ray source. Radiat. Phys. Chem. (2016), http://dx.doi.org/10.1016/j.radphyschem.2016.01.042

laboratory. Among different laser plasma sources, the K_α emission from laser plasma interaction is considered a good choice for applications based on absorption and x-ray diffraction, not only because of the suitable spectral band (2–25 keV), but also the simplicity and reliability. In order to get a high contrast image or diffraction pattern, more photons are needed on the same area of sample. For this reason, a high repetition rate source is generally better than single shot operation even with lower laser pulse energy per shot. With the development of the high power laser operating in kHz (0.5 kHz–10 kHz) mode, the high repetition rate hard x-ray sources have been widely investigated for many years (Hou et al., 2006, 2004; Huang et al., 2014; Ivanov et al., 2011; Jiang et al., 2003; Korn et al., 2002; Witte et al., 2007; Zhang et al., 2014; Zhavoronkov et al., 2005, 2004). Different kinds of target configurations have been demonstrated, including solid metal disk, metal tape, copper wire, liquid jet, and melted gallium. For metallic tape target, the x-ray intensity fluctuation is inevitable which causes extra normalization effort for application (Zhang et al., 2014). Liquid jets also suffer the difficulty in eliminating the fluctuation, in other words, to maintain the density profile of the liquid shot-to-shot, which is very difficult. With a well pre-adjusted target surface, the metal disk could be very stable from shot-to-shot which is verified in our experiment. The surface fluctuation in our experiment is restricted within 2 μm which means our source could continuously work for hours with very small fluctuation. Application experiments including imaging, reflectivity oscillation measurement of superlattice samples and time-resolved x-ray diffraction were also carried out to test the generated sources (Chakera et al., 2008; Silies et al., 2009; Zhang et al., 2014).

Nowadays intensity over 10^{18} W/cm^2 can readily be obtained for kHz laser system, thus it is possible to develop more powerful x-ray sources. In this paper we present a powerful hard x-ray source based on a commercial kHz laser system. By focusing the 14 mJ, 45 fs laser pulses onto a rotating Mo disk target, intense K_α (17.4 keV) x-rays with weak bremsstrahlung are generated. The K_α photon emitted per second is 4.7×10^{10} photons/sr. Corresponding to a conversion efficiency of 5.7×10^{-5}. Incident angle dependence is investigated. The high conversion efficiency indicates efficient heating of the electrons, analysis suggest that VH mechanism is the dominant absorption mechanism during the interaction, which is, to our best knowledge, the first observation of VH stimulation with a KHz laser. Phase contrast imaging and absorption contrast imaging are performed with high resolution.

2. Experimental setup

The experiment was performed at the Laboratory of Laser Plasma in Shanghai Jiao Tong University with a table-top commercial Ti: Sapphire laser system which delivers 800 nm, 14 mJ, 45 fs pulses in 1 kHz repetition rate. The nanosecond contrast ratio is higher than 10^6, which is crucial in our experiment. Former research has revealed that utilization of high contrast femtosecond laser could strongly enhance the x-ray emission via stimulating the VH mechanism (Chen et al., 2008).

The schematic of the experimental setup is shown in Fig. 1. The laser beam with 40 mm diameter is guided into the vacuum chamber and focused by an f/1.5 off axis parabolic (OAP) mirror coated with gold. The focus spot size is measured to be 3.4 μm with full width at half maximum, corresponding with intensity up to 1.2×10^{18} W/cm^2 for 14 mJ single pulse energy. Among different target configuration, we choose to use a rotating Mo disk target due to its simplicity and reliability. The target surface fluctuation while rotating is measured to be less than 2 μm, considering the Rayleigh length is 2 Zr∼23 μm, the target surface fluctuation is negligible. By rotating and translating the disk, every pulse interacts with fresh target surface. We measured x-ray emission with different incidence angle by rotating the target along the vertical axis. When the intense kHz pulses hit the target, pollutional debris is ejected towards the focusing optics. To protect this optics, 12 μm polyethylene terephthalate (PET) thin films is inserted. Noticing in such tight focusing configuration the film is very easy to be damaged if the same area is exposed to the laser beam; two step motors are put in the chamber to keep the film rolling. A 0.9 T magnet is set between the source and the detector in the vacuum to deviate the electrons. The x-ray spectrum and total count detection is realized by using a Cadmium Telluride (CdTe) detector (Amptek Inc., XR-100T-CdTe). The x-rays propagate for 50 cm in vacuum and 100 cm in air before impacting onto the detector. To prevent the pile-up effect, 200 μm aluminum filter and 1 mm diameter Tantalum pinhole is used.

3. Experimental results and discussion

As working on the single photon counting mode in time-integration, the CdTe detector obtains the spectra and the total count of the x-ray photons simultaneously. Taking into account the 2π divergence and attenuation in the air and the filters, the x-ray yield hence conversion efficiency could be deduced. Fig. 2 demonstrates the typical x-ray spectra with the characteristic emission lines superimposed on a broadband bremsstrahlung background. The accumulation time for spectra in Fig. 2 is 10 seconds.

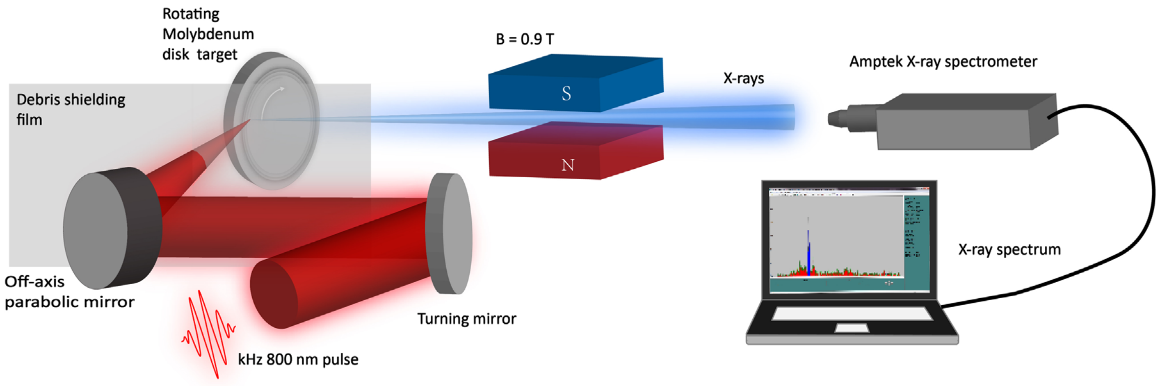


Fig. 1. Schematic of the experimental setup, the x-ray spectrometer is separated from the vacuum chamber by a beryllium window and the rest components are in the vacuum.

Please cite this article as: Li, M., et al., Laser-driven powerful kHz hard x-ray source. Radiat. Phys. Chem. (2016), http://dx.doi.org/10.1016/j.radphyschem.2016.01.042