Multi-keV X-ray conversion efficiencies of laser-irradiated nano-velvet Cu targets

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Abstract: In the study of the interaction between the ultra intense laser and material, it is often focused on the needed quality light source to diagnose the dynamic material structure. In order to obtain a high-quality X-ray source featured with high luminance, quasi-monchromaticity and good contrast, the changes in the structure of matters and materials are often investigated to enhance the absorbability of the ultra intense laser energy and improve the conversion efficiency from the laser radiation to the X-ray. Based on a porous structure principle, the velvet Cu targets were developed with a diameter of 200 nm and the density ratio of 70% solids of Cu. Experiments had been carried out on XG-Ⅲ laser facility in Laser Fusion Research Center, China Academy of Engineering Physics. The laser intensities in these experiments ranged from 4.3 J to 6 J on the target surface. A single-photon- counting X-ray CCD was used to measure $K\alpha$ spectrum of the X-ray source. The X-ray yield was counted to achieve $K\alpha$ peak photons of 3.6×10^8 photons$\cdot$sr$^{-1}\cdot$s^{-1} from femtosecond irradiated velvet Cu target. The $K\alpha$ X-ray conversion efficiency (CE) reaches the maximum value 0.008 68%. Compared with the average CE of the pressed foil Cu target, that of velvet Cu increased 1.2 times. The experimental data showed that the velvet structure can effectively enhance the energy absorption of femtosecond laser and improve the conversion efficiency from the ultra-intense laser to the hot electron and X-ray.

Key words: laser interaction with matter; nano-velvet; conversion efficiency; X-ray source

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激光驱动纳米须靶产生 X 射线转换效率研究

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摘 要: 在研究超强激光与物质相互作用中, 研究的焦点通常需要高质量的光源来诊断动态物质的

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结构。为了获得高亮度、准单能和高对比度 X 射线光源,改变物质及其结构来增强吸收激光能量和提高激光 X 射线的转换效率。利用多孔结构原理,设计了直径为 200 nm、密度为铜 70%的纳米铜靶。在中国工程物理研究院激光聚变研究中心星光-Ⅲ激光装置上进行实验, 作用于靶表面的飞秒激光强度大于 2×10^{18} Wcm^{-2},利用单光子计数型 X 射线 CCD 测量了 Ka 特征 X 射线,获得的 Ka 光子峰值产额达到了 3.6×10^{8} photons·sr^{-1}·s^{-1},X 射线最大转换效率达到 0.008 68%, 是平面铜靶转换效率的 1.2 倍。实验表明纳米须结构能够有效增强飞秒激光的能量吸收,增强了超强激光转换成电子和 X 射线的转换效率。

关键词: 激光与物质相互作用; 纳米须; 转换效率; X 射线源

1 Introduction

The interaction of ultra-short intense laser pulses with a wide variety of targets has been studied in various fields, including the particle acceleration and ultrafast X-ray production. An ultra-short-pulse high-intensity laser not only measures the ultra-hot electron flow behavior under extreme conditions, but also provides temporally resolved ultrafast phenomena in a plasma[1-2]. In early experiments, most laser peak intensity of about 10^{15} W/cm^2 was used to make the knowledge of ultra-electron from laser-sold materials through the excited X-ray[3-5]. With the application of laser chirped pulse amplification (CPA)[6], the power intensity was improved up to 10^{22} W/cm^2[7]. $K\alpha$ X-ray yield was increased under ultra-short and ultra-intense laser- materials. X-ray sources with high multi-KeV conversion efficiency (CE) are important for laser fusion and other applications[8].

Several diagnostic techniques were commonly used to measure fast electron spectra and $K\alpha$ fluorescence in foil targets. Workman et al. reported the space resolution of 10 μm point-backlighter X-ray source[9], which were driven by the peak intensity of 10^{17} W/cm^2 at the energy of 300 J and 40 ps. Chen et al. had researched that the CE was up to 0.01% and the X-ray photonic yield was 1.3×10^{7} photons·sr^{-1}·s^{-1} on the 20 TW laser system, extreme Light (XL-II)[10-11]. They found a CE of laser energy into fast electrons between 20% and 40%, and temperatures between 70% and 95% of what would be predicted by ponder motive scaling.

Additionally, another method was adopted to reform the material structure so as to absorb more laser energy. The CE of the Cu $K\alpha$ was estimated to be 0.019% from the interaction of 4 J, 50 fs laser pulse irradiated on a Cu nano-wire target [12], which showed that low density materials could increase laser absorption up to 93% to improve the CE of hot electrons to X-ray sources[13]. Compared with the foil Cu target, CE of nanostructure was up to 20-40 times on TIFR laser (30 fs, 10 Hz)[14].

In this paper, we studied how the X-ray yield, as well as the CE, was improved as this material density decreased through the nanostructure of 70% density, and emphasized the influence of surface on the yield of the X-ray emission. First, a brief overview of the experiment setup and velvet target was given. Then, the important quantities for optimizing their CE was identified and supporting experiment data was presented.

1 Experiment setup and velvet targets design

The experiments were carried out on the Ti: sapphire laser at XG-Ⅲ laser facility at China Academy of Engineering Physics. The velvet targets were irradiated by using the laser with energy range from 2 J to 5 J working at a wavelength of 800 nm. The experimental layout is shown in Fig.1. The p-

polarized laser beam with a pulse duration of τ_0=30 fs was focused on the Cu target by a *f*/10 off-axis paraboloidal mirror at an incidence angle of 45°, respectively. The measured full width half maximum (FWHM) of the laser focal spot was about 30 μm. For some shots, the main pulses with a maximum intensity of $2-4.6\times10^{18}$ W/cm^2 were applied to create plasma. In order to measure X-ray source scale experimentally, a 16 bit-single-photon-counting X-ray LCX CCD was employed to obtain X-ray yields. PI-MTE X-ray CCD with a knife edge was used to measure the size and central position of the X-ray source, which was 64.1 degree to the incidence of laser and 23.7 degree to the horizontal plane. 0.6 T magnet was set between LCX and target to change the electronic way.

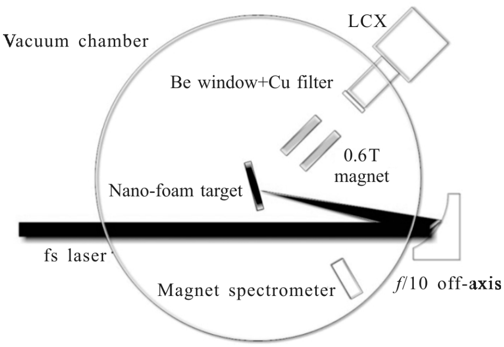

Fig.1 Experiment setup at XG-Ⅲ laser facility

The experimental target was velvet Cu target of 200 nm diameter obtained by alloying process[15]. Fig.2 shows the surface results of velvet target with scanning electron microscopy (SEM). The porous surface was beneficial for absorbing laser energies. After calculation, the target had these characteristics: the proportion of the porosity being about 30%, and the relative density being about 70%. About 64% of the velvet size ranged from 180 nm to 220 nm. The porous material composition was analyzed with the energy dispersive analysis of X-rays(EDAX) equipped with SEM, including Si,O component and so on, which were easily estimated as residual impurities when the etching solution method was used to produce the target with HCl alloy.

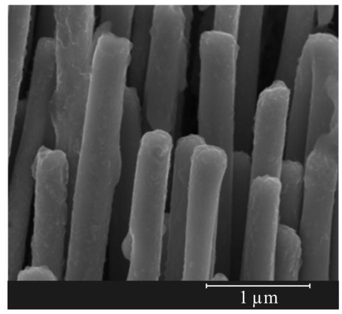

Fig.2 SEM photographs of velvet copper at 40 000 times magnification

In order to block the saturation of CCD photo sensitive element from the intensity of *Kα* X-ray photon, it was essential that the adaptive filter was set to reduce the photon in front of the single-photon CCD. When the X-ray beam transmited through the uniform material, the intensity was proportional to the material thickness, which followed the Beer-Lambert law. In these experiments, the transmittance rate was 0.003 1 followed by copper filter of 120 μm and beryllium of 500 μm in front of LCX CCD at 8 KeV. Obviously, they were effective band pass filters in the range from 7 KeV to 9 KeV by XOP simulation software.

Reich found that the optimum laser intensity $I_{opt}=7\times10^9 Z^{4.4}$ existed for maximum *Kα* yield [16], where *Z* was the atomic number by using analytical and numerical models of hot electron generation and subsequent transport in materials. The result demonstrated that bulk targets were unsuitable for generating sub-ps X-ray pulses, implied that a compromise must be found between small source size and optimum photon yield, and therefore needed future research.

For Cu $I_{opt}\approx1.9\times10^{16}$ W·cm^2-a value consistent with the results reported by Reich model[16]. But Chen et al. found the experimental laser peak intensity was more than 1×10^{18} W·cm^{-2}, which produced the *Kα* yield and CE more than that of Reich model on low contrast laser.

3 Results and discussion

The $K\alpha$ and $K\beta$ spectrum were obtained by single-photon LCX CCD and counted by both WinView/32 and OriginPro/8.5 software (Fig.3). Subtracted background spectrum, $K\alpha$ yields were recorded by X-ray CCD. Based on photon for 4π, the converted rate of the incident laser to $K\alpha$ yields was satisfied with a list mode acquisition.

$$\eta_{K\alpha}=4\pi N(K\alpha)\Delta E\cdot(E\times100\%) \tag{1}$$

Where ΔE is the energy excited Kα, E is the laser incidence energy, N ($K\alpha$) is the number at unit sold angle[17].

$$N(\mathrm{K}\alpha)=\frac{Y(K\alpha)}{\eta T_1T_2\Omega} \tag{2}$$

Here, η is the detector efficiency of CCD. T_1 is called the transmittance efficiency of metal beryllium window. T_2 is called the transmittance efficiency of copper filter and Ω represented sold angle. $Y(K\alpha)$ represented the photon number followed two filters.

$$Y(K\alpha)=N(K\alpha)\eta T_1T_2\Omega \tag{3}$$

Figure 3 showed the $K\alpha$ yield from the foil Cu and velvet Cu targets at angles of 45°. Compared with the $K\alpha$ yield of foil Cu of 1.160×10^8 photons·sr^{-1}·s^{-1}, that of velvet Cu target was up to 3.605×10^8 photons·sr^{-1}·s^{-1} shot by laser intensity of 4.64 W/cm^2.

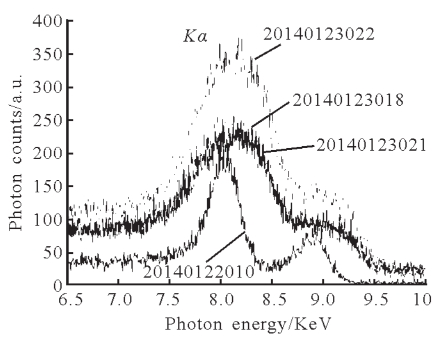

Fig.3 X-ray emission spectrum around the Kα and Kβ line of foil and velvet Cu targets

Table 1 showed that the four-target yields and CEs increased with the laser intensity. The CE of 0.008 68% was the most efficient from the laser to X-ray on velvet targets. Compared with the foil Cu of 0.005 59%, the average conversion of velvet was 0.006 65%. So velvet had produced 1.2 times as CE as foil Cu target. The data showed the velvet structure was beneficial for absorbing laser energies and increasing the electron transport in the material, which could obviously X-ray yields and CE. Rajeev [13] had explained this phenomenon with ´lighting rod´ effects. The result was also similar to Tian′s experiment on PW laser[12].

Tab.1 $K\alpha$ yields and CEs of the four targets driven by laser

Target	Shotnumber	$I\times$1e18 /Wcm^{-2}	Yield× 1e7,$K\alpha$	$\eta_{K\alpha}\times$1e-5	Ave $\eta_{K\alpha}'$	$\eta_x\times$1e-5
Pressed foil Cu	2014012010	2.00	11.60	5.59		1.04
Velvet Cu	2014012018	3.94	17. 10	4.84		0.80
	2014013021	4.09	23.54	6.24	6.65	0.79
	2014013022	4.64	36.05	8.68		0.75

In fact, the angular distribution of all X-ray yields did not satisfy the isotropy and Beer-Lambert law in 4π sold angle. But it was obtained from experiments and appeased express $CE=E_x/E_L$, where E_x is the X-ray energy, E_L is the laser energy. Another instantaneous scaling law of X-ray CE is fitted as a function of the laser intensity I and pulse time τ[16]:

$$\eta_x=0.074\left(\frac{I}{10^{14}\,\mathrm{W\cdot cm^2}}\right)^{-0.386}\left(\frac{\tau}{10^{-9}\,\mathrm{s}}\right)^{0.57} \tag{4}$$

Based on the every laser intensity and continual time, we calculated the CEs and showed it in last column of the table 1. Obviously, the four-shoot CEs were almost equal and CEs were not closely related to the target, and were only related to the laser, which were almost equal to the theory method. Experimental CEs of velvet Cu targets were 11.6 times as that of theory. Because the theory was according to the flat target[18], the porous surface absorption was neglected. With the increasement of the laser power density, CEs were improved as shown in table 1. According to Fig.2(a) of refer [18] about the curved relationship of Cu target and laser intensity, our experimental velvet Cu target didn′t reach the maximum absorption of laser energy.

The imaging experiments had been performed to distinguish the space resolution with 9 lp/mm resolution plate. The acquired raw image was shown in Fig.4, which clearly reconstructed the features of the target. In this case, H and V represented the position and resolution scan direction respectively. The images had been analysed to determine the X-ray source resolution. Features sizes varying from 6 lp/mm to 9 lp/mm were shown from the left to the right. Although all lines were resolvable, the modulation transfer function was noticeably reduced to 50% at 9 lp/mm. According to resolution plate, the X-ray source was distinguished with the spatial resolution of 1 000/9/2/M=42.8 μm, where M is called magnification coefficient, M=1.3 in the experiments.

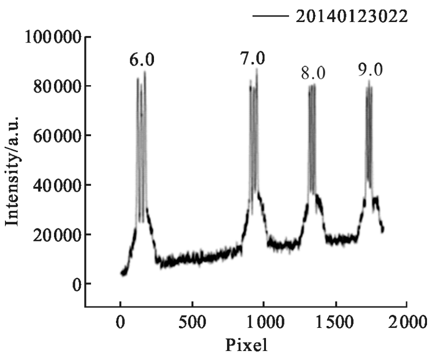

Fig.4 X-ray image of resolution plate

4 Conclusion

Concerning the study on laser-materials, many researchers investigated the improvement of X-ray yields and CEs through increasing laser intensity and the reformation of target materials and structures. This paper examined the target structure and designed velvet Cu target with the porosity of 30% and density of 70%. Experiments were carried out on XG-Ⅲ laser facility. The recorded $K\alpha$ X-ray yields were up to 3.605×10^8 photons·sr^{-1}·s^{-1}. The maximum CE was calculated to 0.008 68% and the average CE was 1.2 times that of foil Cu target. In addition, a 9 lp /mm resolution plate image showed the X-ray space resolution account for less than 42.8 μm. The experimental data showed that reforming structure could increase resonant absorption mechanism and enhance yields of hot electron and X-ray photon. In the future research will be conducted to design multi type velvet targets to develop nano-structure target experiment, to explore the relation of porosity and laser intensity and to apply to ultra-fast image and pump detect experiment.

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