X-ray generation under interaction of a femtosecond fiber laser with a target and a prospective for laser-plasma x-ray microscopy

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Abstract. The possibility of using a tightly focused of a femtosecond ytterbium fiber laser beam interacting with a metal target in the air as an X-ray source is considered. The results of the generation of line X-ray with a number of photons more than $10^5$ photons /s in solid angle for X-ray microscopy are discussed.

1. Introduction

Conventional X-ray projection microscopy is based on the principle of shadow projection of an object in a divergent beam of X-rays emitted by a "point" source [1]. The scheme of a projection X-ray microscope consists of a microsource (diameter of 1-10 μm), which uses a special microfocus X-ray tube, as well as an object table for placing the object under study and an X-ray CCD camera to record object imaging. The object is located at small distances from the X-ray source and the magnification in the X-ray projection microscopy depends on the ratio of the distances from the X-ray source to the object and to the detector [2]. In last year’s tabletop, femtosecond X-ray sources generated by laser-plasma interaction were developed. Due to collisions between energetic electrons formed in hot plasma produced under intense femtosecond laser interaction with the solid target, it serves as a source of incoherent Kα X-ray emitted as a result of the electron transition from the outer shell to a vacancy at the lower level of the atom. The femtosecond laser energy deposition is converted to X-ray from the focal spot microsize of Cu Kα X-ray source. The smaller the spot, the higher resolution the need for the applications in physics, material science and other fields. Therefore, a small plasma spot is a crucial parameter for the X-ray point source.

Since the X-ray source size is governed by the laser pulse intensity, reducing the laser pulse intensity can lead to confinement of the energy diffusion to submicron dimensions, consequently improving the spatial coherence. According to the Van Cittert–Zernike theorem the transverse coherence length $d$ is determined by the following relation $d=\lambda R/r$, where $\lambda$ is the wavelength, $R$ is the source-sample distance and $r$ is the source size. Thus, the transverse coherence length increases with decreasing X-ray energy and source size but rising with source-sample distance. Therefore, it is
necessary to obtain the minimum size of the X-ray source (<10 μm) at a high laser energy deposition. The spatial coherence 1-1.5 μm is enough to observe phase-contrast imaging on laboratory X-ray setup [2]. In a developed setup, the estimated coherence length will be ~1 μm at a distance of 10 cm, which allows obtaining phase-contrast images. This offers the advantages of high brightness and good spatial coherence.

It is necessary to remind a number of key provisions for the creation of an effective laser-plasma X-ray microscope. Firstly, according to the Van Cittert-Zernike theorem, spatial coherence is proportional to the wavelength of the radiation, so the generation of lower-energy photons is preferred. Secondly, from the same theorem, it follows that the minimum size of the source provides better spatial coherence. I.e., sharp focusing allows you to get a spot of hot plasma of the minimum size. Since the laser produced spot size is proportional to the temperature of the hot electrons (or intensity), it may be more advantageous to use low-energy laser radiation having high repetition rate pulses. Besides, obtaining characteristic photons with energy of 4-5 keV may be preferable for measurements, for example, in a helium environment.

Femtosecond fiber lasers have recently taken a leading position due to such advantages as the features of the complete fiber assembly, high beam quality and high average power, which has opened up wide applications in laser plasma processing, precision metrology, microscopy and other applications [3].

In this paper, we have proposed a new approach to the creation of the X-ray projection microscope using femtosecond fiber lasers as a source line X-ray emission.

2. Experimental setup and results
The experimental scheme is based on the use of a femtosecond ytterbium fiber laser with a central wavelength of 1030 nm, operating with a pulse repetition frequency of about 0.1-1 MHz containing energy in the pulse of up to 20 μJ, the pulse duration is 400 fs. The beam quality M2=1.5, beam diameter d=6 mm. To generate X-ray pulses, the near-infrared pulses are tightly focused (f=20 mm, NA=0.15) onto a metal target placed in ambient air (see Figure 1). As targets we used in the experiments Cu, Ni, Ti, Ag and steel plates.

The plane solid target was constantly moving with velocity of 2.7 mm/s or 27 mm/s in order to refresh surface for each laser shot. The laser beam was focused normally to the target surface.
Figure 1. Experimental scheme: (1) ytterbium fiber laser; (2) microfocus objective; (3) dihroic mirror; (4) collimator; (5) fiber; (6) glass color filter; (7) fiber spectrometer; (8) target; (9) X-ray spectrometer Amptek; (10), (11) photodiode; (12) oscilloscope; (13) CCD camera; (14) PC.

The laser intensity on the target surface reached a value of $1.5 \times 10^{14}$ W/cm$^2$. At this intensity femtosecond laser can produce nearsurface plasma to generate X-rays via bremsstrahlung, K-shell ionization, and hot electrons [4]. The focus position relative to the target was monitored using a CCD camera. Control of the process of near-surface plasma formation of the target and measurement of the dynamics of thin foil (in case of use) perforation process as a result of ablation was carried out using two photodiodes installed in the area of the front of and behind the target, recording the beginning of laser exposure to the target and at the moment of its perforation. The developed optical scheme also contained a control channel for the laser-induced emission spectrum, as well as the resulting second harmonic (SH) signals. The useful signal was directed to the input of the collimator located above the focusing lens at a distance (1-3 cm), and then transmitted to the fiber spectrometer. The X-ray radiation was measured using Amptek spectrometer located at 4 cm distance from the target.

Under a tightly focused femtosecond laser beam with an intensity of $1.5 \times 10^{14}$ W/cm$^2$ ambient air molecules are ionized. In the process of precision adjustment of the lens focus position with respect to the target surface we observed second harmonic generation in nearsurface air. Note, that second harmonic generation (SHG) mechanism is the result of the pondermotive force induced free-electron gradient [5]. Spectra of the first and second harmonics are shown in Figure 2. SH signal was observed due to its reflection from the plasma induced on the surface target.
Figure 2. Spectra of reflected main radiation (a) and second harmonic (b). Focus is situated about 300 μm above the target surface.

It was experimentally found that the process of ablation of metal targets (titanium, iron, silver) with low-energy femtosecond fiber laser pulses is accompanied by the generation of X-rays. Under repetition rate mode the line X-ray yield was observed in the range of 2-8 keV (see Figure 3).

Figure 3. Dependence of line X-ray yield on X-ray emission line energy. Data obtained at laser energy of 8μJ.

It was achieved maximum X-ray yield of $10^5$ phot/sec in solid angle both for Ag (2.8 keV, L-line) and Ti (4.5 keV, Ka line) at the laser pulse energy of 8μm with a contrast of more than 10 relative to the background (see Figure 4). Due to the relatively low velocity of the target transmission, the interaction
of the laser beam with the matter occurred in the mode of microcrater production, which provided an increase in the laser field and laser intensity. This leads to an additional contribution to the efficiency of X-ray generation [6].

![Figure 4. X-ray spectrum for Ti target.](image1)

![Figure 5. X-ray spectrum for Cu target.](image2)

The measured X-ray bremsstrahlung spectrum was used to estimate the average energy $T_{hot}$ of hot electrons that responsible for line X-ray production $Y_{X-ray} \propto \exp(-E/T_{hot})$, where $E$ is the energy of X-ray quanta in keV [1]. Based on obtained bremsstrahlung spectrum, we estimated the average energy of hot electrons, which was 1.8 keV. Using data from [6] one can define the value of the intensity under consideration of 200 TW/cm$^2$. That means that in the microcrater with measured depth about 10 μm the laser beam should be not more than 3μm.

It should be noted, an increase in the laser energy leads to a decrease in the X-ray yield. There are two reasons for this effect. First, ionization of the air molecules leads to the appearance of ionized electrons and, accordingly, to the defocusing of the laser beam. Secondly, ionization of the target ablation products is possible, which can also cause defocusing of the laser beam. Besides, an increase in the target moving velocity by a factor of 10 led to a decrease in the X-ray yield. We attribute this effect to the fact that X-rays are more efficiently produced in a deep channel.

### 3. Conclusions

We can conclude, that the new table-top X-ray source reaches an average $10^5$ of $K\alpha$ or $L\alpha$ photons (Ti, Ag). This photon flux is comparable to commonly used table-top X-ray sources driven by femtosecond laser operated in air conditions [7]. Such source parameters open perspectives for microfocus high resolution radiography imaging instead of a conventional X-ray tube.

Our pioneering results indicate that subsequent optimization of the experimental conditions in the mode of blowing a gas with a large ionization potential (helium), it is possible to increase the ionization threshold of the gas in the focal region, reduce, respectively, the local electron concentration and increase the energy delivered to the target [7] by enhancing the fiber laser power up to 20 W and repetition rate up to 1 MHz. We believe that optimized parameters such as focusing, the environment conditions and the surface microstructure of the target it is possible to obtain bright X-rays with a number of photons greater than $10^6$ photons/s at solid angle. It will be suitable for solving problems of projection X-ray microscopy of a new generation.
The compact laser-driven plasma X-ray microfocus source, with high spatial coherence, may be of interest for many applications such as the diagnostic tools that can be used to study the structure and performance of materials, high resolution radiography imaging.

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