X-ray source for microstructure imaging under air conditions based on fs laser plasma

S A Pikuz Jr1,2, O V Chefonov1, S V Gasilov1, P S Komarov1, A V Ovchinnikov1, I Yu Skobelev1, S Yu Ashitkov1, M V Agranat1 and A Ya Faenov1,3

1Joint Institute for High Temperatures RAS, Moscow 125412, Russia
2Moscow Institute of Physics and Technology, Dolgoprudny 141700, Russia
3Kansai Photon Science Institute JAEA, Kizugawa-city, Kyoto 619-0215, Japan
spikuz@gmail.com

Abstract. X-ray emission and possibility of obtaining radiography images with laser plasma X-ray source operating at atmospheric pressure and room temperature is investigated. Table top 40 fs 100 μJ laser and Cu and Fe bulk metal targets were used to produce X-ray emission in spectral range of 3-10 keV. The spectra, yield and size of X-ray source were measured under different experimental conditions. X-ray photons of up to 10 keV energy are produced effectively even by relatively low laser intensity < 1015 W/cm2. The source is applied for absorption imaging provided the sensitivity on 10 μm sample thickness and 30 μm spatial resolution of microstructures. The ability to perform phase contrast measurements is demonstrated. The advantages of the proposed method are in smart setup of investigated object within air environment; spectral range tunability; and sensitivity to low-contrast or micron thin details.

1. Introduction
The development of methods and tools for sensitive and inexpensive diagnostics of low-contrast objects and microstructures becomes important aim for the purposes of material science, medicine and high energy density physics. For radiography applications it is important to use a source with very high brightness that usually provided by synchrotrons. However, recent achievements in femtosecond laser plasma interaction allow to substitute synchrotron sources by compact inexpensive table-top laser facilities. It was shown that femtosecond laser plasma provides intense short-pulsed flow of several keV X-ray photons (see for ex. [1-5]) and hundreds keV fast ions [6, 7], which energies are enough to penetrate through a number of microscale objects. To provide the diagnostics of weakly-absorbed samples the methods of phase-enhanced imaging are commonly used where the size of backlighting source is desirable for [8, 9].

In the case of laser focusing in vacuum it is easily possible to provide the laser intensity of 1017-1019 W/cm2 generating hot dense plasma x-ray source of several microns size. But it is impossible or ineffective to put the sample for radiography inside vacuum environment for a number of microscale objects and life species. Then the process of laser propagation and focalization in ambient gas and following X-ray generation becomes quite more complicated. Recent experiments [10,11] shows the interaction of powerful fs laser pulses with solid target in gas environment causes X-ray generation. The use of micro objective allows to create the plasma blow in air very close to solid target surface. In
this case the some part of laser radiation is able to penetrate through plasma blow, which is enough to create dense hot plasma at solid target surface as a source of X-rays. In the same time, air plasma blow can be considered as a source of fast electrons providing another mechanism of x-ray photon generation at solid target surface.

The aims of present work are: 1) to determine the parameters of X-ray source created on solid target surface standing in air environment; 2) to apply the source for convenient radiography of microstructures in absence of vacuum chamber using inexpensive laser source of 100 uJ energy.

2. Experimental setup
The experiment was performed using a Ti:Sapph laser system consisting of main oscillator (Coherent, Mira) and regenerative amplifier (Coherent, Evolution). The scheme of the experiment is shown in Figure 1. The laser delivers of 100 uJ energy during 40 fs pulse with 1 kHz repetition rate. Pulse contrast of $10^3$ is provided near the pulse pedestal (due to ASE), and of $10^6$ in the picosecond scale. Also there is typical prepulse in the nanosecond scale due to the pockels cells leakage with $10^3$ times lower intensity then the main pulse. Laser radiation was focused by the microfocus objective with $N_a = 4$ to the bulk cylinder-shape solid targets with incidence angle of 45°. To measure the focal spot profile and laser energy inclined glass plate were used to deliver a part of laser beam to calibrated photodiode and imaging system. Intensity distribution in the focal spot was measured for the laser energy below and over ionization threshold in air. In the case of lower energy the focal spot has Gaussian profile with 3 μm diameter, but in the case of gas breakdown the plasma blow is about 20 μm wide (see Figure 2), that corresponds to laser intensity of around $6 \times 10^{14}$ W/cm². In order to provide the best focusing conditions during long time of target irradiation Fe and Cu cylinder-shape targets were rotated continuously.

![Figure 1. Experimental setup. Laser beam was focused by the micro objective on the continuously refreshed target surface standing in air. Imaged object and CCD positions changed in order to provide different magnification and phase-contrast imaging](image1)

![Figure 2. Imaging in visible light of plasma blow in air near solid target surface obtained along laser beam axis for 10 and 100 uJ laser energy. The image of laser focal spot at target surface for the energy below air breakdown is shown in the insertion.](image2)
due to the X-ray absorption in air, only photons with energy more than 2 keV can be detected by the camera. X-ray source size was measured using the penumbra effect in the images of test objects consisting either of two parallel thin wires or knife-like edge or pinhole with the 30 μm diameter.

3. Results and discussion

The experiments were done to investigate the mechanism and spectral distribution of X-ray generation on solid target in air conditions. We did not expect large number of electrons potent to produce characteristic emission with energies higher than 10 keV when the laser intensity of $10^{14}$-$10^{15}$ W/cm$^2$ is applied. However X-ray generation in Cu and Fe bulk target was examined to produce the emission in 5-10 keV spectral region which is still useful for imaging on many objects. The demand energy of X-ray radiation is also limited by air absorption in the gap between target and detector and corresponds to be more than 2-3 keV.

The spectrum of Cu target radiation registered by CCD matrix on 30 cm from the target is shown in Figure 3. The data demonstrates quite large photon flux obtained during 1 sec of exposition. Here Cu K$_\alpha$ and K$_\beta$ spectral lines have a good contrast comparing with adjacent bremsstrahlung background. Total number of photons emitted in K$_\alpha$ line is estimated to be about $2 \times 10^6$ per second per steradian, and $\sim 2 \times 10^5$ in the K$_\beta$ line, which give us conversion efficiency of around $10^{-8}$.

The measurements were done for the dependence of X-ray generation on implied laser energies in the range 10 - 100 μJ (see Figure 4). We were confident that all of this energy is focused in the measured spot size because the intensity does not greatly exceed air ionization threshold. We observed almost linear growth of total X-ray flux with energies more than 3 keV, while noticeable amount of K$_\alpha$ X-ray began to be emitted only for laser energies more than 60 μJ. Source size was also measured for the same energy range by the knife-like method. Intensity profile near the edge-air interface was use to calculate shape and size of the X-ray emission zone. It was found to have the same size of 50 μm under overall laser energy range.

The source was applied for imaging of thin films and low-contrast biological creatures. In Figure 5 the image of an insect are shown obtained using Cu plasma source. The data with probe radiation filtering by 120 μm aluminum foil was obtained additionally to provide the observation in harder x-rays to get the sensitivity on thick part of the object. The trace of insect leg image demonstrates its hollow internal structure and gives us an evidence of phase contrast effect representing the fringes at the leg edge. Similarly the details and features on insect wings having the thickness less than 10 μm are well distinguished that verifies the ability of the suggested imaging technique and also may be explained by phase contrast effect.
The increase of laser pulse energy up to several mJ on the target should cause the photon generation of tens of keV energies. Thus, the source and application method will be convenient for analysis and quality control of thin membranes and microstructures as well as of mm-thick structures and biomedical samples alive in air environment.

4. Conclusion

The approach to provide a common X-ray source for convenient radiography imaging by use of table-top femtosecond laser is successfully examined. Short laser pulse propagation and focalization in air at room pressure causes the gas breakdown before reaching the target surface. X-ray photons of up to 10 keV energy are produced effectively even by relatively low laser intensity < 10^{15} W/cm^2. The spectral distribution and geometry parameters of the source are determined. The source is experimentally proven to be applied for absorption and phase contrast imaging of different microstructures situated at atmosphere environment. The advantages of the proposed method are in smart setup of investigated object within air environment; spectral range tunability and sensitivity to weakly-absorbed or micron-thin details.

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