

LETTERS

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Subsurface generation of hard X-rays by a BaF_2 target exposed to repetitively pulsed radiation from a femtosecond Cr : forsterite laser at power densities below 10^{15} W cm^{-2}

V.M. Gordienko, I.A. Makarov, E.V. Rakov, A.B. Savel'ev

***Abstract*. The subsurface generation of hard X-rays ($E_\gamma > 20$ keV) is found during the formation of a channel by a train of $10^{14} - 10^{15}$-W cm^{-2} femtosecond laser pulses in a BaF_2 target.**

Keywords: *X-rays, femtosecond laser pulses, interaction of laser radiation with matter.*

We report the observation of previously unknown subsurface generation of hard X-rays upon irradiation of a solid target by a train of femtosecond pulses from a Cr : forsterite laser. The hard X-rays ($E_\gamma > 20$ keV) were generated during laser micromachining of a BaF_2 target in vacuum by a train of ablating femtosecond pulses of intensity I below 10^{15} W cm^{-2}. It seems that X-rays are generated in a channel which is initially produced by 30 – 50 laser pulses.

The parameters of a high-temperature plasma produced by femtosecond laser radiation on a solid target surface are most often studied in a single-pulse excitation regime. In [1], an increase in the yield of the hard X-ray component ($E_\gamma > 3$ keV) and overheating of a high-temperature plasma produced on the developed surface of craters appeared under the action of several $I \sim 10^{16}$-W cm^{-2} femtosecond laser pulses. Note that irradiation of a target by trains of $10^{14} - 10^{15}$-W cm^{-2} femtosecond pulses is commonly used in laser micromachining to produce microchannels [2 – 4].

We used in our experiments a femtosecond Cr : forsterite laser emitting 1240-nm, 110-fs pulses with a pulse repetition rate of 1 – 50 Hz. This laser developed at the ILC, Moscow State University is based on the regenerative and multipass amplification of chirped pulses [5]. A 0.4-mJ laser pulse was focused by a quartz lens with the focal distance $F = 10$ cm to a spot of diameter $D \sim 10$ μm (at the 1/e level), providing the radiation power density $\sim 3 \times 10^{15}$ W cm^{-2} and the energy density $E \sim 350$ J cm^{-2} on a BaF_2 target surface.

The angle of incidence of the p-polarised laser beam on the target was 45°. The target was in vacuum at the residual pressure of no more than 10^{-2} Torr. The X-ray yield was measured with two scintillation FEU-119 photomultipliers, one of which detected the integrated X-ray yield in the range above 2.5 keV, while another was used with different band filters for detecting X-rays in different ranges. On the windows of a cell the 200-μm thick beryllium filters were mounted.

The plasma diagnostics used in experiments is based on the two-channel detection of the hard X-ray yield from the plasma [6]. Figure 1 shows the X-ray yield measured in the spectral range $E_\gamma > 20$ keV (by using a 26-μm thick tantalum filter) as a function of the number of the laser shot. One can see that X-rays are generated after irradiation of a target by approximately 30 laser shots, persists during approximately 25 shots, and appears again after 40 shots (a weak signal is also observed in the region of 170th shot).

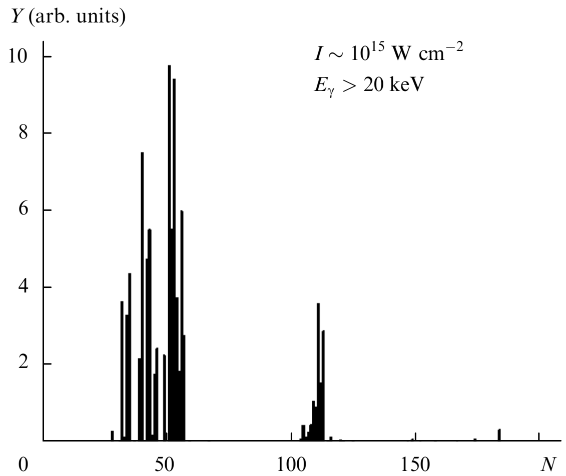

Figure 1. Hard X-ray yield Y in the spectral range $E_\gamma > 20$ keV as a function of the laser shot number N.

During the displacement of the waist of a focused laser beam with respect to the target surface resulting in the variation of the radiation intensity, the hard X-ray generation pattern is qualitatively retained up to the intensity $I \sim 10^{14}$ W cm^{-2}. In this case, the dependence of the laser shot number N at which hard X-rays appear on the beam waist position is approximated by a second-degree polynomial, which suggests the inverse dependence of N on the intensity I. Note also that we detected gamma quanta of energy exceeding 60 keV (a 1-mm thick copper filter was

V.M. Gordienko, I.A. Makarov, E.V. Rakov, A.B. Savel'ev Department of Physics, M.V. Lomonosov Moscow State University, Vorob'evy gory, 119992 Moscow, Russia; International Laser Center, M.V. Lomonosov Moscow State University, Vorob'evy gory, 119992 Moscow, Russia; e-mail: gord@femto.phys.msu.ru;
makarov@femtosrv.phys.msu.ru; rakov@femto.phy.msu.ru;
savelev@femto.phys.msu.ru

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used). The hard X-ray yield in the spectral range $E_\gamma > 20$ keV under these interaction conditions was comparable with the hard X-ray yield in the detected spectral region measured upon the interaction of a tightly focused single laser pulse with the target surface.

Comparative experiments were performed in the latter case by using a special objective providing the laser power density of $\sim 10^{16}$ W cm^{-2} on the smooth surface of the target for the beam waist diameter of ~ 4 μm (Fig. 2). In our opinion, the results of measurements of the X-ray yield upon irradiation by $I \sim 10^{16}$ W cm^{-2} single pulse conclusively show that a channel formed by a train of femtosecond pulses producing the power density on the target less than 10^{15} W cm^{-2} (the residual modification of the target of length ~ 50 μm was observed with a microscope) provides the conditions for generation of a 'hot' femtosecond plasma.

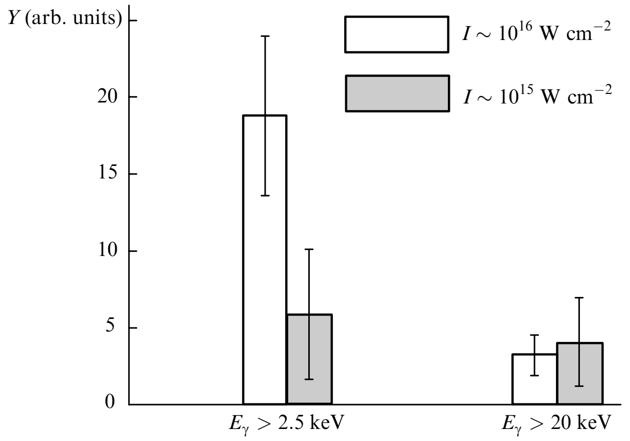

Figure 2. Average hard X-ray yield Y in the spectral ranges $E_\gamma > 20$ keV for different irradiation regimes of the BaF_2 target.

This conclusion is also confirmed by the appearance of the 620-nm second harmonic radiation simultaneously with X-rays [7]. Note that in this case, the integrated X-ray yield in a broader spectral range ($E_\gamma > 2.5$ keV) under our experimental conditions was on average lower by a factor of 3.5 than that for the intensity $I \sim 10^{16}$ W cm^{-2} (Fig. 2).

Let us briefly discuss the features of action of a train of femtosecond laser pulses on a target. One laser shot producing the energy density $E \sim 10^2$ J cm^{-2} removes a layer of thickness ~ 1 μm of the target material [2]. This means that the generation of X-rays after irradiation by 30–50 pulses appears in a channel which penetrates into the target by more than 40 μm at an angle of 45°. The BaF_2 layer of such a thickness transmits gamma quanta with the energy above 7 keV and absorbs quanta with the lower energy. Therefore, the yield of X-rays generated in the channel in the spectral range $E_\gamma > 2.5$ keV should be lower than the yield of X-rays generated in this spectral range directly from the target surface irradiated by a single pulse and should not vary for gamma quanta with energies above 7 keV.

Thus, prolonged irradiation of a BaF_2 target by $\sim 10^{15}$ W cm^{-2} femtosecond laser pulses (more than 25 pulses) leads to the generation of hard X-rays with energies above 20 keV in a channel produced by laser pulses, which penetrates into the target by a few tens of micron.

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