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Increase in the yield of X-ray photons upon two-pulse laser excitation of a solid target in air

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***Abstract*. A scheme is proposed for efficient generation of hard X-rays upon two-pulse excitation of a solid target in air by nanosecond and femtosecond laser pulses. The yield of hard X-rays upon two-pulse excitation increases by a factor of ~17 compared to that upon single-pulse femtosecond excitation. The optimal delay time between pulses was 10 μs.**

Keywords: *two-pulse excitation, X-rays, femtosecond laser plasma.*

Upon irradiation of a solid target in vacuum by high-power femtosecond pulses ($I > 10^{15}$ W cm^{-2}), a hot plasma is produced. Such plasma is a source of incoherent hard X-rays, whose yield strongly depends on the exciting radiation intensity [1, 2]. In the case of repetitively pulsed excitation of the target by high-power femtosecond pulses, deep craters (channels) are formed, which is accompanied by a considerable increase both in the yield of hard X-rays and the temperature of the hot electron component of the plasma in a channel [3, 4]. The generation of the hot femtosecond plasma in such schemes, but in the presence of a gas involves difficulties of delivering high-power laser radiation appearing due to nonlinear self-action processes [5]. The production of the near-surface region of a rarefied gas ('fireball') by irradiating preliminary the target surface, for example, by nanosecond laser pulses [6 – 8], can be used to suppress the self-action processes of femtosecond laser radiation.

The aim of this letter is to present the results of our experiments on the efficient generation of the hot microplasma produced by periodic two-pulse irradiation of a solid target in air by nanosecond and femtosecond laser pulses.

We used in experiments an excimer XeCl laser ($E \approx 5$ mJ, $\lambda = 308$ nm, $\tau \sim 30$ ns) and a femtosecond Cr : forsterite laser ($E \approx 400$ μJ, $\lambda = 1240$ nm, $\tau \sim 110$ fs) [9]. The scheme of the experiment is shown in Fig. 1. The radiation of the excimer laser was focused on a 100-μm-thick aluminium target at an angle of 45° by a lens with the focal distance $F = 28$ cm. This radiation formed a crater of diameter ~300 μm on the target surface. The radiation intensity I on the target surface was $\sim 10^8$ W cm^{-2}. Femtosecond laser radiation was focused to a spot of diameter ~5 μm in the central region of a spot normally to the target with the help of an objective with the focal distance 6 cm, which provided the 'vacuum' intensity $I \sim 10^{16}$ W cm^{-2}. This radiation was incident on the target with a delay of 5 – 100 μs after irradiation by a nanosecond pulse. The system was aligned by using a helium – neon laser. Hard X-rays were detected with a scintillation NaI detector based on a FEU-119 photomultiplier with a 100-μm-thick beryllium filter mounted at the detector input.

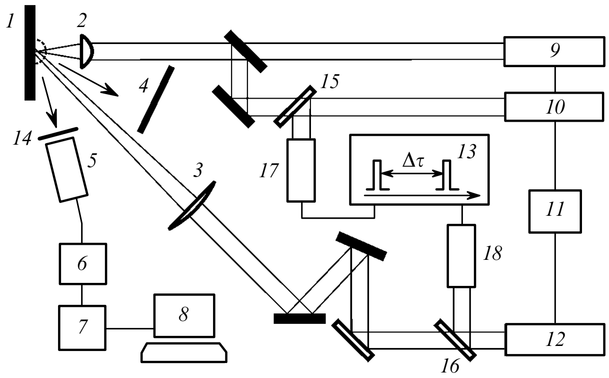

Figure 1. Scheme of the experimental setup: (*1*) target; (*2*) objective ($F = 6$ cm); (*3*) lens ($F = 28$ cm); (*4*) screen for visualisation of speckles; (*5*) photomultiplier; (*6*) charge-sensitive amplifier; (*7*) analogue-to-digital converter; (*8*) computer; (*9*) helium – neon laser; (*10*) Cr : forsterite laser; (*11*) pulse delay control unit; (*12*) excimer XeCl laser; (*13*) oscilloscope; (*14*) beryllium filter; (*15*, *16*) glass and silica beamsplitters; (*17*, *18*) laser radiation detectors.

We measured the dependences of the yield of hard X-rays (the total energy of X-ray photons was $E_\gamma > 2.5$ kV) on the number of a 'femtosecond' shot upon two-pulse (nanosecond or femtosecond) and single-pulse (femtosecond) irradiation of the target (Fig. 2). The optimal delay $\Delta\tau$ between pulses was ~10 μs. We found that the X-ray yield increased after the first shot by a factor of 17 compared to that in the single-pulse irradiation regime. Such an increase of the X-ray yield in the two-pulse irradiation regime suggests that the radiation intensity on the surface target increases by more than four times compared to the single-pulse regime, because $Y \sim I^2$ [4]. A channel was produced in the target, whose depth (and the yield of a 'packet' of X-ray

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pulses from it) depended on the laser shot number [4]. The maximum of the hard X-ray yield in a 'packet' upon two-pulse irradiation of the target increased approximately by a factor of eight. By comparing our results with the dependences of the hard X-ray yield on the gas pressure measured earlier (see inset in Fig. 2), we estimated a decrease in the gas density in the channel and near-surface region by factors of 19 and 8, respectively. The estimate of the degree of gas rarefying in the near-surface region of the target is in good agreement with data obtained in papers [5–7], where the gas density achieved in a 'fireball' upon irradiation by nanosecond pulses with similar parameters ($\tau \sim 10$ ns, $I \sim 10^8$ W cm^{-2}) was $\rho \sim (0.02 - 0.04)\rho_{\rm atm}$ (where $\rho_{\rm atm}$ is the air density under normal conditions).

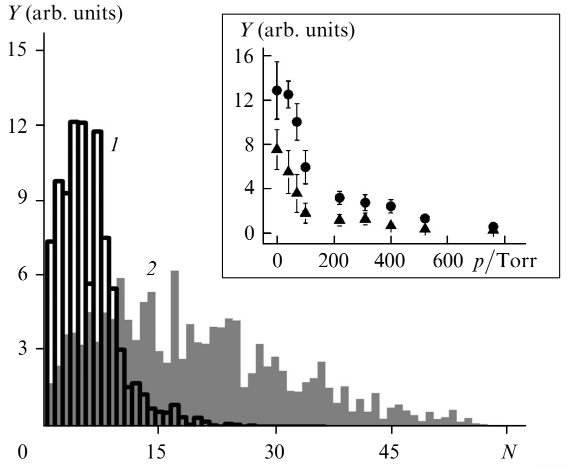

Figure 2. Dependences of the hard X-ray yield Y on the number N of a 'femtosecond' shot upon two-pulse (*1*) and single-pulse (*2*) laser irradiation of an aluminium target in air. The scale of diagram (*2*) is enlarged by a factor of five. The inset shows the dependences of the hard X-ray yield Y a femtosecond laser pulse of aluminium on the target surface (▲) and in a channel for the maximum yield Y (●) on the air pressure p.

The number of pulses in a 'packet' in the two-pulse regime decreased compared to that in the single-pulse regime and the maximum of the hard X-ray yield was achieved after a smaller number of shots. This circumstance is probably related to the increase in the mean velocity of femtosecond laser ablation caused by the increase in the exciting radiation intensity upon 'vacuum pumping' and rapid perforation of the target.

Thus, we have demonstrated the efficient suppression of the nonlinear self-action of high-power femtosecond laser radiation during the production of hot microplasma in the near-surface region of a solid target in air. The results obtained in our study can be used to develop quick methods for X-ray spectral analysis of materials by using characteristic X-rays emitted by a femtosecond laser plasma [10] in the absence of a vacuum chamber.

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