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High-intensity interaction of picosecond laser pulses with metal target

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The results of experimental investigation of the interaction of picosecond light pulses with a Cu target at light intensities up to $3\cdot10^{16}$ W/cm^2 are presented and discussed. The experiment was performed with the use of a terawatt chirped-pulse-amplification Nd:glass laser and the apparatus for corpuscular (ion collectors, electrostatic ion energy analyser) and X-ray (*p-i-n* Si photodiode) diagnostics of laser-produced plasma. The charge spectra of ions emitted from a picosecond plasma as well as the energy-dependent (or intensity-dependent) characteristics of ion emission and soft X-ray yield are determined. The electron temperature and the average charge state of the plasma are evaluated as a function of light intensity.

1. Introduction

High-power lasers generating pico- and femtosecond pulses made the study of laser-matter interaction at extremely high intensities of light and very short times of the interaction possible [1], [2]. The process of the interaction of a high-power ultrashort light pulse with a target is very complex, however, it comprises many various phenomena and its run depends on a lot of factors. Therefore, in spite of the recent intensive study of this process [1]–[3], understanding of some properties and effects of the interaction is still not satisfactory. Particularly, it is referred to the properties of generation of multicharged ions from a plasma produced as a result of the interaction of an ultrashort pulse with a solid target. Although this problem was studied in detail for a plasma produced with nano- or subnanosecond light pulses (*e.g.*, [4]–[6]), it was investigated to a very limited degree for ultra-short-pulse-produced plasmas [7]–[9].

The main purpose of the study presented in this paper was determination of the characteristic features of ion stream generation at the interaction of a high-power picosecond light pulse with a metal target, as well as the investigation of the influence of light intensity on some parameters (electron temperature, charge state) of picosecond laser-produced plasma. The measurements were carried out with the use of corpuscular and X-ray diagnostics at intensities of light on the target (Cu) up to $3\cdot10^{16}$ W/cm^2.

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2. Experimental arrangements

The investigation of the interaction of a high-intensity picosecond light pulse with a metal target was performed in the set-up presented in Fig. 1. In the experiment terawatt chirped-pulse-amplification Nd:glass laser, described in detail in [10], was used. The laser generates joule-level pulses of duration $\tau \approx 1.2$ ps and intensity contrast ratio in the long-time scale ($\geqslant 1$ ns) of $\geqslant 10^8$. The short-time scale (< 1 ns) contrast ratio of the pulse is estimated to be $\geqslant 10^3$. The 85×60 mm^2 cross-section linearly polarized laser beam was focused onto a flat, polished, massive Cu target with the use of a parabolic mirror of the focal length $f = 27$ cm. For high-energy beam the diameter of focal spot was typically about 30 µm. The surface of the target was put up perpendicularly to the laser beam's axis. The target and the parablic mirror as well as devices meant for measuring characteristics of ion and X-ray emission were placed in a vacuum chamber evacuated to the pressure $\sim 5{\cdot}10^{-6}$ torr.

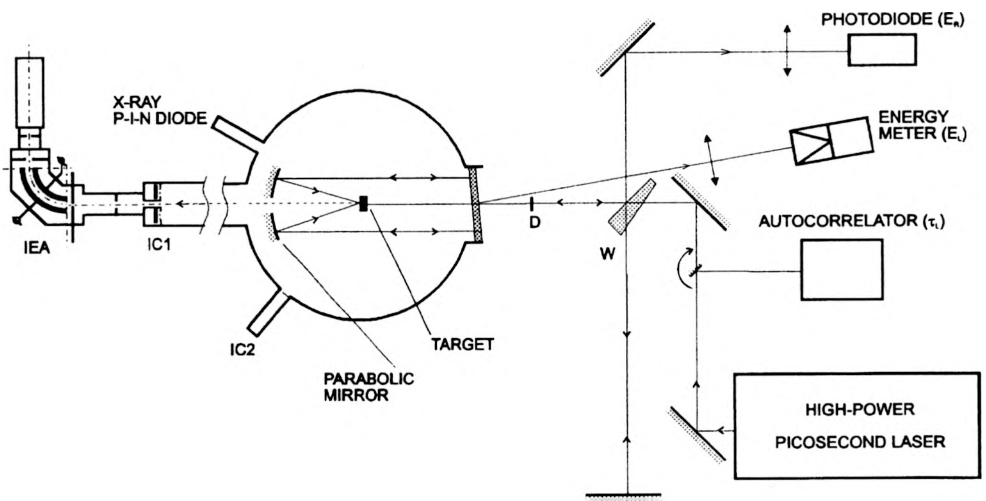

Fig. 1. Experimental set-up.

The principal diagnostic techniques for studying laser-produced ions were based on the time-of-light method [5]. Ion collectors (ICs) and a cylindrical electrostatic ion energy analyser (IEA) were used in the far expansion zone. Two ion collectors of different construction were used: the ring collector IC1 ($\varnothing_1 = 3.8$ cm, $\varnothing_2 = 5.0$ cm) and the standard circular collector IC2 ($\varnothing = 1.5$ cm). The first one makes the measurements close to the IEA and laser beam axis possible. The IEA had a bending radius of $R_0 = 10$ cm, the deflection angle $\Psi = 90°$ and the gap between the cylindrical electrodes of the analysing capacitor was $\Delta R = 0.5$ cm. A windowless electron multiplier (WEM) was used as an ion detector behind the IEA. The use of the parabolic mirror with the hole in the centre allowed the measurement of ions emitted perpendicularly to the target surface and moving along the laser beam axis (Fig. 1). For the measurement of X-rays a *p-i-n* Si photodiode (with 100-µm acive and

0.7-μm dead layers) filtered with 7-μm Al was used. There were two ranges of sensitivity 1 – 1.6 keV and 3 – 30 keV. In practice the first one was useful, because the harder emisssion was rather minor.

Absolute values of the energy of light incident on the target were measured with the use of energy meter Scientech AD 30. The ratio of the energy of light incident on the target to the energy of light reflected from the target, perpendicularly to the target surface, was measured with the use of the fast photodiode TF 1850 and the oscilloscope Tektronix SCD 1000 (for details see [11]). The measurements of the pulse duration were performed in the system employing a single-shot autocorrelator applying noncolinear second-harmonic generation in a $LiIO_3$ crystal and a CCD camera with a 668 × 586 – pixels array [10].

3. Results and discussion

The corpuscular diagnostics used in our experiment enabled us to obtain various characteristics of ion streams at a long distance from the target (*e.g.*, velocity or energy of ions, the number and total charge of ions, ion charge state distribution, the abundance of ion species, *etc.*) as well as some information about the parameters of laser-produced plasma near the target surface (in the hot centre of the plasma) [5], [12]. A methodology and processing methods for obtaining these characteristics from measurements are described in detail in paper [5]. Below we present only some final results of our measurements and analysis.

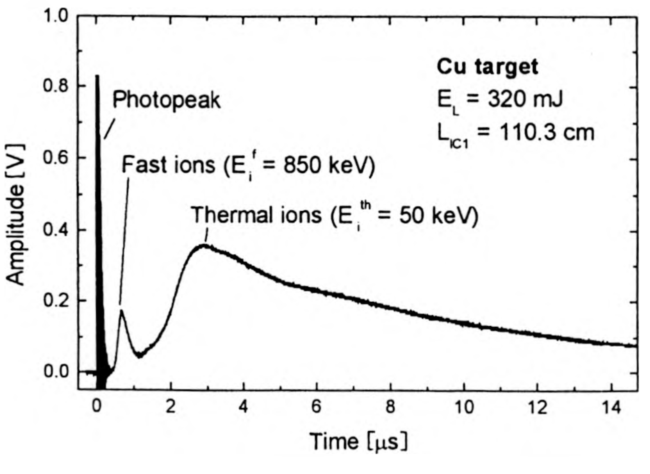

Fig. 2. Ion collector signal with two ion groups: the fast one and the thermal one.

Figure 2 illustrates a typical structure of the ion collector signal registered with the help of the IC1 and TDS 784A Tektronix oscilloscope. The existence of two distinct ion groups can be seen: relatively slow ions and fast ions. The slow ions can be named thermal ions because the main source of their motion is hydrodynamic expansion of thermalized plasma. It is believed that an essential role in the motion of fast ions is played by ambipolar electric field originating from a charge separation due to an escape of hot (suprathermal) electrons from the plasma corona [5], [7], [13]. A part of the total number of ions can be accelerated in this field to high energies. These fast ions can be named nonthermal or suprathermal ions. As it results from Fig. 2, the energy of suprathermal ions may be one order of magnitude (or more) higher than the energy of thermal ions. Thus, in spite of the fact that the number of fast ions is relatively small (in comparison to the number of thermal ions), they can carry a considerable part of the total energy of ions.

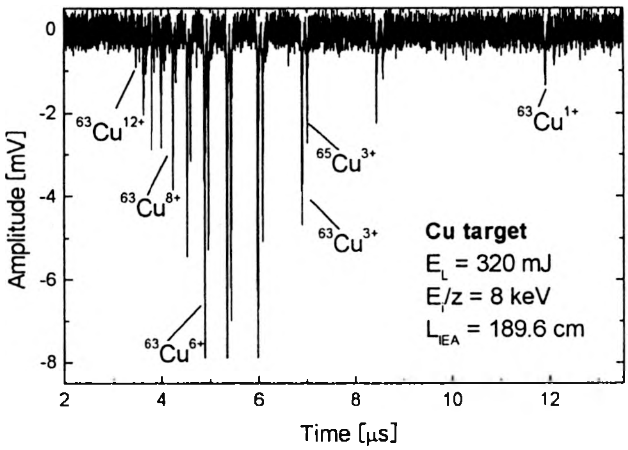

Fig. 3. Ion charge spectrum of Cu ions measured by the electrostatic analyser.

The IEA gives the possibility to identify the ion species produced, *i.e.*, to determine their mass-to-charge ratios, energies and abundance. A typical signal from the IEA acquired by TDS 784A oscilloscope is presented in Fig. 3 (for the same laser shot as in Fig. 2). It shows ion charge spectrum of Cu ions for the chosen value of ion energy-to-charge state ratio $E_i/z = 8$ keV. The maximum charge state of Cu ions registered with the use of the IEA was $z = 13^+$ and energy of Cu^{13+} ions was equal to 150 keV. Various ion species existing in the plasma can be revealed by the IEA by changing the value E_i/z. The percentage abundance of ion species in the plasma, obtained by processing the IEA signals, is presented in Fig. 4. The presence of H, C, and O ions originating from contaminants of the Cu target is evident. It results from this figure that the average charge state of Cu ions at a long distance from the target is rather low, $\langle z \rangle \sim 3$. This value is several times lower than the value $\langle z_0 \rangle \sim 19$ measured and calculated for the plasma in the laser focal spot (see further). It suggests the existence of strong recombination processes in the plasma during its expansion.

The ion yield depends strongly on the laser beam focusing conditions. We varied the focus position in the range from -0.6 mm to $+0.6$ mm with respect to the target surface. These variations were equivalent to the change of the light intensity incident on the target at approximately constant energy of laser pulse. The influence of the

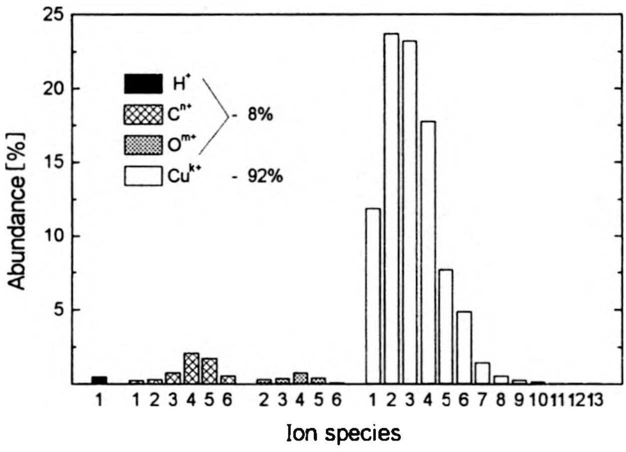

Fig. 4. Percentage abundance of ion species existing in laser-produced plasma.

focus position on the ion collector (IC1) signals and total charge of Cu ions is illustrated in Figs. 5 and 6. For comparison the amplitudes of soft X-ray signals registered by *p-i-n* Si diode are shown in Fig. 6 as well. As expected, X-ray signal has maximum at focus position near the target surface where intensity of the light is the highest (compare Fig. 8). However, contrary to our nanosecond experiments [14], the ion flux reaches minimum when the focus of the laser beam is close to the target surface. This probably results from the fact that at the best focusing the volume of the laser-produced plasma is the smallest due to the smallest focus spot. Displacing the target away from the minimum focal spot causes an increase of the plasma

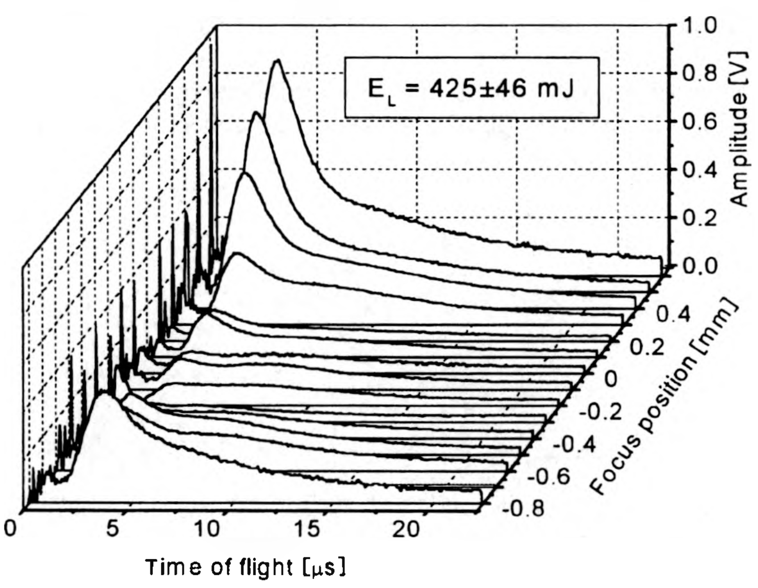

Fig. 5. Influence of the focus position with respect to the target surface on the ion collector signals.

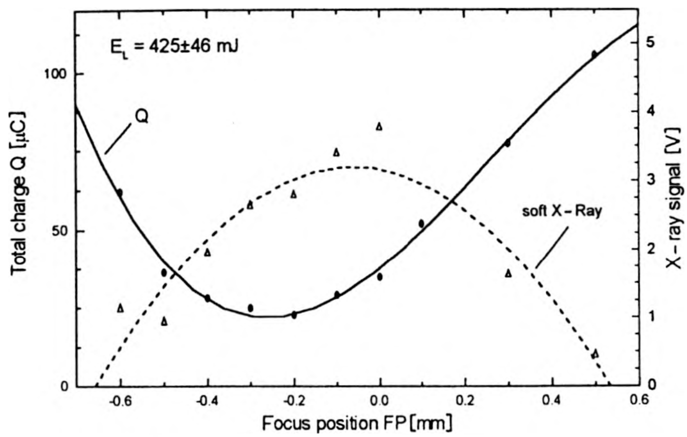

Fig. 6. Total charge of Cu ions and soft X-ray signal as a function of the focus position.

volume, and it results in an increase of ion emission as long as the light intensity is still high enough to heat the plasma to high temperature. In the nanosecond experiments, when the light intensity in the focus is much lower, strong defocusing causes that a large amount of low-temperature plasma is produced which emits very slow ions registered separately.

The results presented above refer to the case when energy of the light pulse incident on the target was established (although intensity of the light could be changed, Figs. 5 and 6). However, the interaction of an ultrashort high-power pulse with a target is essentially a non-linear process, so it is important to know how the parameters of ion and X-ray emission depend on the energy of a light pulse or on its intensity (particularly in the case when the intensity is changed by variation of the pulse energy).

Figure 7 presents the dependences of the charges of thermal and fast ions (seen by the IC1) and the velocities of the ions (in the peaks of the collector signals) on

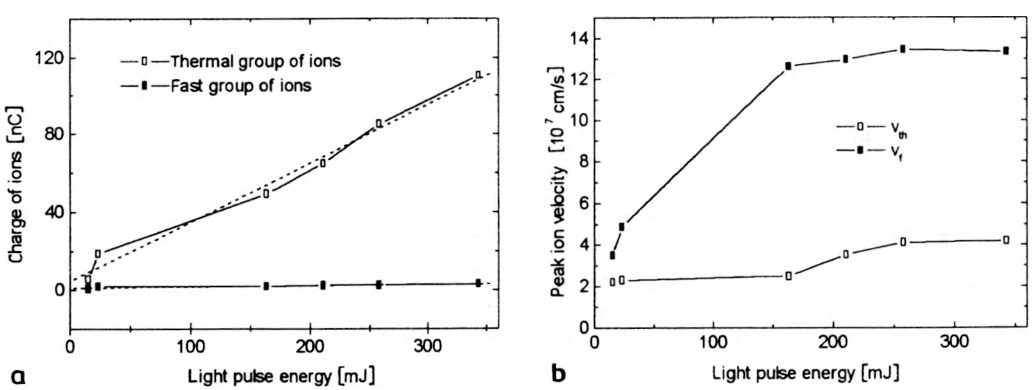

Fig. 7. Charge (a) and velocity (b) of thermal and fast ions as a function of light pulse energy. Charge of ions is measured with the use of the IC1 collector within the solid angle $\Omega = 3.95 \cdot 10^{-4}$ sr.

the light pulse energy. The most characteristic feature of these dependences is their essentially different run for thermal and fast ions. Particularly, it results from the figure that:

– the number of thermal ions (proportional to the charge) increases almost linearly and the number of fast ions almost does not change with an increase in the pulse energy,

– the velocity (or energy) of thermal ions increases slowly and the velocity of fast ions increases much more quickly with an increase in the pulse energy.

The observed characteristics for thermal ions can be explained if we notice that the amount of thermalized plasma increases more quickly with an increase in the pulse energy than the plasma temperature increases. If we take a reasonable assumption that, roughly, the amount of plasma is proportional to the pulse energy, then the number of thermal ions, dominating in the plasma (Fig. 2), increases linearly (as observed). As we can see further (Fig. 9), the electron temperature of the plasma changes as $T_e \propto I_L^{0.44}$ or, roughly, $T_e \propto E_L^{0.4}$. Regarding that $v_{th} \sim v_s \propto T_e^{0.5}$ [15], where v_s is a velocity of sound in a plasma, we obtain $v_{th} \propto E_L^{0.2}$. Thus, velocity of thermal ions changes very slowly with the pulse energy, which is observed in the experiment. The behaviour of fast ions depends on acceleration processes in the plasma stimulated by hot electrons. These processes are essentially non-linear and are amplified with an increase in light intensity. So, the pulse energy increase (accompanied with the intensity increase) has a considerable influence on the velocity of fast ions. However, it is not clear why the growth of the fast ion velocity saturates and why the number of fast ions is almost independent of the pulse energy.

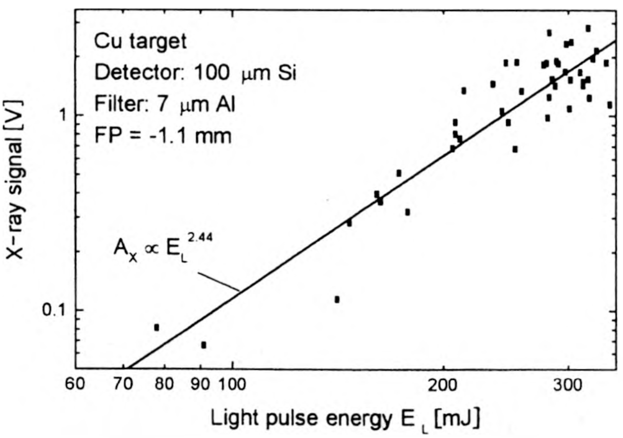

Fig. 8. The ***p-i-n*** diode X-ray signal as a function of light pulse energy.

Figure 8 presents the dependence of the amplitude of soft (~1 keV) X-ray signal on the energy of laser pulse. The soft X-ray yield depends strongly on the pulse energy, approximately in accordance with the function $A_x \propto E_L^{2.44}$. Because the divergence of the laser beam changes only slightly [10] with the pulse energy in the energy range indicated in the figure, it can be assumed that the dependence of the X-ray yield on the light intensity follows the function given above for the pulse energy. This result agrees quite well with the result obtained in [16]. The dependence $A_x \propto I_{abs}^{2.2}$ has been revealed there with the use of a 400 fs KrF laser and an aluminium target (at the absorbed intensity in the target in the range 10^{15} W/cm$^2 - 5 \cdot 10^{16}$ W/cm^2).

Knowing the mean ion energy (derived from the analysis of the IC signal) it is possible to estimate the electron temperature T_e and the average charge state $\langle z_0 \rangle$ of plasma created at the focal spot with the use of the analytical formulas proposed by BUSQUET [17]. The results of the estimation are presented in Fig. 9. The dependence of T_e on the light intensity is in a good agreement with the formula $T_e \propto I^{4/9}$ suggested in [18] for the plasmas produced by an ultrashort pulse. On the other hand, the experimental dependence of $\langle z_0 \rangle$ does not agree with the relation $\langle z_0 \rangle \propto I_L^{2/9}$ given in [18]. The estimated value of the average charge state of Cu ions at $I_L \sim 10^{16}$ W/cm^2 (see the figure) is close to the $\langle z_0 \rangle = 19$ determined from the X-ray spectral measurement [19] performed in another experiment of ours.

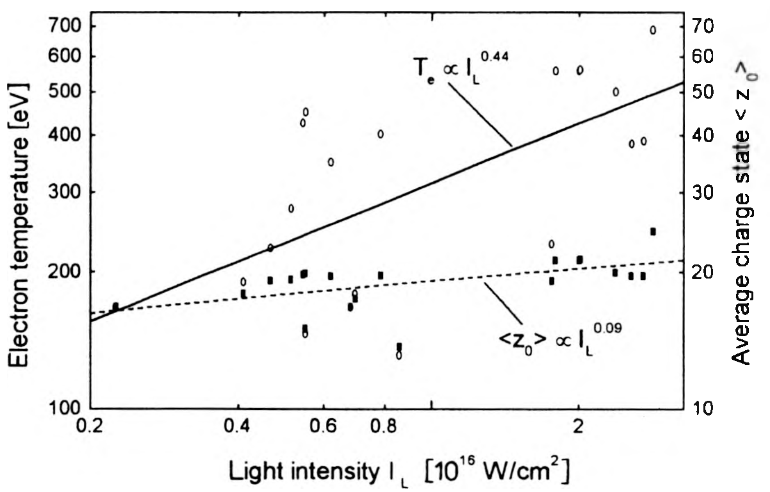

Fig. 9. Electron temperature and average charge state of Cu plasma in the focal spot as a function of light intensity.

The investigation of the interaction of a picosecond pulse with Cu target performed with the use of corpuscular and X-ray diagnostics was supplemented with the measurements of specular reflectivity of the picosecond pulse from the target. These measurements were described and discussed in detail in the work [11]. It was found that, contrary to the experiments with high-contrast femtosecond pulses [20], the reflectivity decreases as light intensity increases from $3 \cdot 10^{14}$ W/cm^2 to $7 \cdot 10^{15}$ W/cm^2, and in the range $7 \cdot 10^{15} - 3 \cdot 10^{16}$ W/cm^2 the value of the reflectivity is approximately constant. A qualitative explanation of observed changes of the reflectivity was done, assuming that the interaction of the main picosecond pulse with the target is modified by a short-lasting (<1 ns) prepulse producing a small amount of expanding preplasma on the target surface. It can be supposed that this prepulse has also some influence on the characteristics of ion streams and X-ray yield measured in our experiment.

4. Conclusions

The main conclusions from our investigation can be summarized as follows:

– A picosecond laser-produced plasma emits two groups of ions: relatively slow–thermal ones and fast–nonthermal ones; the energy of nonthermal ions can be one order of magnitude (or more) higher than energy of thermal ions.

– The dependences of parameters of ions on laser pulse energy (or intensity) for thermal ions are essentially different from those for fast ions (*e.g.*, the number of thermal ions increases and the number of fast ions almost does not change with an increase in laser pulse energy).

– Due to the strong recombination processes, the average charge state of ions at a long distance from the target is low (several times lower than that in the hot centre of the plasma).

– The ion flux emitted perpendicularly to the target reaches the minimum when the focus of the laser beam is close to the target surface (contrary to our nanosecond experiments).

– Soft X-ray yield from a picosecond laser-produced plasma depends strongly on laser intensity (energy) and the dependence is similar to that obtained for the 400-fs laser-produced plasma [16].

References

[1] Perry M.D., Mourou G., Science **264** (1994), 917.
[2] Mourou G., Appl. Phys. B **65** (1997), 205.
[3] Milchberg H.M., Freeman R.R. [Eds.], *High-Field Interaction and Short-Wavelength Generation*, J. Opt. Soc. Am. B **13** (1996), special issue (No. 1 and 2).
[4] Mróz W., Parys P., Wołowski J. Woryna E., Láska L., Mašek K., Rohlena K., Collier J., Haseroth H., Kugler H., Langbein K.L., Shamaev O.B., Sharkov B.Yu., Shumshurov A.V., Fusion Eng. Design **32** (1996), 425.
[5] Woryna E., Parys P., Wołowski J., Mróz W., Laser Part. Beams **14** (1996), 293.
[6] Láska L., Krása J., Mašek K., Pfeifer M., Rohlena K., Králiková B., Skála J., Straka P., Woryna E., Parys P., Wołowski J., Mróz W., Haseroth H., Golubev A., Sharkov B., Korschinek G., Rev. Sci. Instrum. **69** (1998), 1072.
[7] Meyerhofer D.D., Chen H., Delettrez J.A., Soom B., Uchida S., Yaakobi B., Phys. Fluids B **5** (1993), 2584.
[8] Guethlein G., Foord M.E., Price D., Phys. Rev. Lett. **77** (1996), 1055.
[9] VanRompay P.A., Nantel M., Pronko P.P., Appl. Surface Sci. **127** (1998), 1023.
[10] Badziak J., Chizhov S.A., Kozlov A.A., Makowski J., Paduch M., Tomaszewski K., Vankov A.B., Yashin V.E., Opt. Commun. **134** (1997), 495.
[11] Badziak J., Makowski J., Parys P., Woryna E., Opt. Appl. **29** (1999), 393.
[12] Gupta P.D., Tsui Y.Y., Popil R., Fedosejevs R., Offenberger A.A., Phys. Rev. A **34** (1986), 4103.
[13] Eidmann K., Amiranoff F., Fedosejevs R., Maaswinkel A.G.M., Petsch R., Sigel R., Spindler G., Young-lu Teng, Tsakiris G., Witkowski S., Phys. Rev. A **30** (1984), 2568.

[14] PARYS P., WOŁOWSKI J., WORYNA E., FARNY J., MRÓZ W., Inst. Phys. Conf. Ser. **140**, Series 9 (1995), 371.
[15] KRALL N.A., TRIVELPIECE A.W, *Principles of Plasma Physics*, McGraw-Hill, New York 1973.
[16] TEUBNER U., BERGMANN J., VAN WONTERGHEM B., SCHÄFER F.P., SAUERBREY R., Phys. Rev. Lett. **70** (1993), 794.
[17] BUSQUET M., Phys. Rev. B **25** (1982), 2302.
[18] ALEKSEEVITCH I.V., *Hydrodynamic theory of interaction of ion and laser beams with the solid state matter* (in Russian), Ph.D. Thesis, FIAN, Moscow 1996.
[19] DYAKIN V.M., VNIIFTRI, Mendeleevo, Russia, unpublished data.
[20] PRICE D.F., MORE R.M., WALLING R.S., GUETHLEIN G., SHEPHERD R.L., STEWART R.E., WHITE W.E., Phys. Rev. Lett. **75** (1995), 252.

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