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Investigations of ion streams emitted from plasma produced with a high-power picosecond laser

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This work reports on investigations of parameters of ion streams emitted from a plasma produced with a picosecond laser at the power densities $\geq 10^{16}$ W/cm^2. Not many papers dealing with such investigations have been published up to now, in spite of the fact that the application of precise corpuscular diagnostics enables better learning of the physical properties of such a plasma. As a result of the investigations carried out, the average and maximum energies of Cu ions were 30 keV and 150 keV, respectively. The maximum charge of Cu ions was 13+. The dependencies of parameters of ions emitted from the plasma on the laser-pulse energy as well as on the location of the focus of the laser beam with respect to the target's surface were also found out. The results obtained from the ion measurements in relation to the results of measurements of X ray are discussed.

1. Introduction

This work presents the results of the first stage of investigations of a high-*Z* plasma produced with a short pulse of a high-power neodymium laser. The ion diagnostics were the main measuring method which have been applied hitherto to investigate such a plasma to a limited degree (e.g., Meyerhofer *et al.* 1993; Guethlein *et al.* 1996). The studies of ion emission from a laser-produced plasma create the possibility of determination of the properties of this plasma and the processes occurring in it to complement other kinds of diagnostics, for example, X-ray diagnostics.

The charge state of ions, the ion velocity (or the ion energy), and the ion current density were the basic parameters of our interest. A significant question we try to answer by these investigations is how intensely and with what effects the nonthermal processes occur in a plasma produced with a very short high-power laser pulse. This is because it is interesting what portion of the laser energy being absorbed in such a plasma is converted into the energy of overthermal ions and what the characteristics of such ion streams are.

2. Experimental arrangement

In the experiment, a chirped pulse amplification (CPA) Nd:glass laser described in detail by Badziak *et al.* (1997) was used. The Nd:glass oscillator produces a single pulse of duration $\tau \approx$ 1–1.5 ps and energy $E \approx 0.5$ μJ. The double-pass grating stretcher (two holographic gratings, 1800 lines/mm), elongates the pulse to about 0.5 ns. The elongated chirped pulse is

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injected to the regenerative amplifier which amplifies the pulse to the energy $E \approx 5$ mJ. The subnanosecond pulse from the regenerative amplifier is directed to the system which enhances the long-time-scale ($\geq$1 ns) intensity contrast ratio of the pulse up to 10^8. Then, this pulse is being amplified in the system of single-pass Nd:glass amplifiers to the energy level $\sim$1 J. In the output of the amplifying system, two holographic diffraction gratings of 110×110 mm^2 in dimensions (1700 lines/mm), compresses the subnanosecond joule-level pulse to $\approx$1.2 ps. By now, the compressor operates in a single-pass version and it produces a rectangular beam of 85×60 mm^2 in dimensions. Thanks to the application of an optimized image relay system in the chain of amplifiers, the transverse distribution of the energy in the beam is quite uniform.

The plasma was investigated with the application of ion diagnostics employing the time-of-flight method [ion collectors (IC) and electrostatic ion-energy analyzer (Woryna *et al.* 1996)] as well as semiconductor detectors of X ray. The ion-energy analyzer (IEA) and the ring ion collector examined the ion beam emitted perpendicularly to the target's surface and in parallel to the axis of the laser beam and passing through the hole in the middle of the parabolic mirror ($f = 27$ cm) focusing the laser beam on the target. The laser beam could be focused to the focal spot diameter of about 30 μm. Most of the laser shots were performed with the power density $\leq 3 \times 10^{16}$ W/cm^2. The ion current was registered 110.3 cm from the target with the use of the IC.

The experimental setup is shown in Fig. 1. The IEA had a mean radius of $R_0 = 10$ cm, the gap between the electrodes of the analyzing capacitor was $\Delta R = 1$ cm, and the deflection angle $\psi = \pi/2$. The width of the input and output slits was 400 and 1000 μm, respectively. A windowless electron multiplier of the overall electron gain about 2×10^7 at 4 kV voltage was used as a detector after the IEA. The paths of flights of the IEA was 189.6 cm. The IC parameters were the following: effective collector surface 4.8 cm^2; and bias voltage -100 V. To minimize the charge exchange effect, both IEA and the target chamber were evacuated to about 5×10^{-6} Torr.

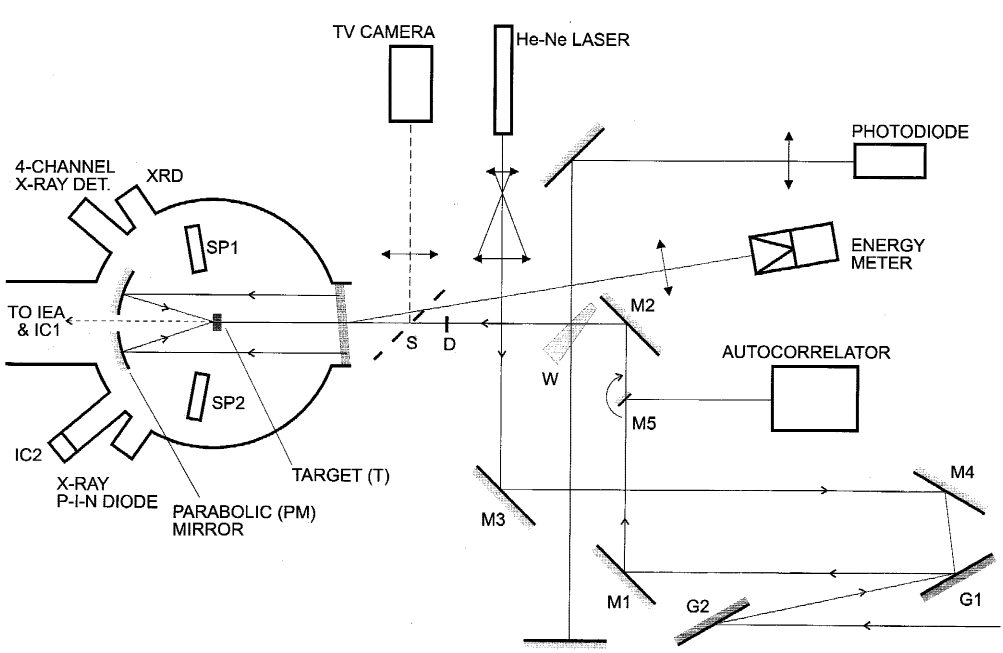

FIGURE 1. Experimental arrangement.

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3. Results of measurements

The ion collector measures a charge-integrated time-resolved signal of ions from which the energy-charge product and the total charge carried by ions, as well as mean ion energy, can be derived (Woryna *et al.* 1996). The shape of this signal together with its amplitude give also an indication about the operating conditions (focus setting, laser stability). If a realistic value of the secondary ion-electron emission coefficient of the detector material is available, the ion current density and the corresponding number of ions can be calculated from the IEA and IC signals.

The IEA gives the possibility to identify the ion species produced, that is to determine their mass-to-charge ratios, energies, and abundance. In addition, the peaks of the contaminating ions (especially H, C, and O) are mixed with the ion peaks of interest. To make the evaluation

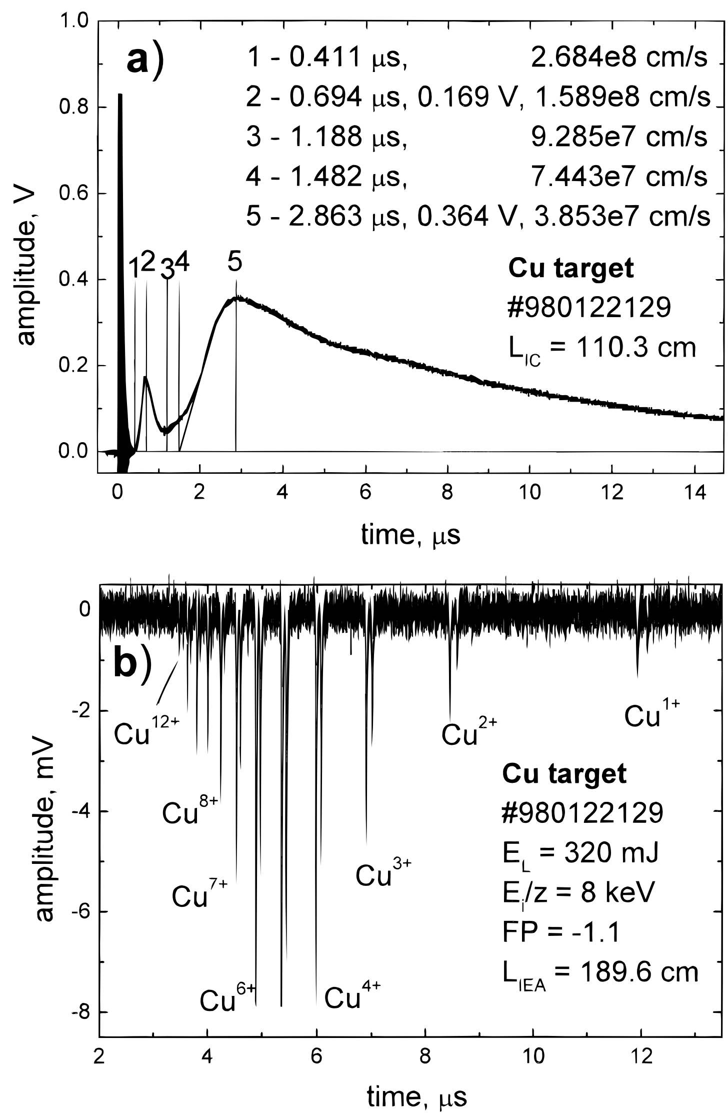

FIGURE 2. (a) Ion collector signal with two ion groups, and (b) ion charge spectrum of Cu ions measured by the electrostatic analyzer.

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of the experimental spectra easier and to help further data processing, a computer program was developed (Pfeifer *et al*. 1995).

The structure of the collector signal (figure 2a) points to the existence of two distinct ion groups (maximum velocities $\sim 2.7 \times 10^8$cm/s and $\sim 7.4 \times 10^7$cm/s in this case) corresponding to a different mechanism of their generation. Signals from IEA (figure 2b) show the abundance of Cu ions for the chosen value of ion energy-to-charge state ratio $E_i/z = 8$ keV. In this experiment, the maximum registered charge states and energies were 13+ and 150 keV (Cu ions are the thermal group of ions). The velocity of ions which corresponds to every point of the collector signal can be seen in figure 3.

We varied the focus position versus the target surface, in the range from −0.6 mm to 0.6 mm (figure 4). The ion yield depends strongly on the focus position with respect to the target surface. Soft X-ray radiation emitted from laser–plasma was registered simultaneously for different laser focus positions. Both dependencies have extremes for focus positions near the target surface.

We have also investigated the dependencies of the number and velocity of fast and thermal ions on the laser-pulse energy, in the range from 15 mJ to 350 mJ, when the target is placed in a position corresponding to the minimum of ion emission (and the maximum of X-ray emission). Figure 5a presents the dependence of the total charge drifted by fast and thermal ions into the solid angle determined by the position and the surface of the IC on the laser-pulse energy. This charge does not depend on the laser energy for fast ions, whereas for thermal ions it increases linearly with the laser energy. However, the dependence of the velocity of fast and thermal ions counted for corresponding maxima of the signal from the IC (figure 5b) on the laser energy is different. Initially, the velocity of fast ions increases rapidly, and next it becomes fixed on the level of 1.3×10^8 cm/s.

4. Discussion

Analyzing the results of ion measurements obtained, completed with the results of X-ray measurements, one can formulate the following conclusions:

- The number of thermal ions increases and the number of fast ions does not change with an increase in the laser energy.
- The velocity and energy of thermal ions increase slowly and those of fast ions increase quickly with an increase in the laser energy.

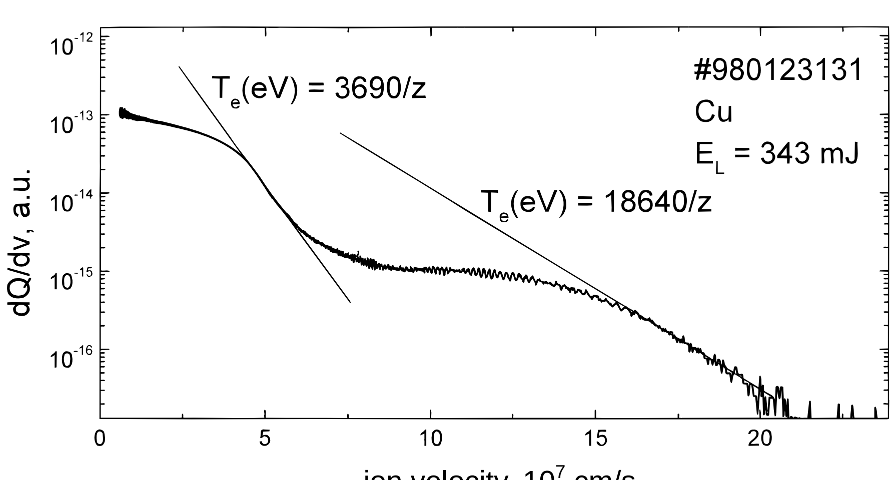

FIGURE 3. Ion-velocity distribution for ion-collector signal.

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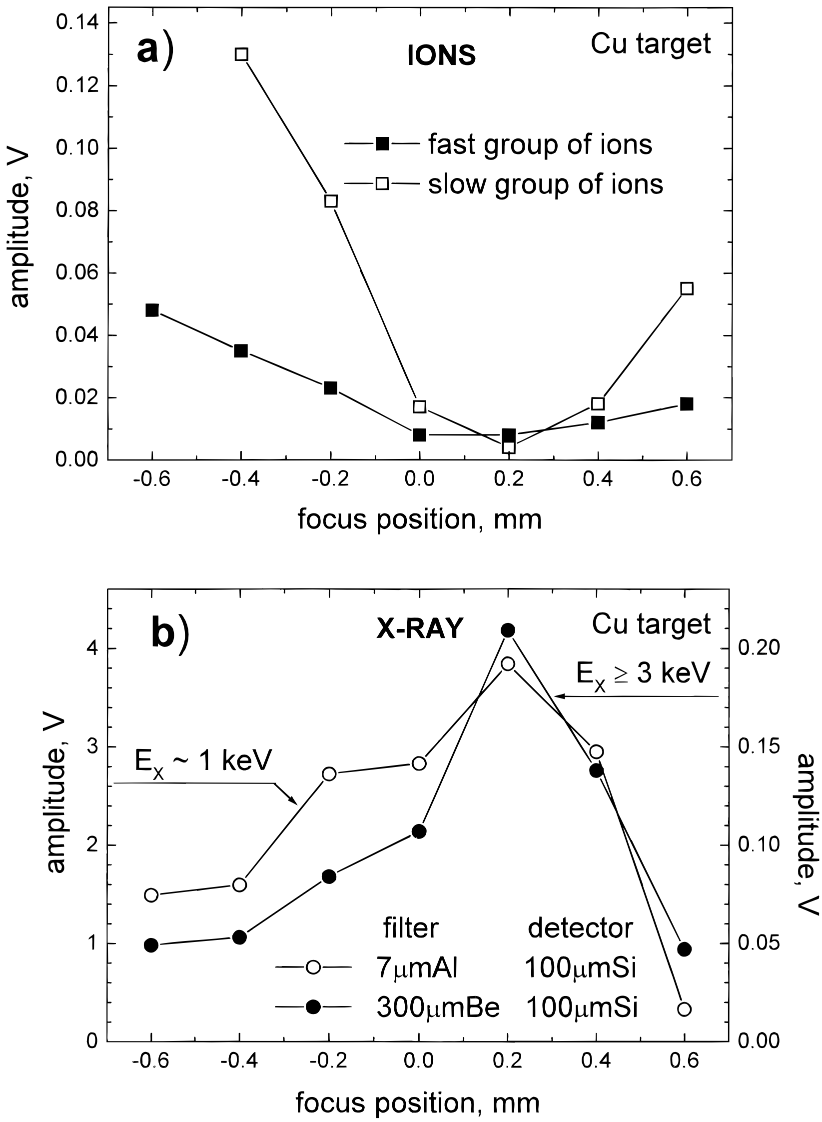

FIGURE 4. Amplitudes of ion-collector signal (a) and X-ray detector signals (b) as a function of laser focus position.

The above-mentioned behavior results from the fact that together with an increase in the energy of a picosecond laser pulse, the amount of thermalized plasma increases with moderate increase in its temperature. Simultaneously, the number of fast ions accelerated nonthermally increases weakly, but their velocity and energy increase due to enhancement of acceleration processes with an increase in the laser power density.

In this experiment, contrary to our nanosecond experiments (Parys *et al.* 1995; Krasa *et al.* 1997), the ion stream emitted perpendicularly to the target reaches the minimum and X-ray emission achieves the maximum when the focus of the laser beam is on the surface of the target. This results from the fact that in the case of the picosecond beam being defocused, much more thermal plasma is produced than at a nanosecond beam. In the second case, a large amount of a cold plasma is created which emits slow ions registered separately.

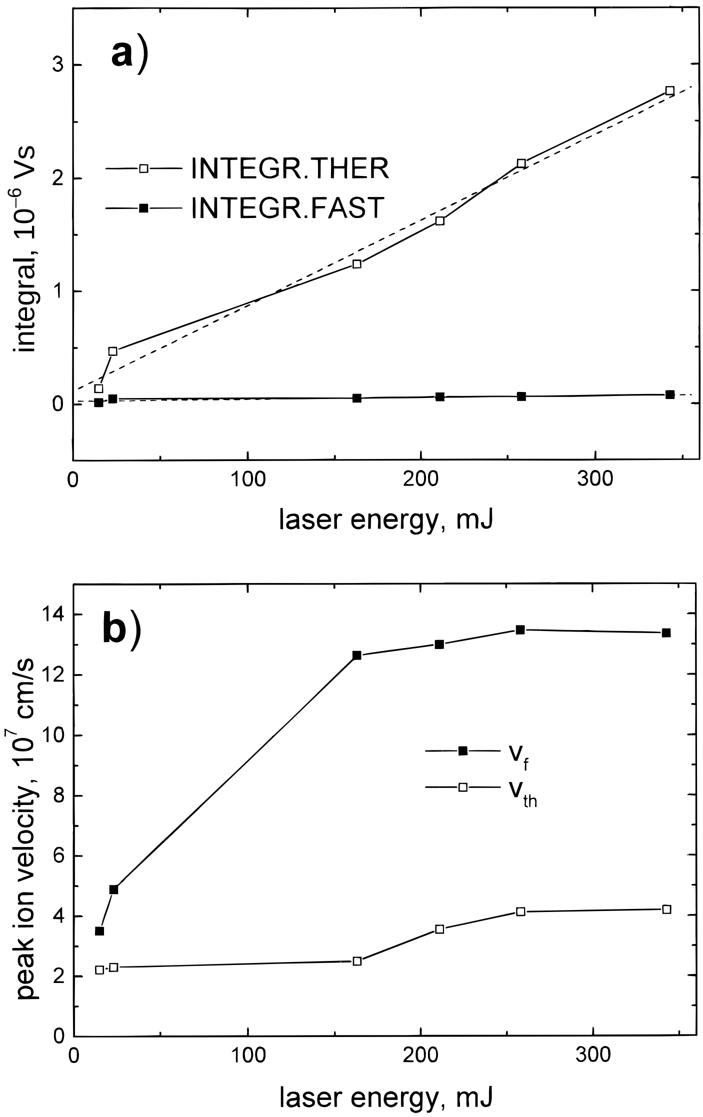

FIGURE 5. Ion charge (a) and ion velocity (b) registered by ion collector as a function of laser-pulse energy.

Following the model of isothermal expansion of two-temperature plasma (Wickens 1978), the ion velocity distribution can be sufficiently accurately described by an exponential relation. The slope of the ion-velocity distribution plot determines the ion-sound velocity corresponding to temperature. A fitting procedure gives: T_e^{th} (keV) $= 3.7/z$ and $T_e^f = 19/z$ for the ion-collector signal with distinctly separated two ion groups, where z is the average charge state of ions in the hot plasma region.

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