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Influence of corundum structure on the characteristics of multiply charged ions in a laser-produced plasma

M R Bedilov, Kh B Beĭsembaeva, M S Sabitov

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Abstract. An investigation was made of the interaction of intense laser radiation ($\lambda = 1.06$ μm) with previously irradiated corundum. The studies were performed in the collecting mode by employing time-of-flight mass spectrometry. Electron and ion currents were considered simultaneously with charge-state and energy characteristics of multiply charged ions of the plasmas produced at the source and previously irradiated targets. The combined consideration allows the conclusion that the prior neutron irradiation of a sample by a fluence of $10^{15} - 10^{19}$ neutron cm^{-2} makes for production of a higher-temperature plasma.

The interest in a laser-produced plasma, which is a source of radiation in a broad spectral range and of charged particles and neutrons, is caused by its unique properties — high density, very high temperatures and pressures [1 – 3]. The plasma formation at moderate intensities of laser radiation at the target surface involves destruction of the target [4]. That is why different static and dynamic effects occurring in a target can exert influence on the efficiency of processes which take place in laser radiation – target interactions [5 – 7].

The purpose here is to study the impact of structural imperfections of a target on its interaction with the radiation of a neodymium laser ($\lambda = 1.06$ μm). The structural disruptions of the sample under investigation were produced by exposure to reactor radiation at a fluence of $10^{15} - 10^{19}$ neutrons cm^{-2}. Corundum was chosen as the object of research, because corundum makes it possible not only to elucidate the effect of neutron-induced structural defects, but to assess the part played by the γ-component of reactor radiation.

The radiation of a neodymium laser (pulse length $\tau \sim 50$ ns, pulse energy 3 J) was focused on the surface of a sample. The radiation intensity at the target surface q was varied by using neutral density filters between 1 and 100 GW cm^{-2}. A study was made of electron and ion currents as well as of charge-state and energy distributions of the multiply charged ions in an expanding laser-produced plasma. Moreover, we studied the impact of prior irradiation on the target properties (thermal conduction, optical absorption, and resistance to radiation).

M R Bedilov, Kh B Beĭsembaeva, M S Sabitov Institute of Nuclear Physics, Academy of Sciences of Uzbekistan, pos. Ulughbek, 702132 Tashkent, Uzbekistan

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The collecting method was used to measure electron and ion currents. The charge-state and energy ion characteristics were studied by the technique of time-of-flight mass spectrometry. After every exposure to laser radiation, the point of laser radiation – target interaction was changed to eliminate the effect of cratering on the parameters of charged particles [8].

The study of electron and ion currents as well as of the charge-state and energy characteristics of multiply charged ions in the plasma produced by exposing the surface of a pre-irradiated target to intense laser radiation revealed the following. In this case, the basic relationships observed in the interaction of light with an unexposed solid are retained: with increasing q, the ion yield increases, as do the ion charge and energy.

A comparison of the charge-state distribution of the plasma emitted from a pre-irradiated target with the same characteristic of the plasma originating from unexposed samples revealed that the radiation-induced defects change the efficiency of interaction of the laser radiation with the object investigated. It was determined experimentally that the qualitative pattern of changes depends on the type and dose of pre-irradiation.

The dominant role of the structural defects, which influence the interaction efficiency, in modifying the properties of the targets investigated is amply demonstrated by the results obtained with an Al_2O_3 target (corundum). For instance, a γ-ray irradiation of corundum of 10^{10} R, which does not induce structural disruptions in it [9], has no effect on the charge Z_{max} of Al and O ions. By contrast, when the laser radiation with the same q acts on a reactor-irradiated sample, the charge-state distributions of Al and O ions are broader than they are prior to reactor irradiation. In particular, when an unexposed Al_2O_3 sample was irradiated at $q = 10^{11}$ W cm^{-2}, Z_{max} for O and Al was respectively 4 and 3; when the target was pre-exposed to a fluence of 2×10^{18} neutron cm^{-2}, the intensity of ion-produced signals recorded from the plasma increased in comparison with the plasma of an unexposed sample while the charge-state spectrum itself was supplemented by the lines of $O^{5+} - O^{7+}$, Al^{4+} ions (Fig. 1).

The influence of structural disruptions is also confirmed by the results obtained on recovery annealing of reactor-irradiated corundum. When irradiating Al_2O_3 previously exposed to neutrons at the specified fluence and annealed for 1 h at 6000 °C, the ion charge state of the resultant plasma is somewhat lower than prior to annealing but higher than was the case prior to neutron irradiation. If a sample thus annealed is subsequently exposed to additional γ-radiation with a dose up to 10^8 R, the $O^{5+} - O^{7+}$ ions are recorded

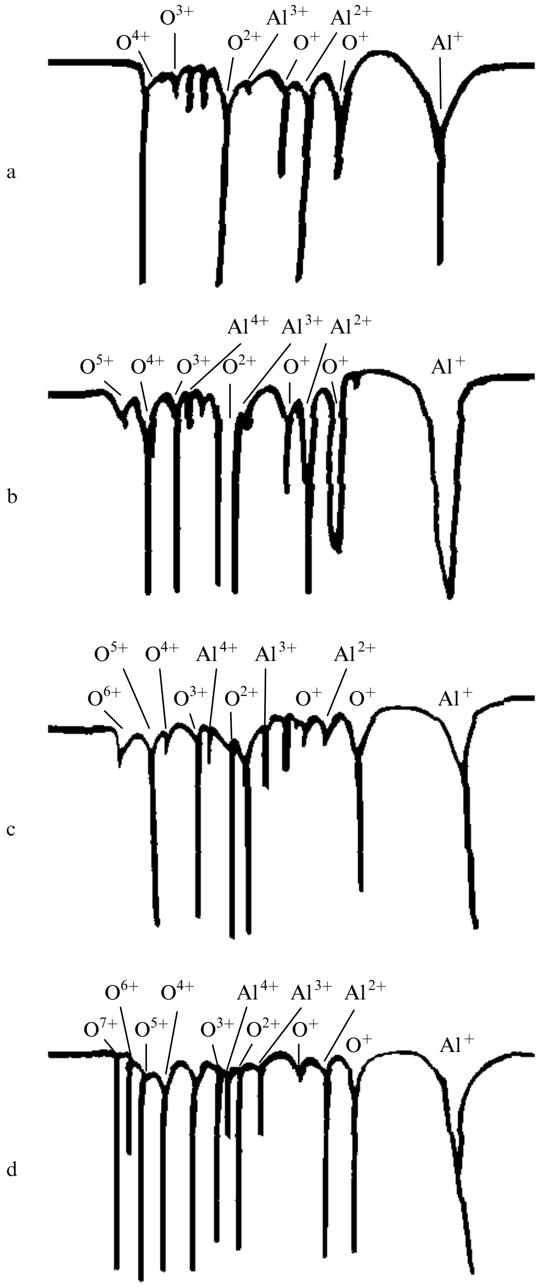

Figure 1. Ion charge spectra produced by laser irradiation of Al_2O_3 at $q = 10^{11}$ W cm^{-2} following exposure to neutrons with a fluence of 2×10^{18} neutron cm^{-2} (a), following exposure to neutrons with a fluence of 2×10^{18} neutron cm^{-2} and subsequent annealing at 600 °C (b), following γ-ray irradiation with a dose of 10^8 R after pre-exposure to neutron flux with a fluence of 2×10^{18} neutron cm^{-2} and annealing at 600 °C (c), as well as prior to exposure (d).

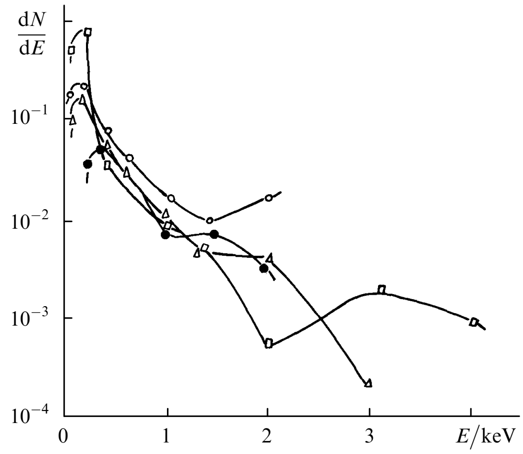

Figure 2. Energy spectra of Al^{2+} ions produced by laser irradiation of a single-element target at $q = 10^{11}$ W cm^{-2} prior to (●) and after neutron exposure with a fluence of 2×10^{15} (○), 2×10^{17} (△), and 2×10^{18} neutron cm^{-2} (□).

as before in the plasma produced at $q = 10^{11}$ W cm^{-2}. At different stages of similar treatment, an additional absorption band, which peaks at 305 nm, exhibits a similar behaviour. This band is attributed to the structural defect [10] related to Al bond rupture and displacement of Al from its site in the lattice. We emphasise that this is demonstrated most amply at $q \sim 10^{10}$ W cm^{-2}.

A comparison of the ion energy spectra of the plasma produced from a pre-irradiated target and the plasma from an initial (unexposed) sample revealed that radiation processing of the sample to be studied is reflected in the regularities of ion formation. The energy distribution of the Al and O ions produced by irradiation of corundum previously exposed to γ-rays is identical to that observed with an unexposed Al_2O_3. An investigation of the ion energy spectra of the plasma originating from a reactor-irradiated target showed that ions with any Z value are characterised by distribution broadening owing to the addition of low- and high-energy ions with increase in the radiation dose (Fig. 2). Apart from that, there occurs a reduction of the minimum energy E_{min} required of an ion with a given Z to escape the dense plasma region.

The observed nature of change of the formation dynamics and the distribution range of ion energy spectra of the plasma produced by laser irradiation of pre-irradiated sample is evidence that it is heated to higher temperatures and that the likelihood of recombination is lower in it. The experimental parameters obtained in studies of electron and ion currents of the plasma formed from pre-irradiated solids were higher than those in the case of an unexposed target.

A study of the target properties showed that reactor radiation impairs the thermal conduction in the target and its resistance to radiation. The optical absorption spectrum of neutron-irradiated corundum was indicative not only of the defects caused by the shifts of crystal-forming particles but also of the defects increasing the background in the 240 – 1200 nm range.

The impairment of thermal conduction and the increase of optical absorption in the target cause its ablation, induced by intense light flux, to commence earlier. In this case, the velocity of the ablation (vaporisation) front increases, because the energy absorbed increases [4, 11]. The intensity of vaporisation of a solid is known to be determined by the binding energy [5]. According to the theory of absolute rate coefficients [12], the probability of an elementary vaporisation event is

$$\omega = \frac{kT}{h}\frac{f^*}{f}\exp\left(-\frac{\lambda_1}{kT}\right),$$

where f^* is the statistical sum of an activated complex which does not take into account the contribution of the 'reactive' coordinate, f is the statistical sum of an atom bound inside a crystal lattice, λ_1 is the activation energy equal to the energy it takes to vaporise one atom at the absolute zero, and T is the temperature of the layer from whence vaporisation proceeds.

If it is assumed that λ_1 and f are invariable during exposure, the probability of vaporisation should be higher in the case of a pre-exposed sample, because T is in this case higher than for an unexposed sample. Taking into consideration the existence of domains in which a part of the atoms has split bonds, it is conceivable that these factors could enhance the vaporisation efficiency. The existence of an optimal laser radiation intensity ($q_{\rm opt} \geqslant 10^{10}$ W cm^{-2}) for which the effect is most conspicuous confirms our assumption, because the vaporisation of a solid by electromagnetic radiation at these q values is caused by the thermal mechanism [4].

The increase in density of the material flung outward results in a reduction of the time taken to screen the target surface from the incident laser flux. This is responsible for an increase in the fraction of energy that goes into the heating and the ionisation of a plasmoid.

On exposure, a sample tends to get rid of the stress (which appeared inside of it in the formation of structural disruptions) in the wave of dumping, which proceeds in the target as the shock wave reaches the surface, thereby enhancing the hydrodynamic acceleration. This, as well as the formation of a higher-density plasma, accounts for the experimentally observed reduction of $E_{\rm min}$ for the ions generated from a pre-exposed target. Since the plasma itself is in this case heated to higher temperatures, it is clear that the factors listed above increase its expansion velocity. The duration of plasma stay within the recombination region decreases to reduce the efficiency of recombination processes, and the ions escape the dense plasma region with less loss in charge and number.

The results obtained in this work can be used in the development of the sources of multiply charged ions.

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