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IONIZING ACTION OF RADIATION DUE TO HEATING OF SUBSTANCE IN THE FOCUS OF A LASER BEAM AND PRODUCTION OF A PLASMA WITH HIGH DEGREE OF IONIZATION

T. U. Arifov, G. A. Askar'yan, and N. M. Tarasova
P. N. Lebedev Physics Institute, USSR Academy of Sciences
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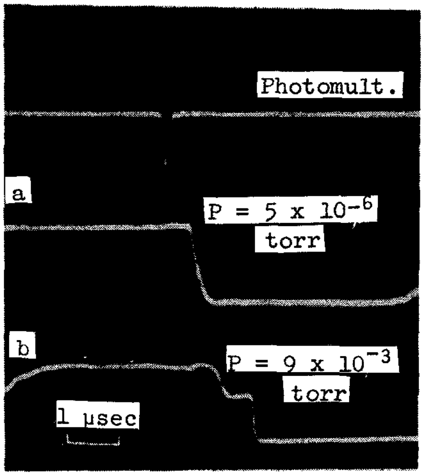
It is known that when a laser beam is focused on a substance, the latter can be heated to high temperatures, on the order of several dozen electron volts, at which hard ultraviolet and x-ray emission is produced [1 - 4]. No data were available, however, on the intensity or the ionizing ability of this radiation. In this article we show, for the first time, that such radiation has a strong ionizing effect, thus evidencing high intensity, and we indicate that this radiation can play an important role in the production of plasma with high degree of ionization, since it ionizes the neutral atoms ejected together with the plasma when the laser acts on the substance (a particle, a target, or a gas volume).

Since the ionization cross section is $\sigma_f \sim 3 \times 10^{-17} - 10^{-18}$ cm^2, we can expect a strong ionizing action, with an atom-ionization probability close to unity, at intensities $N_1 \sim 1/\sigma_f \sim 10^{17} - 10^{18}$ quanta/cm^2, corresponding to a vacuum-ultraviolet radiation density on the order of a fraction of a Joule per square centimeter. It will be shown below that this is readily attainable even with medium-power lasers. Unprecedented ultraviolet flux densities can be attained near the hot spot.

Special experiments were set up to investigate the ionizing action of the radiation produced by focusing a laser beam on matter. The beam of a Q-switched ruby laser was focused on a target in a vacuum chamber. The laser emission energy was 1.5 J at a pulse duration ~30 nsec at half-width. The focal length of the lens was f = 14 cm.

The plasma was registered with the aid of microwave radiation of 1 cm wavelength; the radiating antenna produced a directed beam of radio emission parallel to the target surface, at a distance 4 cm from the target. An auxiliary metal grid, placed 3 cm away from the target, shielded part of the chamber with the target from the microwave radiation and made it possible to reconcile more accurately the start of the blocking of the microwave radiation with the instant when the plasma first appeared in front of the grid.

With a high vacuum in the chamber, the microwave radiation revealed only the arrival of plasma due to the action on the target (Fig. a); when gas was added to the chamber, a so-called "foreplasma" was produced, due to the action of the ionizing radiation ahead of the arrival of



the front of the main plasma from the target (Fig. b). With increasing gas pressure, the degree of overlap of the microwave radiation by the "foreplasma" increased and became comparable, at a pressure P_{cr}, with the strong overlap from the main plasma of the target. This was taken as evidence that the foreplasma concentration becomes close to the critical $n_{e_{cr}} \approx 10^{13}$ el/cm^3 for the used radio emission. Comparison with the molecule concentration, $n_a = 3.5 \times 10^{16} P$ (torr), makes it possible to determine the ionization probability $W_i(R) = (n_{e_{cr}}/n_{a_{cr}}) \approx 3 \times 10^{-4}/P_{cr}$(torr). In order of magnitude we have $P_{cr} \approx 10^{-2} - 10^{-}$ torr, yielding an ionization probability $W_i \sim 10^{-2}$ at a distance R = 4 cm from the focal point, which agrees quite well in order of magnitude with theoretical estimates made under the assumption that an appreciable part of the energy ($\sim 10^{-1}$) of the laser emission goes over into the ionizing ultraviolet. Inasmuch as for a specified laser enrgy we have for the ionization probability $W_i \sim 1/R^2$, where R is the distance from the hot point, it follows that total ionization can be expected at distances $R \sim \sqrt{R^2 W} \sim 1$ cm.

The targets investigated were made of aluminum, titanium, molybdenum and lead, and the chamber was filled with air and with hydrogen. Figures a and b pertain to the case of a titanium target and air. In this case $P_{cr} = 3 \times 10^{-2}$ torr and $W \approx 3 \times 10^{-2}$. The table lists the values of the critical pressures, from which it follows that a lead target affords the best ionizing action, and the ratio of the photoionization cross sections $\sigma_f(\text{air})/\sigma_f(H_2)$ equals approximately 10 for a titanium target and 5 for a lead target1).

Control experiments were performed to verify the possible role played in the production of the foreplasma by the fast electrons from the hot spot of the target, and of other possible non-photoionizing factors. Application of a transverse magnetic field (H = 200 Oe) did not hinder the production of the foreplasma, thus showing that the contribution of the electrons to the production

Target material	Crit. press. for air, torr	Crit. press. for H_2, torr
Pb	$9 \cdot 10^{-3}$	$4{,}5 \cdot 10^{-2}$
Mo	$1{,}9 \cdot 10^{-2}$	$2 \cdot 10^{-1}$
Ti	$2{,}2 \cdot 10^{-2}$	$1{,}9 \cdot 10^{-1}$
Al	10^{-1}	$5 \cdot 10^{-1}$

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1)An ultraviolet flash was registered also by a salicyl luminor placed 5 cm away from the target. The flash duration was on the order of 100 μsec. The absorbing filters used for control were a layer of air admitted into the chamber or thin plates of quartz and glass.

The quartz plate, which passed wavelengths exceeding 2000 Å, decreased the magnitude of the flash by a factor 1.5. Admission of air at an approximate pressure 1 torr increased the luminescence flash by 1.3 times. This shows that the hard ionizing ultraviolet contains an appreciable fraction of the luminescence-producing radiation energy.

hinder the production of the foreplasma, thus showing that the contribution of the electrons to the production of the foreplasma is small. The short time of foreplasma production (< 0.1 μsec) at a sufficiently large distance from the target (4 cm) precludes its being produced by the fast fraction of the plasma from the target. The more intense production of the foreplasma when a heavy target is heated likewise confirms this conclusion.

The described experiments show that heating of matter in the focus of a laser can result in a strong ionizing flash in the vacuum chamber. This flash can be used to ionize gas batches and atom beams to produce plasma, to fill traps, to obtained polarized electrons, etc. The presence of ionizing radiation should greatly reduce the number of neutral atoms in the laser-produced plasma. We verified the possibility of using different mirrors to focus the ionizing radiation and to prevent plasma from the target from entering the volume in which the photoionization takes place. The target was placed in one focus of a spheroidal mirror, the reflection from which produced gas ionization behind the target at the other focus.

We note that when laser energy is released in air at normal pressure (laser spark, action on a target), the ionizing radiation also produces rapidly an ionization aureole [5]. In this case, however, the ionizing ultraviolet quanta are absorbed in a layer of air on the order of a fraction of a millimeter, and are therefore ineffective for the ionization of a large aureole volume with dimensions on the order of several centimeters. The probability of ionization at such distances therefore amounts to only 10^{-6}. It is possible that an important role in the ionization of the air is played at such pressures and thicknesses by multistage ionization or by x-ray quanta.

Our experiments have shown that the ultraviolet output increases strongly with increasing laser power, so that the action of a powerful laser beam on a target can provide highly efficient generation of hard ultraviolet. This radiation can be used not only for concentrated ionization of atoms and molecules, but also for photoexcitation or photodissociation of molecules, etc. In particular, the excited atoms obtained thereby can be used to produce stimulated emission in the ultraviolet region.

Ultraviolet radiation from a plasma produced by the laser action on the target may be the cause of powerful photocurrent from the target. With this, photoionization of the gas near the target ensures also compensation of the Coulomb charge and makes it possible to obtain large currents without applying an external voltage. We observed, together with I. M. Raevskii, currents reaching about 100 A at a gas pressure $P \sim 10^{-2}$ Torr [6]. Similar current-flow effects can take place in high-temperature radiation flares near the earth's surface.

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In the figure on p. 78, the lower oscillogram must be turned 180°. A correct photograph will be printed in the errata section of a forthcoming issue.

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The correct figure is shown below: