ULTRASHORT–WAVE EMISSION OF LASER–INDUCED PLASMA INITIATED BY WATER–DROPLET AEROSOL

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Received January 31, 1994

It has been found experimentally that emission spectrum of the plasma initiated by a water droplet upon exposure to a pulsed CO_2 *laser radiation of microsecond duration exhibits X–ray spectral components. Possible physical mechanisms of this emission and its characteristic spectra are discussed.*

Considerable recent attention has been given to investigations on the emission spectra of the plasma resulting from an optical breakdown initiated by aerosol particles of various origin. Experiments that have been accomplished on spectral analysis of this plasma cover the spectral range extending from the vacuum ultraviolet to the infrared. However, the question of whether shorter–wavelength spectral components with $\lambda \leqslant 20$ nm exist in the emission spectrum of the plasma is still an open question. Much research devoted to investigation of X–ray spectra of laser–induced plasma centered around the problem of thermonuclear fusion, in particular, the plasma induced at the surfaces of various targets upon exposure to superhigh–power laser radiation was studied. In experiments of this short, multichannel laser systems were used and radiant power densities $P \sim 10^{12}$–10^{16} W/cm^2 were achieved (see Ref. 1 and the references therein).

In our experiments on investigations of the interaction of laser radiation with aerosol particles, we used less energetic lasers delivering $P \sim 10^7$–10^{10} W/cm^2.

However, the possible existence of X–ray spectral components in the spectrum of the plasma initiated by the aerosol cannot be ignored. In this connection we detected ultrashort–wavelength emission of the plasma resulting from the breakdown initiated by a water droplet upon exposure to a pulsed CO_2 laser radiation (see Fig. 1).

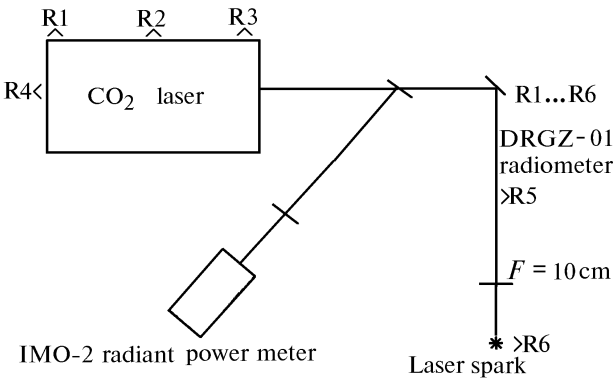

FIG. 1. Diagram showing the experimental configuration. Laser pulse energy is 6 J, *radiant power density at the focus is* 10^9 W/cm^2.

To create the plasma resulting from the breakdown, we used a laser with energy up to 6 J per pulse and a pulse width of 1.5 μs. The pulse used for breakdown experiments consisted of a high–power peak with a full width at half–maximum of 300 ns followed by a lower powered tail. Laser radiation was focused with a lens of focal length $F = 10$ cm, and the radiant power density at the focus was no more than $P \sim 10^9$ W/cm^2 (in excess of the breakdown thresholds not only for targets[2] but also for water–droplet aerosol[3–5]). A droplet of undistilled water 1 mm in radius was suspended on a filament 5–10 μm in diameter fabricated from bakelite–phenol glue and placed in the focal plane of the lens. The standard DRGZ–01 radiometer intended to measure X–ray and gamma radiation doses and equipped with a sensitive element fabricated from NaJ was used for recording of the plasma emission. The device was situated at a distance of 10 cm from the droplet. Readings in excess of the background level were considered. To eliminate possible effects of emissions from a power supply unit of the laser and from gas discharge, measurements were performed without breakdown, when laser radiation was focused into the air.

Our experiment was performed in the following order: the breakdown was initiated 1) by the water droplet, 2) at the surface of a steel plate, and 3) by a duralumin particle. The input window of the measuring device was shut by a black paper screen to prevent beta radiation from entering this device.

The existence of supershort–wavelength radiation in the emission spectrum of the plasma was unambiguously recognized in our measurements.

The measured dose rates (μR/s) for the steel plate, water droplet, and duralumin particle (Table I) were in the 1:2:4 ratio and were equal to 0.01, 0.02, and 0.04 μR/s, correspondingly. Since our measurements were performed with the device intended to measure gamma radiation, it should be stipulated at once that the recorded radiation cannot be gamma radiation because it is emitted by an excited nucleus and "hot" electrons with energies of the order of hundreds of kiloelectronvolts.

Thus we recorded undoubtedly X–rays. As is well known, X–rays are due to the interaction of high–energy electrons with atoms and manifest themselves either as bremsstrahlung radiation exhibiting continuous spectrum whose frequency is bounded by the inequality $\nu < m\upsilon^2/2h$, where ν is the radiation frequency, υ is the velocity of electrons, and h is Planck's constant, or as radiation whose characteristic spectrum is due to the excitation of atomic electrons from low–lying energy levels. Experimentally recorded emission exhibits most likely both continuous and characteristic spectra.

0235-6880/94/09 675-02 $02.00

TABLE I.

Radiometer position	Dose rate, μR/s
R1...R4	0.02
R5 (without breakdown)	0.00
R5 (breakdown initiated by water droplet)	0.00
R6 (breakdown initiated by water droplet)	0.02
R6 (breakdown induced by steel plate)	0.01
R6 (breakdown initiated by duralumin particle)	0.04

TABLE II.

Instability mechanisms	Threshold of manifestation, W/cm^2	Reference
Aperiodic instability	$> 10^{14}$	1
Plasma waves	$2\cdot10^{12}$	1
Two–plasmon decay	$7.5\cdot10^{13}$	1
Brillouin instability	10^{12}	6
Raman instability	$5\cdot10^{12}$	6

With the parameters of the plasma that are typical of the breakdown initiated by the aerosols, namely, mean electron temperature $T_e \sim 10^4$–10^5 K and electronic density $N_e \sim 10^{17}$–10^{19} cm^{-3}, X–rays are most likely due to "hot" electrons from the tail of a Maxwell distribution of electron energy. Other factors associated with parametric instability[1–6] cannot reveal themselves because these effects have higher breakdown thresholds $P \sim 10^{12}$–10^{14} W/cm^2 (see Table II). Although we performed only preliminary experiment and the data obtained are insufficient, a tentative conclusion on different readings indicated by the device for different materials can be made from experimental observations. The most probable reason is the characteristic spectrum lines.

From an analysis of X–ray terms of some elements presented in Ref. 7 it is evident that characteristic X–ray spectrum of ferrum exhibits lines with $\lambda \sim 1$–2 nm and excitation energy of 0.5–1 keV.

At the same time, characteristic spectrum of aluminum exhibits the L–lines L_{α_1} and L_{α_2} corresponding to the $3d_{5/2} \to 2p_{3/2}$ and $3d_{3/2} \to 2p_{1/2}$ transitions, respectively. Electrons with energy as low as ~70 eV may be translated into excited state with subsequent emission of lines with $\lambda \sim 17$ nm.

As to the breakdown initiated by water droplets, it seems likely that the primary contribution to X–rays comes from the particulate matter in the form of various salts. More definite conclusion can be made after further experiments on recording of X–ray spectra of the plasma initiated by the aerosols. Investigations on these spectra may yield additional information on physics of origin, formation, and development of plasma centers initiated by real aerosol particles upon exposure to laser radiation.

REFERENCES

1. N.G. Basov et al., Zh. Eksp. Teor. Fiz. **67**, 118 (1974).
2. S.A. Metz et al., J. Appl. Phys. **46**, No. 4, 1634 (1975).
3. D.E. Lencioni, Appl. Phys. Lett. **25**, 15 (1974).
4. R.G. Pinnick et al., Appl. Opt. **27**, No. 5, 997 (1988).
5. A.A. Zemlyanov, A.V. Kuzikovskii, and L.K. Chistyakova, Zh. Tekh. Fiz. **51**, No 7, 1439 (1981).
6. W.L. Kruer, *Progress in Lasers and Laser Fusion* (Plenum Press, New York).
7. I.K. Kikoin, ed., *Tables of Physical Constants* (Atomizdat, Moscow, 1976), 1006 pp.