X radiation of a plasma produced by picosecond ruby laser pulses

V. V. Blazhenkov, A. N. Kirkin, L. P. Kotenko, A. M. Leontovich, G. I. Merzon, A. M. Mozharovskiĭ, A. L. Chernyakov, and A. N. Chuzo

P. N. Lebedev Physics Institute, USSR Academy of Sciences
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We have investigated the continuous x rays emitted from a plasma arising on interaction of picosecond ruby laser pulses with massive targets of 20 different materials from Be to Bi. The laser flux density at the target surface was up to $\sim 10^{14}$ W/cm^2 with pulse length 10–20 psec and energy ~ 0.5 J. Absorption curves for the x rays were measured for cutoff energies $E_c = 4$–60 keV. The electron temperature of the plasma was determined on the basis of the continuous x rays in the region $E_c = 4$–8 keV and also on the basis of the x-ray line spectra. For all targets in the flux density range $> 10^{13}$ W/cm^2 in the region $E_c \approx 10$ keV an inflection was observed in the x-ray absorption curve, corresponding to deviation of the electron velocity distribution function from Maxwellian. The effective temperature of the suprathermal electrons for various targets amounted to 2–6 keV and in individual laser pulses reached 15 keV. Measurement of the angular distribution of the suprathermal x rays in the target plane showed that it is isotropic for normal incidence of a linearly polarized laser beam on the target.

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INTRODUCTION

Study of the x rays from a laser plasma is one of the principal means of diagnostics and permits study of many processes occurring in it. From the slope of the absorption curve of the continuous x rays it is possible to determine the electron temperature of the plasma,[1] and from the line spectra of multiply charged ions one can determine the electron temperature and density of the plasma and also its ionization state (see for example Ref. 2). Measurement of the angular distribution or polarization of the x rays provides information on the direction of the electron beams arising in the laser plasma,[3,4] and therefore it is of interest to study systematically the x rays from a plasma over a wide spectral region.

The continuous x rays of a laser plasma have already been studied by a number of workers.[5-9] Most of them have observed a deviation of the x-ray spectrum from thermal, which usually is associated with the appearance of fast (suprathermal or hot) electrons as the result of various anomalous mechanisms of absorption of the laser radiation—development of parameteric instabilities[3] and resonance absorption (linear transformation of a light wave into potential Langmuir oscillations on oblique incidence onto a layer of inhomogeneous plasma[10]), and also the appearance in the plasma of megagauss magnetic fields which affect the magnitude of the transport coefficients.[8] In addition, the possible effect of self-focusing of the laser beam and of ponderomotive forces[12] on the velocity distribution of the electrons of the laser plasma has been discussed.

In the present work we have investigated the continuous x rays from a plasma on interaction of ruby laser radiation of picosecond duration with targets of 20 different materials from Be to Bi. The measurements were made in the spectral region 4–60 keV. Preliminary results have been published previously.[13]

1. EXPERIMENTAL APPARATUS

In study of laser plasmas at the present time neodymium and CO_2 lasers of nanosecond duration are usually used. At the same time many processes occurring in such a plasma, including processes important for solution of the problem of controlled nuclear fusion, can be studied by means of picosecond laser pulses. Here the flux densities $I \sim 10^{14}$ W/cm^2 and higher which are characteristic of most contemporary nonosecond laser installations can be obtained by simpler means as a result of the shorter length of the pulse. With use of picosecond pulses values $I \sim 10^{16}$ W/cm^2 have already been obtained.[8]

Our apparatus used a ruby laser ($\lambda = 0.69$ μm) with self-synchronization of the modes, operating at a temperature 100 K.[14] The choice of a ruby laser was due to the fact that with it a flux density 10^{13}–10^{15} W/cm^2 can be obtained with a much smaller volume of active medium than in the case of a neodymium laser. This is due to the large cross section for the laser transition of ruby at low temperatures. The radiation at the output of the laser, which consisted of a generator and one amplifier with a total active-medium length 24 cm, consisted of a short train containing 1–3 pulses of duration 10–20 psec with total energy up to 0.5 J. The laser beam was focused by a lens ($f = 50$–60 mm) onto massive targets of the various materials. The diameter of the focal spot was measured by an optical multichannel analyzer[15] and amounted to 60 μm at half intensity in the case of a lens with $f = 50$ mm. In this case half of the laser energy was contained in a spot of diameter ~100 μm. The limiting value of the energy flux density at the focus of the laser was determined beforehand by measurement of the pulse duration by means of a high-speed optical grate with a saturated filter[16] and amounted to 10^{14} W/cm^2 for a pulse duration 10–20 psec and an energy 0.5 J.

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The laser radiation was linearly polarized. The degree of polarization was measured with a Glan-Thompson prism and was at least 0.9. The laser used permitted 50 pulses per hour and about 100 pulses per run. The general arrangement of the experimental apparatus is shown in Fig. 1.

2. DETECTION OF CONTINUOUS X RAYS

Study of the x rays arising in a laser plasma involves a number of difficulties due primarily to the short duration of the laser pulse, which makes it impossible to determine the spectrum of the radiation by detection of individual x-ray photons. To measure the rapidly dropping energy spectrum of x rays over a wide spectral region it is necessary to have a large dynamic range of the detecting equipment. In addition, oscillations of the x-ray intensity from pulse to pulse produced by instability of the laser parameters leads to the need of measuring the entire spectrum during a single laser pulse.

A multichannel spectrometer with a minicomputer operating on-line with the experiment comes closest to meeting all of the requirements enumerated. We put together an apparatus of this type on the basis of a PDP-11/05 minicomputer and an electronic modular system conforming to CAMAC and NIM standards. The apparatus performs a pulse-height analysis of signals from the x-ray detectors, measures the energy of the incident and reflected laser beams, and protects the measuring circuits from interference. The system carries out automatic calibration of the spectrometer circuits, preliminary processing of the data obtained, recording of the data on a floppy disk for subsequent analysis and processing, and can transmit on-line α-numeric and graphical information to external devices. The programs were written in the compiler languages ORACLE and FORTRAN-4, and also the assembly language MACRO of the fPT-11 operating system. A detailed description of the experimental apparatus has been given elsewhere.[17,18]

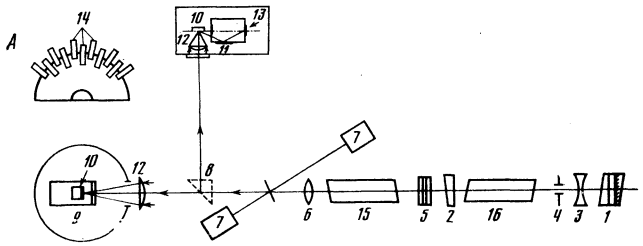

FIG. 1. Diagram of experimental apparatus. 1—contact cell with saturating filter, 2—glass wedge backing, 3—negative lens in resonator, 4—diaphragm, 5—decoupler, 6—lens for correction of divergence, 7—FÉK-09 photoelements, 8—removable rotatable prism, 9—vacuum chamber, 10—target, 11—mica crystal, 12—focusing lenses, 13—cassette with film, 14—scintillation spectrometers, 15—amplifier, 16—generator. A—shows the arrangement of the spectrometers on a sphere.

3. MEASUREMENT OF THE SPECTRUM OF CONTINUOUS X RAYS

The x-ray spectrum and the electron temperature of a plasma are usually measured by the absorber method, which permits determination of the total energy of the continuous spectrum (bremsstrahlung or recombination) passing through absorbers of various thickness. The results of the measurements are frequently presented as a function of the cutoff energy E_c (E_c corresponds to the energy of monochromatic radiation which is attenuated by e times in an absorber of a given thickness). In our work, as in most studies of the continuous x rays from a laser plasma, we measured the x rays integrated by a detector during the entire time of operation of the laser pulse. The spectrum obtained here is averaged both in time and in space. We used aluminum absorbers of thickness from 10 μm to 25 mm.

In determination of the electron temperature T_e from the x-ray absorption curve it is necessary to choose a spectral region in which there is no intense line radiation of the plasma and no jumps in recombination radiation. In the investigated region $E_c > 4$ keV there is no such radiation. This is evident from the line spectra recorded by us and corresponds to the results of Boĭko *et al.*[19]

Systematic measurements were made of the continuous x-ray spectrum over a cutoff-energy range $E_c = 4-40$ keV for various targets with atomic number from 4 (Be) to 83 (Bi). To reduce the energy threshold for detection of x-ray photons, the target and the detectors were placed inside a vacuum chamber (Fig. 2) pumped to 10^{-2} Torr. The x-ray detectors were eight scintillation spectrometers with FÉU-85 photomultipliers. In five of them, corresponding to cutoff energies $E_c = 4-15$ keV, plastic scintillators were used, and in the three others, operating in the range $E_c = 20-40$ keV, NaI(Tl) scintillators were used. All spectrometers were located symmetrically with respect to the direction of the laser beam, which was incident normally on the target plane. To expand the dynamic range of the detecting system, we placed in front of the detector lead diaphragms with opening diameters from 0.2 to 20 mm.

The spectrometers were calibrated by means of the radioactive γ emitters Co^{57} (122 and 136 keV), Na^{22} (511 and 1270 keV), and Y^{88} (900 and 1840 keV). The

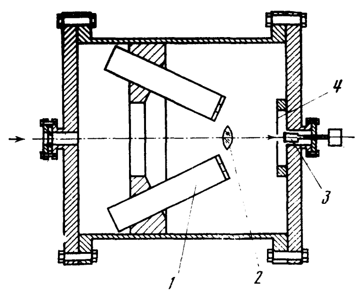

FIG. 2. Location of spectrometers inside the vacuum chamber: 1—spectrometers, 2—focusing lens, 3—target, 4—diaphragm.

energies of the γ rays of the calibration isotopes corresponded in order of magnitude to the total energy of the continuous x rays of the laser plasma recorded by an individual probe during one laser pulse. This provided high accuracy in absolute calibration of the spectrometers.

The target was placed inside a hollow aluminum cylinder covered on the laser-beam side by a diaphragm of thin (80 μm) black paper with an opening for passage of the beam. With this experimental geometry the fraction of detected x rays from the chamber walls was substantially smaller than that from a massive target. The data measured in the region $E_c = 4-40$ keV for three different targets (Be, In, Bi) and averaged over 30 pulses with $I \approx 5\times10^{13}$ W/cm^2 are given in Fig. 3. Here the spread in the absolute value of the x-ray intensity E_γ in individual pulses was up to a factor of ~10 as the result of inadequate reproducibility of the laser-beam parameters.

In contrast to the results obtained by Boiko *et al.*,[19] we observed a break in the dependence of E_γ on E_c corresponding to intense continuous x rays of hot electrons in the region $E_c > 10$ keV for all targets studied with $Z = 4-83$—metallic targets of Be, Mg, Al, Ti, Fe, Ni, Cu, Zn, Mn, Cd, In, W, Pb, and Bi; dielectric targets of C, S, and $(CH_2)_n$; and also semiconductor targets of Si and Ge. The electron temperature T_e of the plasma and the effective temperature of the hot electrons T_H were determined from absorption curves of the continuous x rays in the regions $E_c = 4-10$ and 15–40 keV, respectively. It was found that the value of T_H depends strongly on the flux density of the laser radiation. On attenuation of the laser beam by a factor of five, i.e., to ~10^{13} W/cm^2, the break in the absorption curve disappeared (Fig. 4), which indicates absence of hot electrons. At the same time the electron temperature T_e changed only slightly in this range.

In Figs. 5 and 6 we have shown the temperatures T_e and T_H as a function of the atomic number of the target material. As can be seen from these figures, on increase of Z from 4 to 83, T_e increased from 0.4 to 0.9 keV while T_H increased from 2 to 6 keV. The value of T_H reaches saturation for $Z = 30-40$, which is evidently explained by saturation of the effective charge of the ions Z_{eff}.

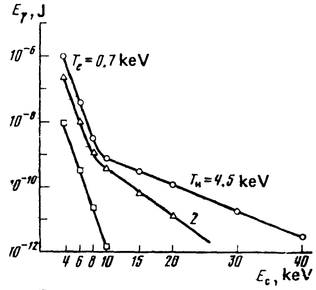

FIG. 4. Dependence of E_γ on E_c for a copper target: ○—$I \approx 5\times10^{13}$ W/cm^2, △—$I \approx 2\times10^{13}$ W/cm^2, □—$I \approx 10^{13}$ W/cm^2.

4. MEASUREMENT OF THE ANGULAR DISTRIBUTION

The angular distribution of the continuous x rays in the suprathermal region for cutoff energies $E_c > 12$ keV was measured by us previously.[13,18] The present measurements were performed under conditions of improved experimental geometry with a large number of spectrometers and increased statistics. We used 28 x-ray detectors [NaI(Tl) scintillators with FÉU-85 photomultipliers]. They were placed on a sphere at the center of which, in a vacuum chamber pumped to 10^{-2} Torr, the target was placed. The detectors were placed in the target plane at various angles to the direction of the laser-beam polarization vector.

Measurements were made of the angular distribution for absorber cutoff energies E_c equal to 12, 16, 20, and 25 keV for targets of Al, Fe, Cu, and W at a flux density ~10^{14} W/cm^2. The experimental data for a copper target given in Fig. 7 were obtained by averaging the experimental results over two neighboring spectrometers oriented identically with respect to the laser-beam polarization vector. (The direction of the polarization vector corresponds to an angle 0° in the figure.) The measurements were made with normal incidence of the beam on the plane target.

In Fig. 8 we have shown the absorption curve of continuous x rays obtained in the same experiment by means of eight detectors, in the cutoff-energy region 25–60 keV. It was obtained for a copper target at $I \approx 10^{14}$ W/cm^2 by averaging the results of ten laser pulses with a maximum temperature T_H. The effective temperature of the hot electrons in this series was 15 keV.

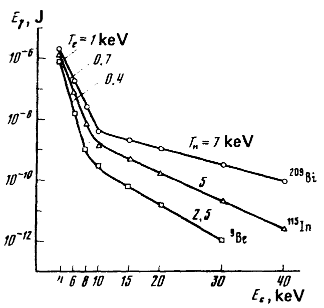

FIG. 3. Dependence of x-ray total energy E_γ on the cutoff energy E_c for targets of Be, In, and Bi; $I \approx 5\times10^{13}$ W/cm^2.

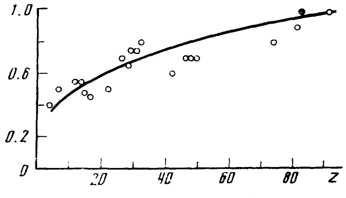

FIG. 5. Electron temperature T_e as a function of the atomic number of the target material Z. The curve is a plot of the function T_e (keV) $= 0.2(AZ_{eff})^{1/6}$; $I \approx 5\times10^{13}$ W/cm^2.

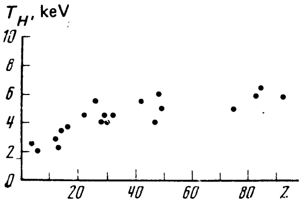

FIG. 6. Effective temperature of hot electrons T_H as a function of the atomic number of the target material Z; $I \approx 5 \times 10^{13}$ W/cm^2.

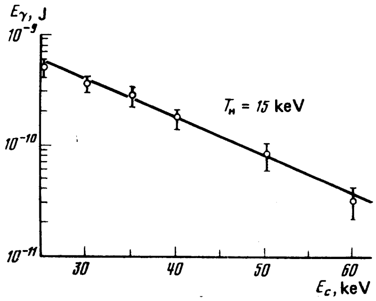

FIG. 8. Absorption curve for a copper target at $I \approx 10^{14}$ W/cm^2.

5. DETERMINATION OF THE ELECTRON TEMPERATURE OF THE PLASMA FROM THE LINE SPECTRA OF MULTIPLY CHARGED IONS

In experiments with targets of Mg, Al, and $NaNO_3$ we recorded x-ray spectra of multiply charged ions in the laser plasma. The electron temperature T_e of the plasma was determined from the relative intensities of the satellites (j, k, l) and the resonance line of the helium-like ions.[20] The measurements were made at $I \approx 10^{14}$ W/cm^2. The experiment utilized a high-aperture x-ray spectrograph of the Hamos design with vertical focusing.[21] The spectra were recorded on type UF-BR x-ray film. The experimental results are given in the table. It should be noted that the values of T_e determined from the relative intensities of the spectral lines correspond to a temperature averaged over the region of the plasma in which the luminescence of these lines is observed.

For the targets of $NaNO_3$ and Mg we also recorded the resonance lines of the hydrogen-like ions. From the relative intensities of the resonance lines of hydrogen-like and helium-like ions we estimated the electron temperature T_{cr} near the critical region of the plasma. Since the absorption of the laser radiation and the ionization occur near the critical region, it is possible to find the average rate of ionization of helium-like ions $\langle v\sigma_i \rangle$ from the kinetics of the ionization process, which establishes a relation between the concentrations [H] and [He] of these ions:

$$[H] \approx [He] N_{cr} \langle v\sigma_i \rangle \tau,$$

where N_{cr} is the critical plasma density (2.3×10^{21} cm^{-3} for $\lambda = 0.69$ μm) and τ is the time spent by the ions in the dense hot region of the plasma. Since the laser plasma cools off rapidly after the end of the laser pulse, in calculation of the quantity $\langle v\sigma_i \rangle$ we took a value $\tau = \tau_p$, where τ_p is the duration of the laser pulse. This assumption corresponds to the experimental data of Bradley *et al.*[22]

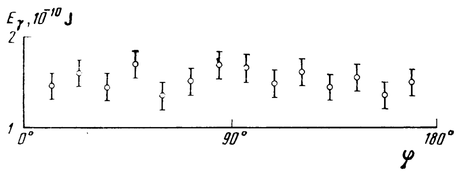

FIG. 7. Angular distribution of x rays for copper target for $E_c = 16$ keV and $I \approx 10^{14}$ W/cm^2.

We note that, as the result of nonuniformity of the laser plasma, the time spent by the ions in the hot dense region of the plasma can, generally speaking, be even less than the duration the laser pulse. To estimate T_{cr} from the rate of ionization of helium-like ions at a given temperature T_e we used the results of Vaǐnshteǐn *et al.*[23] It must be emphasized that the inaccuracy in the value of $\langle v\sigma_i \rangle$ as the result of uncertainty in the choice of τ does not greatly affect the evaluation of the critical temperature. The values of T_e obtained from the absorption curve of continuous x rays and also the values of T_{cr}, which are given in the table, are 2–3 times greater than the values of T_e obtained from the line spectra of multiply charged ions. This apparently is a consequence of the difference in the sizes of the region of hot plasma from which the x rays studied originate.

DISCUSSION OF RESULTS

As can be seen from Fig. 3, for all of the targets studied the radiation differs from thermal for $I \gtrsim 10^{13}$ W/cm^2. This result can be understood if we assume that in the hot region of the plasma, in addition to the main fraction of electrons with a temperature $T_e \sim 1$ keV, there is a group of hot electrons with temperature $T_H \sim 10$ keV.[24] The x radiation in the region 4–6 keV at the temperature values T_e obtained is mainly recombination radiation.[25] The observed x rays in the region ~10 keV correspond to the bremsstrahlung of hot electrons. The electron temperature T_e can be estimated by equating the flux of laser energy absorbed by the plasma near the critical region to the total energy flux into this region. The mean role in the energy balance is played by the fluxes of thermal conduction and hydrodynamical energy. The first of these fluxes is estimated as $\chi T_e / L_1$ where χ is the electronic thermal conduction and L_1 is the characteristic dimension in which the temperatures are equalized during the time of action of the laser pulse τ_p:

$$L_1 \approx (2\chi\tau_p / 3N_{cr})^{1/2}.$$

TABLE I.

Target	Continuous spectrum	Line spectrum	
	T_e, keV	T_e, keV	T_{cr}, keV
$NaNO_3$	–	0.135–0.15	0.55–0.6
Mg	0.55	0.175–0.21	0.55–0.7
Al	0.55	0 21	–

To estimate the hydrodynamical flux we assume that the velocity of separation of the plasma from the critical region is equal to the velocity of sound $c_s = (T_e Z_{eff}/m_p A)^{1/2}$, where m_p is the proton mass and A is the mass number. The resulting value obtained for the hydrodynamical energy flux is $3N_{cr}T_e c_s$. If we evaluate the electronic thermal conduction according to the usual formula,[26] it turns out that under our experimental conditions the thermal and hydrodynamical fluxes are comparable. At the same time it is known that in a laser plasma there is a limitation of the thermal flux, and the effective value of the thermal conduction coefficient can be decreased by an order of magnitude in comparison with the case of a cold rarified plasma.[27] A possible cause of the limitation of the flux is the presence of strong magnetic fields in the plasma.[12] Accordingly, in the estimate of T_e given below it is assumed that the energy loss from the critical region is determined by the hydrodynamical flux of the plasma.

We shall assume that anomalous mechanisms of absorption do not play an important role in the energy balance, but the absorption of radiation is due to the inverse bremsstrahlung effect, and we shall use an approximate expression for the absorption coefficient[28]

$$\Lambda \approx 2L\nu_{ei}/c, \tag{1}$$

where $L = (d\ln N_e/dx)^{-1}$ and ν_{ei} is the frequency of electron-ion collisions. Then the energy-balance equation is written in the form

$$2L\nu_{ei}I/c = 3N_{cr}T_e c_s, \tag{2}$$

where I is the flux density of the laser radiation. Using the known relations for ν_{ei} (Ref. 26) and substituting into Eq. (2) the numerical values of the constants and the experimental values $I = 5\times10^{13}$ W/cm^2 and $\tau_p = 20$ psec, we obtain in final form

$$T_e\,(\text{keV}) \approx 0.2\,(AZ_{eff})^{1/4}L^{1/2}\,(\mu\text{m}) \quad . \tag{3}$$

The value of Z_{eff} can be estimated from the ionization kinetics, i.e., assuming that the time necessary for formation of an ion of the next multiplicity is $\tau_i \approx 1/N_{cr}\langle v\sigma_i\rangle$. This estimate, with use of approximation formulas for the ionization rate,[23] gives values $Z_{eff} \approx 35$ for Bi, $Z_{eff} \approx 15$ for Ti, and $Z_{eff} \approx 10$ for Mg. The last value agrees with the data obtained by us from the line spectra. In Fig. 5 we have shown the dependence of the expression (3) plotted for the Z_{eff} values found. It is in good agreement with the experimental values of T_e if we set $L \approx 1\,\mu$m.

Substituting into Eq. (1) the values of L and ν_{ei}, we find that the plasma absorption coefficient varies in the range from 10 to 35% for all targets studied. We note that on inclusion in the energy-balance equation (2) of fluxes of other forms of energy, the values of the absorption coefficient should increase. The increase of Λ with increase of Z_{eff} agrees qualitatively with the decrease recorded by us previously in the reflection coefficient with increase of Z.[13]

In the estimates given above it was assumed that the presence of hot electrons does not substantially affect the energy balance. The validity of this assumption can be confirmed by evaluating the density of hot electrons n_H on the basis of the absolute intensity of bremsstrahlung,[29]

$$Q_{\tau_H} = 1.6\cdot10^{-25}Z_{eff}\,(T_H)^{1/2}\exp\left(-E_c/T_H\right)N_{cr}\,n_H V\tau_p. \tag{4}$$

Here V is the volume of the plasma in which the suprathermal radiation arises. From Eq. (4) and the results obtained above (see Fig. 3) it follows that for all targets investigated the ratio n_H/N_{cr} does not exceed 0.1%. The determining mechanism for production of hot electrons in our case is apparently resonance absorption, since the development of parametric instabilities is hindered as the result of the short duration of the laser pulse.

The values of T_H obtained by us are close to those obtained in experiments with a neodymium laser[30-32] and in particular to the results of Luther-Davies,[30,32] who used similar parameters of the laser radiation. It was shown in these studies that an important role in interaction of laser radiation with a plasma is played by resonance absorption. However, the T_H values obtained exceed the values obtained in numerical calculations[33] carried out on the assumption of a resonance-absorption mechanism. They also exceed the values of T_H obtained with use of CO_2 laser for comparable values of the parameter $I\lambda^2$.[34]

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