LEBEDEV PHYSICAL INSTITUTE
RUSSIAN ACADEMY OF SCIENCES

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CHARACTERISTIC EMISSION SPECTRA OF LASER AND DISCHARGE PLASMAS

Moscow 2003

CHARACTERISTIC RADIATION SPECTRA OF LASER AND DISCHARGE PLASMAS

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Abstract

In the present paper the characteristic spectra of soft x-ray radiation of multicharged ions plasma, obtained under the action of laser pulses onto substance, as well as in various discharge facilities, are considered. The basic attention is given to research of influence of a degree of non-equilibrium plasmas on its radiation.

The purpose of the paper is to formulate the problems connected with non-equilibrium effects in radiating plasma, to give the characteristics of typical parameters of such plasma, and to plan possible ways of the radiation control. These questions are important for obtaining the maximal yield of radiation both in the given spectral range and the maximal integrated output. Besides, the experimentally measured spectra of radiation form the basis for development of test problems for various theoretical models.

*The work was supported by **ISTC Project #2165** ("Production of the maximum radiative yield in the plasma of pulsed and laser systems") (all authors) and **INTAS 2001-0572** grant (authors from P.N. Lebedev Physical Institute only).*

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Introduction

In recent years a lot of scientific centers carry out investigations on radiation of various substances under the influence of powerful laser pulses or high-current discharges. The obtained high-temperature dense plasma of multicharged ions is of significant interest for fundamental problems of atomic physics and physics of plasma. Besides, for various applications, in particular, in problems of lithography, it is necessary to have the radiation sources of the given spectral structure and intensity.

Essential nonstationarity of the processes leads to non-equilibrium plasma, in particular, to the deviation of ionisation state and population of excited levels from the appropriate values in condition of Local Thermodynamical Equilibrium (LTE). The description of such plasma requires the use of kinetic models accounting for the level kinetics and radiation transfer. The experimental research of the spectra of multicharged ions plasma allows one to carry out calibration of the codes intended for obtaining of spectral emission and absorption coefficients.

In the present paper a brief description is given of the experimental spectra of non-equilibrium plasma of multicharged ions obtained during the various influences on the substance.

1. Interaction of ultrashort laser pulses with matter.

1.1. Spectra in experiments with "short" and "long" laser pulses

For the radiation of high-Z plasma a high integrated emission is characteristic. The structure of spectra is very complicated, as these spectra are formed by an enormous quantity of closely located set of overlapped spectral lines forming arrays of non-resolved lines which belong to the transitions of a certain type. The radiation of a large number of intensive lines which form a quasi-continuum can find use in the applications where high-intensity x-ray radiation in the given range is required. As an example of typical spectra of heavy elements we shall consider the *M* - spectra of tantalum (*Z*=73) for different spectral ranges shown in Fig. 1-3. Spectra were obtained with different facilities under various conditions of irradiation of solid-state targets. By convention all the considered experimental situations can be divided into two groups. The first group includes the data obtained from the experiments on target irradiation by laser pulses of the duration less than 1 ps, and the second group – by the pulses of duration less than 1 ns. We shall consider in more detail the conditions of concrete experiments.

Experiments with the pulses less than 1 ps ("short" pulses) were carried out with the laser facility "Table Top Terawatt" (or "T3") [1]. Laser radiation with the energy up to 1 J and duration about 550 fs at the wavelength of 1.053 microns was generated by the *Nd*-glass CPA-laser. After the frequency doubling the laser pulses had the energy about 450 mJ at the wavelength 0.527 microns and the contrast higher than 10^{10}:1. The pulse about 400 fs at normal incidence was focused into a 100-micron spot by means of a spherical lens. The flux density on the target surface reached 10^{16} W/cm^2. The time-integrated spectra obtained by summation from 10 up to 100 shots, depending on the wavelengths for which measurements were carried out, were registered in the experiments.

In the experiments [2-5] the pulses with duration about 1 ns ("long" pulses) acted on the targets. In [3] the radiation of the 2-nd harmonic of *Nd*-glass laser with the wavelength of 0.53 microns acted on the flat target made of *Ta*. The energy of the pulses made 25 J, and duration ~ 0.6 ns. In [4] the experimental conditions were as follows: the radiation on the 2-nd harmonic (l =1.05 microns) of phosphate glass laser was focused onto the target surface at flux density of 10^{13}? $5 \cdot 10^{14}$ W/cm^2. The laser pulse duration made 0.6 ns. The time-integrated spectra were registered. In [5] the spectra of *Ta* plasma were obtained using a photo-dissociation iodine laser "Perun". At the wavelength of 1.315 microns the energy of a 0.35 ns pulse made 13-15 J. The intensity in a focal spot reached (3? 5)$\cdot 10^{14}$ W/cm^2. High aperture ratio of the equipment used allowed one to register the spectra for one laser flash.

Table 1 illustrates the experimental conditions, and the densitograms of the experimental spectra obtained under listed conditions are shown in Figs. 1-3. In Fig.1 the spectra of *3d-5f* transitions in *Ta* plasma in a short-wave range weakly depend on the pulse intensity and duration. Analysis of Fig. 2 shows that in the wavelength range $l > 5.5$ A the spectra obtained under different conditions have similar character. However, it is seen that for the spectra (a) and (d), which correspond to intensity of $3 \cdot 10^{14}$ W/cm^2 for long pulses, the spectral line broadening is smaller than for spectra (b) and (c). The reason may be the following: for long pulses and smaller intensity (case (b)), or for short pulses but higher intensity the arising plasma has greater density. Similar circumstance should be taken into account in the applications when one needs large ratio between the intensity of spectral lines and the continuum intensity.

Table 1. Experimental conditions for tantalum M - spectra.

Laboratory	Laser wave-length, μm	Pulse dura-tion, ps	Pulse en-ergy, J	Flux density at the target, W/ñm^2	Refer-ence
Institut National de la Recherche Scientifique (INRS-Quebec)	0.527	0.3	0.45	10^{16}	[1]
Groupe de Recherches Coordonnees de l'Interaction Laser-Matiere (GRECO-ILM)	0.530	600	25		[3]
Laboratorie d'Utilisation des Lasers Intenses (LULI)	1.050	600		10^{13}? $5·10^{14}$	[4]
Institute of Physics of Czech Republic Academy of Sciences, Prague	1.315	350	13? 15	(3?5)$·10^{14}$	[5]

The comparison of spectra from [1] and [4] given in Fig. 3 for a long-wavelength area shows the disagreements, which are of interest. Within the range of 6.9-7.3 A for the spectrum from [1], obtained for larger intensity and smaller pulse duration, one can observe two bands of overlapping spectral lines M_a and M_b (shaded areas). Their presence is most likely connected with the radiative transitions in the internal shells. The spectrum from [5] does not possess such features. In sub-picosecond mode a possible reason for such transitions is the presence of non-stationary effects. More exact conclusions require a detailed analysis. Such a character of the dependence of spectra on the intensity and duration of a laser pulse opens up possibilities to control the integrated flux of radiation within the spectral range 6.9-7.3 A, and the comparison of a relative level of radiation in this range and a level of radiation in the range 7.3-7.7 A allows one to draw conclusions about the processes in plasma and to estimate the influence of non-stationary effects.

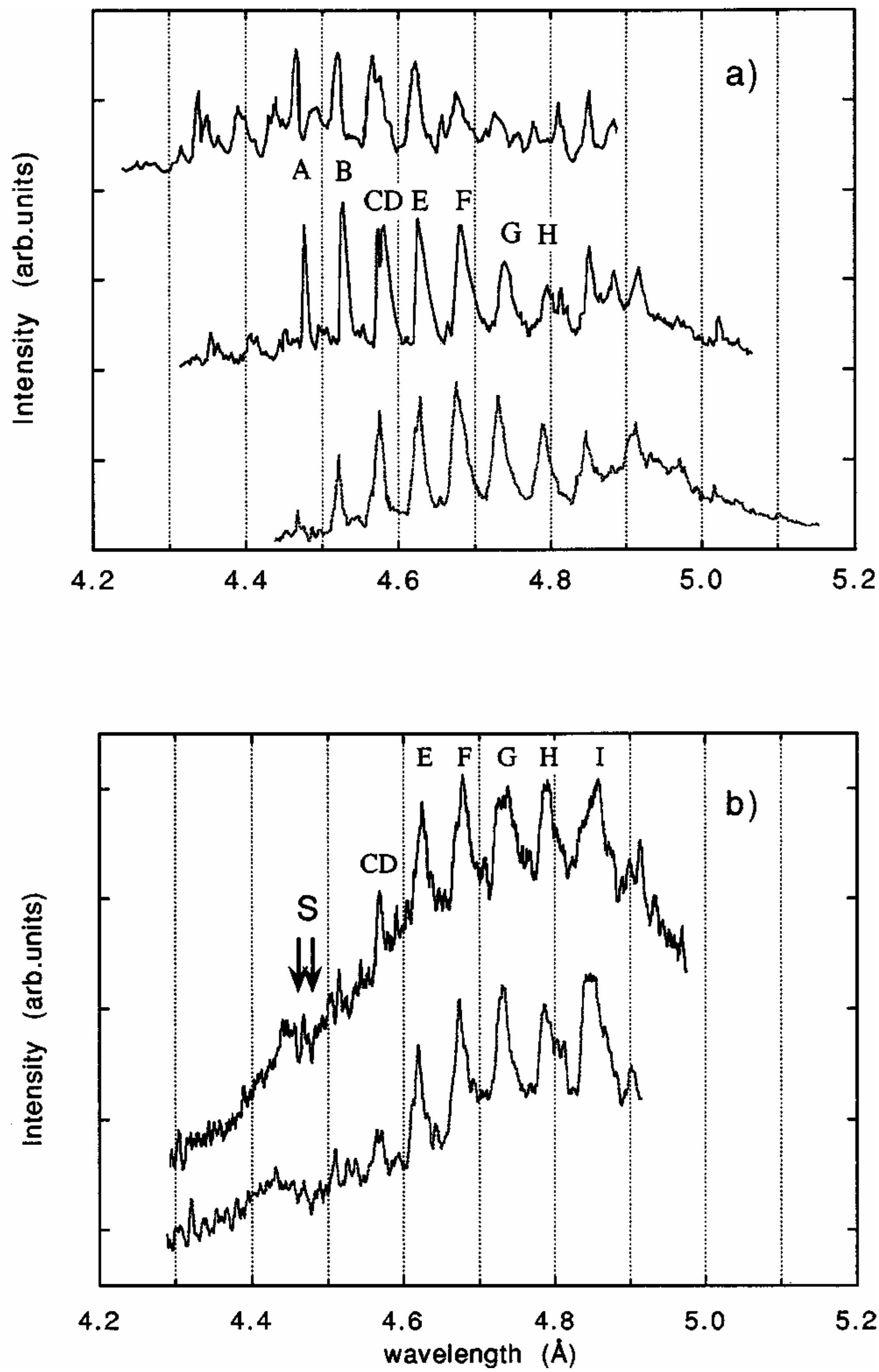


Fig. 1. *3d-5f* spectra of *Ta* plasma : a) experiments with laser pulses of nanosecond duration (the top spectrum is from work [2], middle [3], bottom [4]); b) experiments with pulses of sub-picosecond duration [1] at intensities 10^{16} W/cm^2 (the top spectrum) and $5{\cdot}10^{15}$ W/cm^2 (the bottom spectrum).

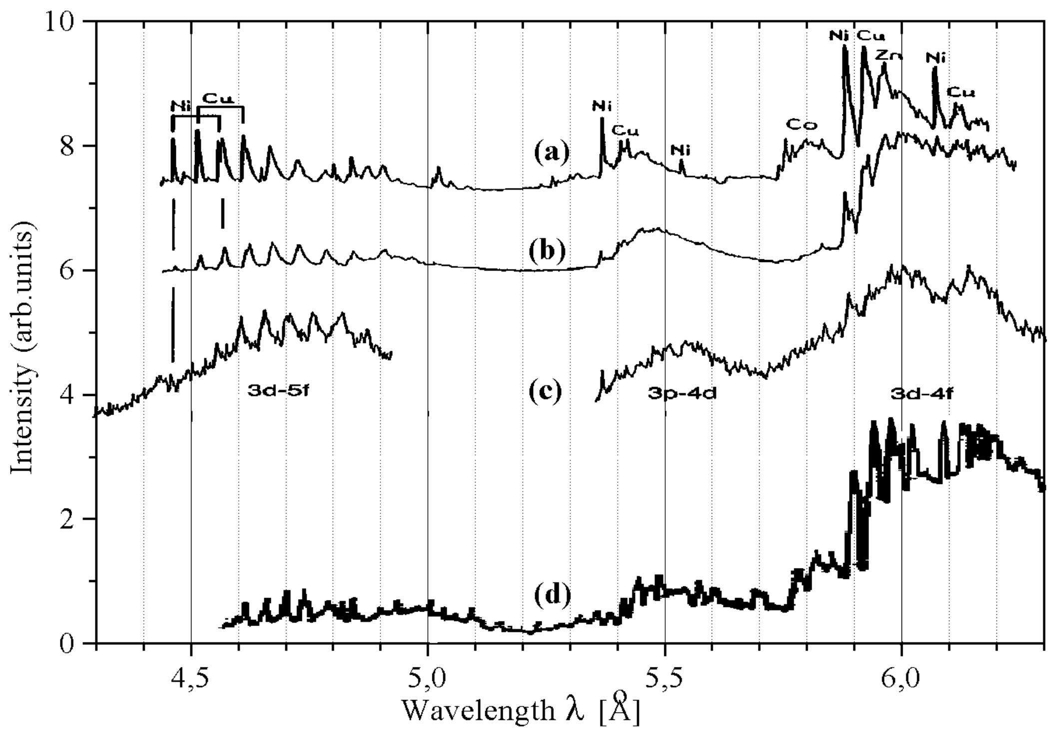


Fig.2. Spectra of *Ta* plasma in the wavelength range of 4.3-6.3 A: a) spectrum from [4] for t_{las}=0.6 ns and intensity of $3{\cdot}10^{14}$ W/cm^2 ; b) from [4] for t_{las}=0.6 ns and intensity of $3{\cdot}10^{13}$ W/cm^2 ; c) the data for t_{las}=0.3 ps and intensity of 10^{16} W/cm^2 ; d) spectrum from [5] obtained at the intensity of incident laser radiation of $3{\cdot}10^{14}$ W/cm^2 and laser pulse duration t_{las}=0.35 ns.

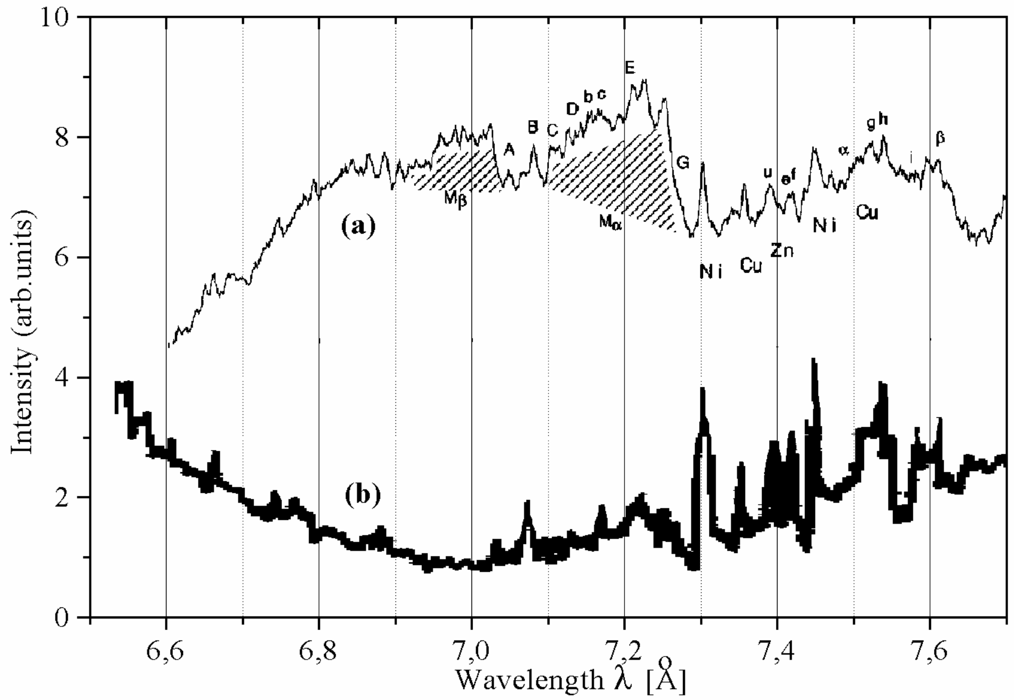


Fig. 3. *3d-4p* spectra of *Ta* plasma in the range 6.5-7.7 A: (a) from paper [1] for t_{las}=0.3 ps and intensity of 10^{16} W/cm^2; (b) from paper [5] for t_{las}=0.35 ns and $3{\cdot}10^{14}$ W/cm^2.

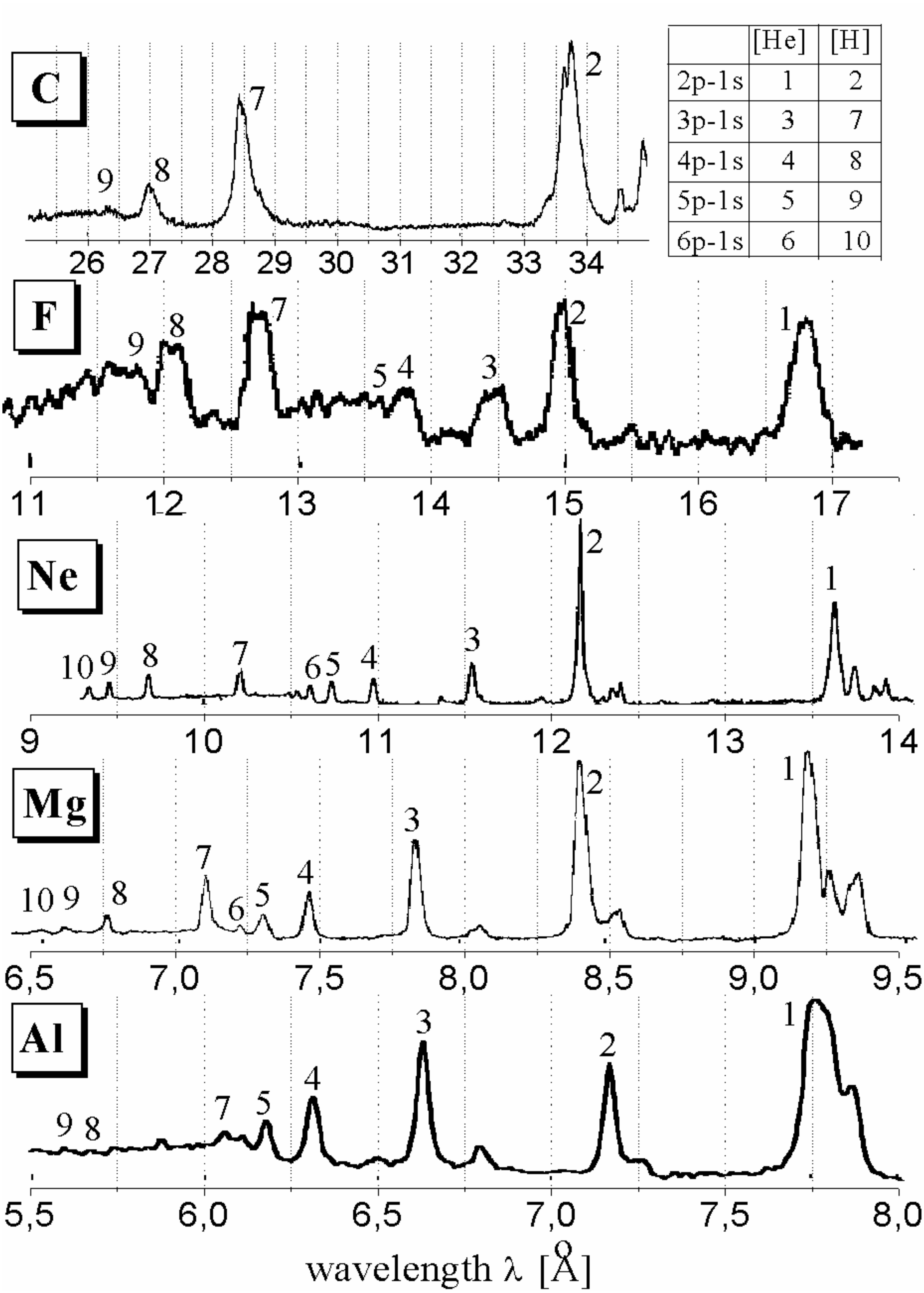
1.2. *Ê*-spectra

The next group of typical experimental spectra which frequently occurs in laser and discharge experiments is the *K*-spectra relating to [H]- and [He]-like ions of various elements. A number of diagnostic techniques are based on the measurement of such spectra. They are of interest for the purposes of the given paper, as these spectra are well investigated. Their relative simplicity opens up the possibilities for informative and simple investigation of the radiation properties connected with non-equilibrium character of both the radiation and matter. Similar problem in the application to more complicated spectra with larger number of the lines, corresponding to different ions, is considerably burdened by a number of factors, and that is why it is difficult to distinguish between the role played by non-equilibrium properties of the matter and radiation in the formation of spectra and the role of other effects. In particular, in case of optically transparent plasma at the known plasma density and temperature the analysis of *K*– spectra allows one to determine the degree of plasma deviation from the local thermodynamic equilibrium. In case of optically thick plasma the analysis of similar spectra allows to investigate the influence of optical thickness on the plasma properties, and to estimate the role of effects of self-absorption in the spectra formation. Examples of spectra for various elements are given in Figure 4. The experimental conditions of spectra registration are listed in Table 2.

Table 2. The experimental conditions for K - spectra.

Target material	Laser	Laser wavelength µm	Pulse duration, ps	Pulse energy, J	Flux density on the target, W/ñm^2	Reference
Ñ	*KrF** eximer laser	0.248	0.7	0.018	$2\cdot10^{16}$	[6]
F	*Nd-glass* laser	0.530	1.0	10	10^{14}	[7]
Ne	Pinch – plasma focus	*p*=400 Pa, *I*=260 kA, *U*=8? 12 kV, *L*=20 nHn, *Ñ*=36 µF, anode radius 1 cm.				[8]
Mg	Iodine photodissotiation laser	1.315	350	13? 15	$(3?5)\cdot10^{14}$	[5]
Al	*Nd-glass* laser	1.055	1.0	1.0	10^{17}	[9]

Enumerate the reasons why the concrete spectra shown in Fig. 4 are interesting for studying the properties of non-equilibrium plasma. According to the data from [6] for the carbon plasma in LTE approximation, the profiles of the lines corresponding to transitions *2p-1s* and *3p-1s* of H-like ion C VI are subject to strong influence of the effects of self-absorption. However, even the account of self-absorption effects does not allow one to reproduce the experimental data precisely, therefore, the analysis in non-equilibrium conditions and, probably, the consideration of a non-stationary problem is necessary. In [7] it is noted that the capture of radiation should influence the intensity of a resonant line of He-like ion F VIII



	[He]	[H]
2p-1s	1	2
3p-1s	3	7
4p-1s	4	8
5p-1s	5	9
6p-1s	6	10

Fig. 4. Experimental K-spectra of plasma of carbon [6], fluorine [7], neon [8], magnesium [5] and aluminium [9]. In the table: the identification of transitions for intensive resonant lines of H-like and He-like ions.

(transition $1s2p$ ^{1}P-$1s^2$ ^{1}S). Similar influence of self-absorption effects on the given line is observed for the spectrum of plasma of aluminum (numerical estimations are given in [9]) as well. However, a more detailed analysis of these spectra is beyond the scope of this work.

The above-mentioned *K*-spectra are of interest for studying the plasma non-equilibrium state associated with the deviation of ionized structure and level populations from the value set by Saha equations and Boltzmann distribution in the case of local thermodynamic equilibrium (LTE). With the decrease of density and increase of temperature of the plasma the rates of radiative processes (spontaneous radiative transitions and photorecombination) become comparable to the rates of collisional processes (impact excitation and de-excitation, ionization by electron impact and three-body recombination). The plasma is already in the conditions of a so-called collisional-radiative equilibrium (CRE) or partial LTE.

1.3. Experiments with "supershort" pulses

The use of intensive pulses of sub-picosecond duration for the target irradiation offers a possibility to reach in the experiments the completely new extreme conditions of matter, and, as a consequence, a new type of x-ray spectra appears which is of interest for the researchers. Under the action on the solid-state *Mg* target of a pulse with the energy of 1 J at 0.53 micron wavelength and 400 fs duration and very high contrast ~10^{10}:1 (the flux density on the target surface ~ $0.5 \cdot 10^{19}$ W/cm^2) the authors of [12] received in the experiments the plasma with Ne~$3 \cdot 10^{23}$ cm^3 and T_e=200-300 eV. Figure 5 demonstrates the experimental x-ray spectra of such plasma. For comparison in the same figure are shown the densitograms of the spectra obtained under similar conditions, but under the presence of a pre-pulse with the total energy of 2 J and the delay of 2 ps. The spectra obtained with high contrast essentially differ from the spectra obtained under the presence of a pre-pulse. At high contrast the basic resonant lines are practically absent on the background of an enormous number of intensive dielectronic satellites, which become the main spectral features. The shape of such spectra reminds one of *L*-and *M*-spectra of heavy elements (in particular, the considered above spectra of tantalum) – a great number of overlapped and high-intensive lines.

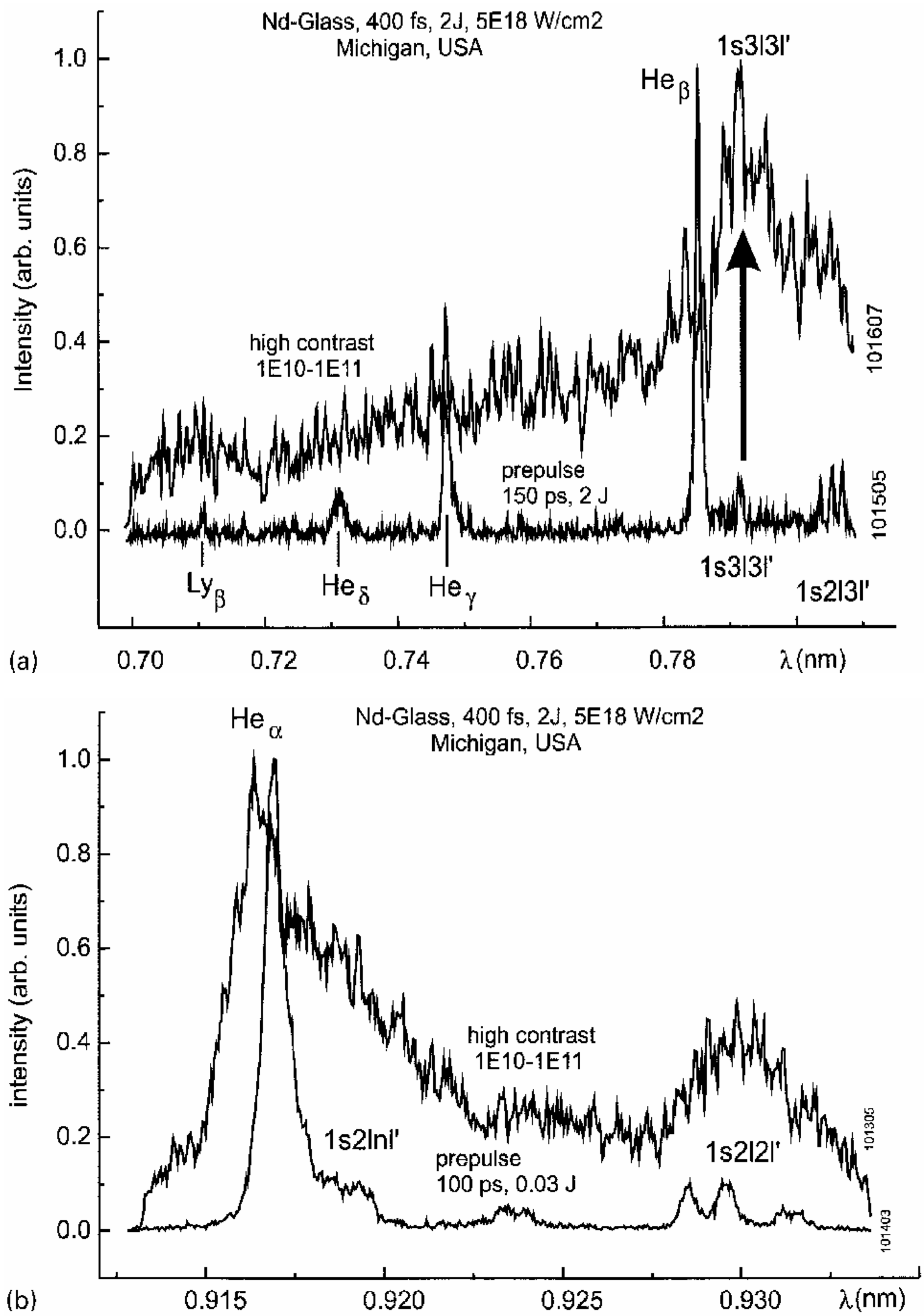


Fig. 5. The x-ray spectra of *Mg* plasma obtained in the experiment with high contrast and the prepulse (Figure is taken from [12]).

Under the presence of a pre-pulse the spectra are similar to the ones obtained in a nanosecond mode (for *Mg* plasma see Fig.4). Thus, such new states of the matter require the approaches to the plasma spectroscopy, which would differ from the traditional ones. The occurrence of completely new spectral lines is observed in those ranges where under usual conditions only a continuous radiation is found. The properties of the plasma formed under the action of sub-picosecond pulses, fundamentally differ from the properties of plasma formed under irradiation of the target by the pulses with duration of hundred of picoseconds or longer.

1.4. Spectra in the experiments with indirect irradiation

More complicated for the researches non-equilibrium conditions are realized under the presence of a strong external field of radiation, when the processes of photoionization and photoexcitation become important. Under certain conditions similar situation can be realized in the experiments with indirect inertial fusion in the *hohlraum* targets. In [10] the authors studied the x-ray self-radiation of materials with miscellaneous Z (*C, Al, Ti, Ag, Au*) under conditions of irradiation of a thin foil by the radiation produced in a hohlraum capsule. The experiments were carried out with the use of radiation on the 3-rd harmonic of an iodine laser ASTERIX IV. The pulse energy was 200 J, the pulse duration, 400 ps, the wavelength, 0.44 microns. Laser radiation was focused on a target by the lens *f*/2. The details of experiment and target construction are given in [10]. It is important, that in the experiment it was possible to obtain a very homogeneous field of x-ray radiation with radiative temperature of 120 eV. At the laser pulse duration of 400 ps the radiation from the target was observed about 2 ns. The experimental spectra within the range of 1-7 nm are demonstrated in Fig. 6 taken from [10]. The spectra were registered with the spectral resolution of 0.12 nm, and averaged over the time interval of 600 ps. The analysis made in [10] showed that in the interpretation of experimental spectra of carbon and aluminium the account of non-equilibrium, associated with photoionization and photoexcitation due to the pumping by radiation, is essential. In the experiment the foil density was taken so small, that the produced plasma was transparent for radiation. Hence, the temperature of the matter was much lower than the temperature of radiation. Besides, the matter and heating radiation were not in balance (most likely it is caused by small duration of a laser pulse). Thus, the observed high degree of ionization of carbon and aluminum can be associated with the nonequilibrium effects, when the heating is carried out by Planck radiation with the brightness temperature much higher than the temperature of the heated optically transparent matter. The pumping by such external field of radiation leads to direct photoionization and photoexcitation, and this increases the average charge of the matter ions.

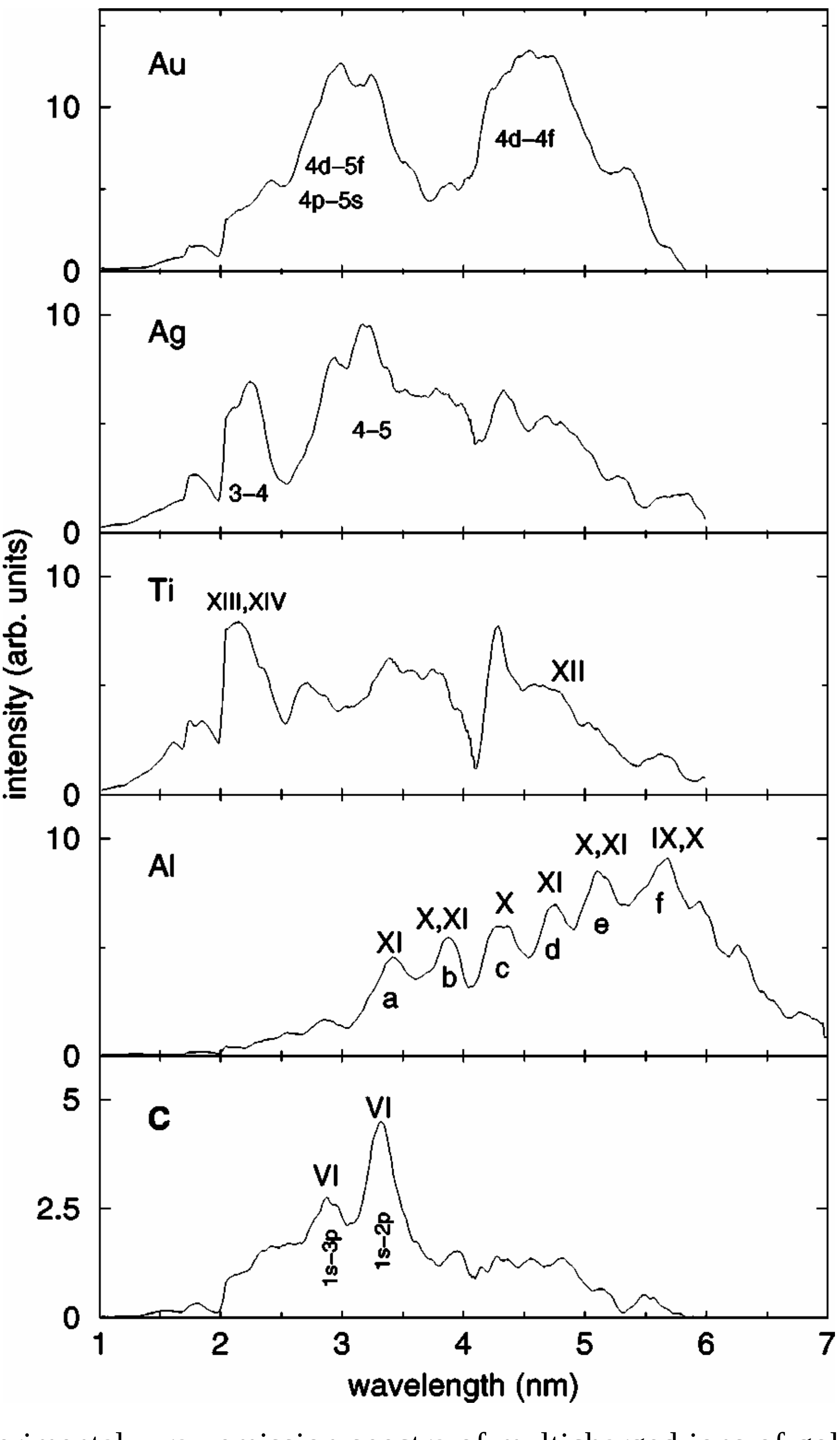


Fig. 6. Experimental x-ray emission spectra of multicharged ions of gold, silver, titanium, aluminum and carbon [10]. Notation for the spectrum of aluminum : (a) Al XI 2s-5p, (b) Al X 2s2p-2s5d and Al XI 2s-4d, (c) Al X $2s^2$-2s4d, (d) Al XI 2s-3p, (e) Al X $2s^2$-2s3p and Al XI 2p-3d, (f) Al IX $2s^2$2p3p-2s2p3p and Al X $2p^2$-2p3d.

The dependence of integrated emissivity on the charge of a nucleus is of interest also. As seen from Fig. 6, the most intensive radiation is observed for *Au*, i.e. an element with the largest charge of a nucleus. For aluminum and titanium the integrated emissivities in the given spectral range are approximately identical. However, for aluminum the basic contribution to radiation comes from individual intensive resonant lines of highly-ionized ions *Al IX - Al XI*, and for titanium – from the overlapped lines of ions of moderate ionization state *Ti XII - Ti XIV*.

1.5. Methods of increase of an output of radiation

Another experimental situation, which deserves attention, is connected with the methods of increasing the output of radiation (both the integrated over spectrum, and in the given spectral range) by inclusion into the target design of the layers of matter with small density and volumetric structure, for example, the agar. On the one hand, the volumetric - structured media in a solid state have higher manufacturability as compared to a gaseous media of the same density, and, on the other hand, in the experiment the small density of targets provides much smaller expansion than in case of solid targets.

Figure 7 gives an example of the experimental spectra of multi-charged *Cu* ions obtained with the "Mishen" facility (TRINITI) [11]. The spectra were obtained under irradiation of the targets of various structure by *Nd*-laser (wavelength, 1 μm). The pulse was focused into a 100 μm focal spot, and thus the flux density on the target surface made $5 \cdot 10^{13}$ W/cm^2 at pulse duration of 2.5 ps. Figure 6 illustrates three types of the targets: 1) a copper foil of solid-state density; 2) a target made of agar $(C_{14}H_{18}O_7)_n$, the density 1.5 mg/cm^3, the impurity $CuCl_2$ (0.5 mg/cm^3), in front of which the x-ray converter (a copper layer of 0.1 μm thickness) was placed; 3) the same target without a converter. As seen from the spectra comparison, within the range of 7.5-9 A for the agar targets with impurity there is observed an intensive line radiation of *Cu XXI* ion, while for the spectra obtained under irradiation of a solid-state foil the radiation in this range is negligible. The presence of radiation of highly-ionized ions is indicative of higher electronic temperature which is reached due to smaller hydrodynamic scattering of the agar target with the impurity, which has small density. The higher electronic temperature results also in more intensive radiation per one copper ion in the range 10-13 A under irradiation of agar target with the converter (2), as compared to the case of copper foil irradiation (1). Thus, from Fig. 7 follows, that the absolute intensities of lines in this range, owing to greater concentration of high-Z multicharged ions, are higher for the case of solid copper target irradiation. A considered example of the spectra behavior depending on the structure and design of the target shows the presence of a possibility to

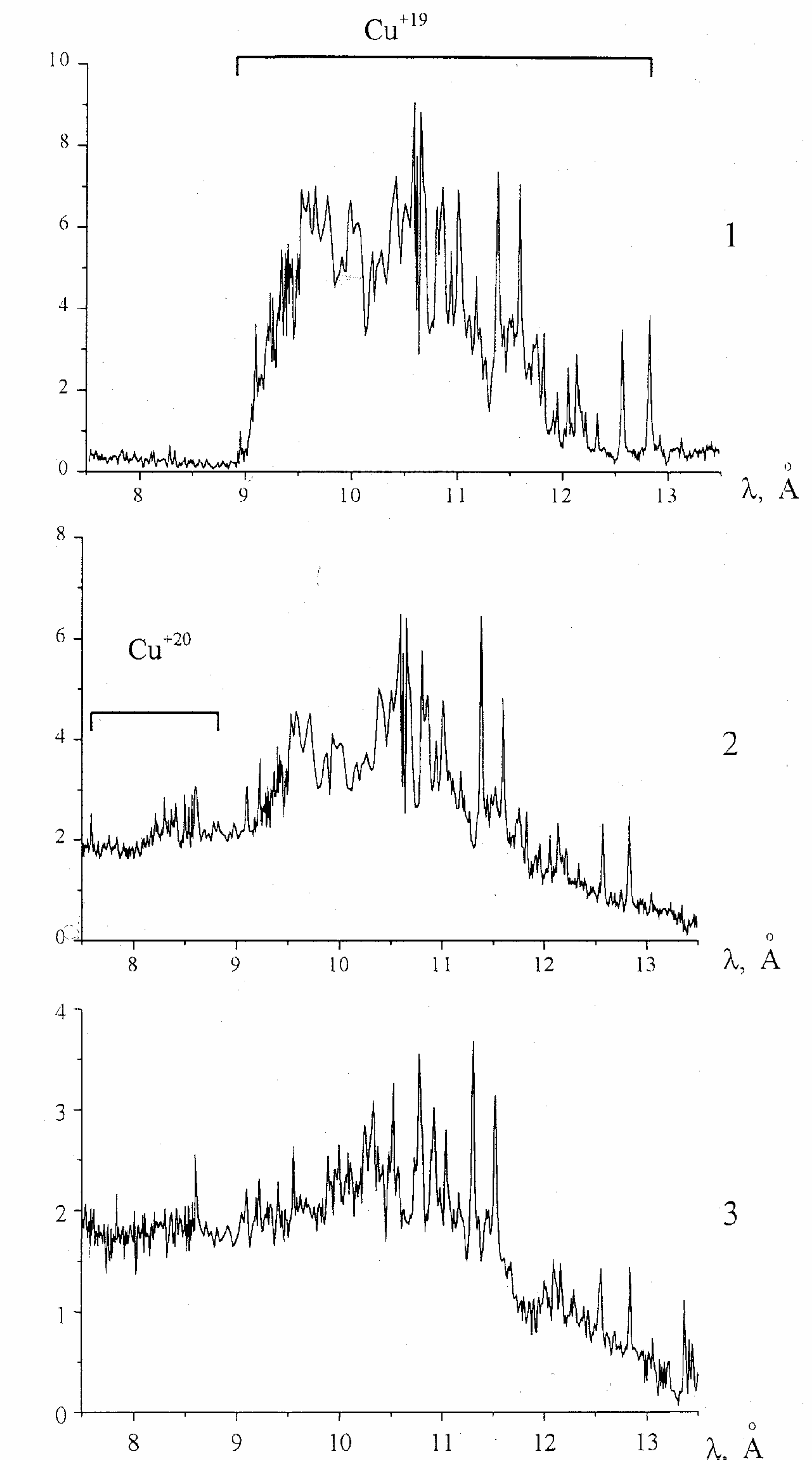


Fig. 7. Emission spectra of multicharged Cu ions obtained at the "Mishen" facility [11] for the targets of various structure: (1) copper foil; (2) the agar target of the density of 1.5 mg/cm^3 with impurity $CuCl_2$ (0.5 mg/cm^3) in front of which the x-ray converter is placed (a 0.1 μm thick copper layer); (3) agar target of the density of 1.5 mg / cm^3 with impurity $CuCl_2$ (0.5 mg /cm^3), but without converter.

control the spectral structure and power characteristics of radiation of the laser facilities by choosing the target design without changing the power and other characteristics of the experimental facility and the laser pulse.

2. Spectral properties of discharge plasma radiation

2.1. Z-pinches

Magnetic compression of plasma shells and Z-pinches in powerful electric generators allows one to obtain dense high-temperature plasma of multicharged ions. In such generators the plasma is heated up due to the kinetic energy transferred to plasma by pressure of a magnetic field and dissipated in shock waves, the Joule heating and *PdV* work of pressure and a magnetic field on the preheated plasma. Energy contribution in plasma can exceed tens of keV per one ion, however, the most part of this energy has time to radiate due to high capability of multicharged ion plasma for emission.

For applied problems the *K*- and *L*-radiation of multicharged ion plasma is of interest. In experiments with the generator "Angara - 5-1" (the current 4 MA [17]) and the accelerator " Z " (the current 20 MA [18]), as well as with a number of other pulse generators, the Z-pinches, obtained by compression of many-wire constructions (liners) from various materials were studied. The greatest efficiency of generation of *K*-radiation on " Angara - 5-1 " generator was obtained with aluminum liners. In Figure 8a are shown the detailed spectrum of *Al* H-and He-like ions in an interval 1.5-2.5 keV. The power of pinch radiation was ~1.5 TW, and within the range h?~ 1 keV this power reached 0.3-0.4 TW. The comparison of the measured radiation with the calculations [19] showed that the pinch temperature is about 250-400 eV, and the electron density $N_e \sim 2{\cdot}10^{20}$ cm^{-3}. Figure 8b also presents the spectrum of Z-pinch copper plasma [17, 19] in an interval 8-13 A. The spectrum consists of the lines corresponding, basically, to transitions in Ne-like *CuXX* and F-like *CuXXI* (~40 lines). The temperature of copper plasma reaches 200 eV. The rate of the liner calculated from the comparison of radiation in the resonant H- and He-like and intercombination He-like lines [19] reached $2.5{\cdot}10^7$ cm/s.

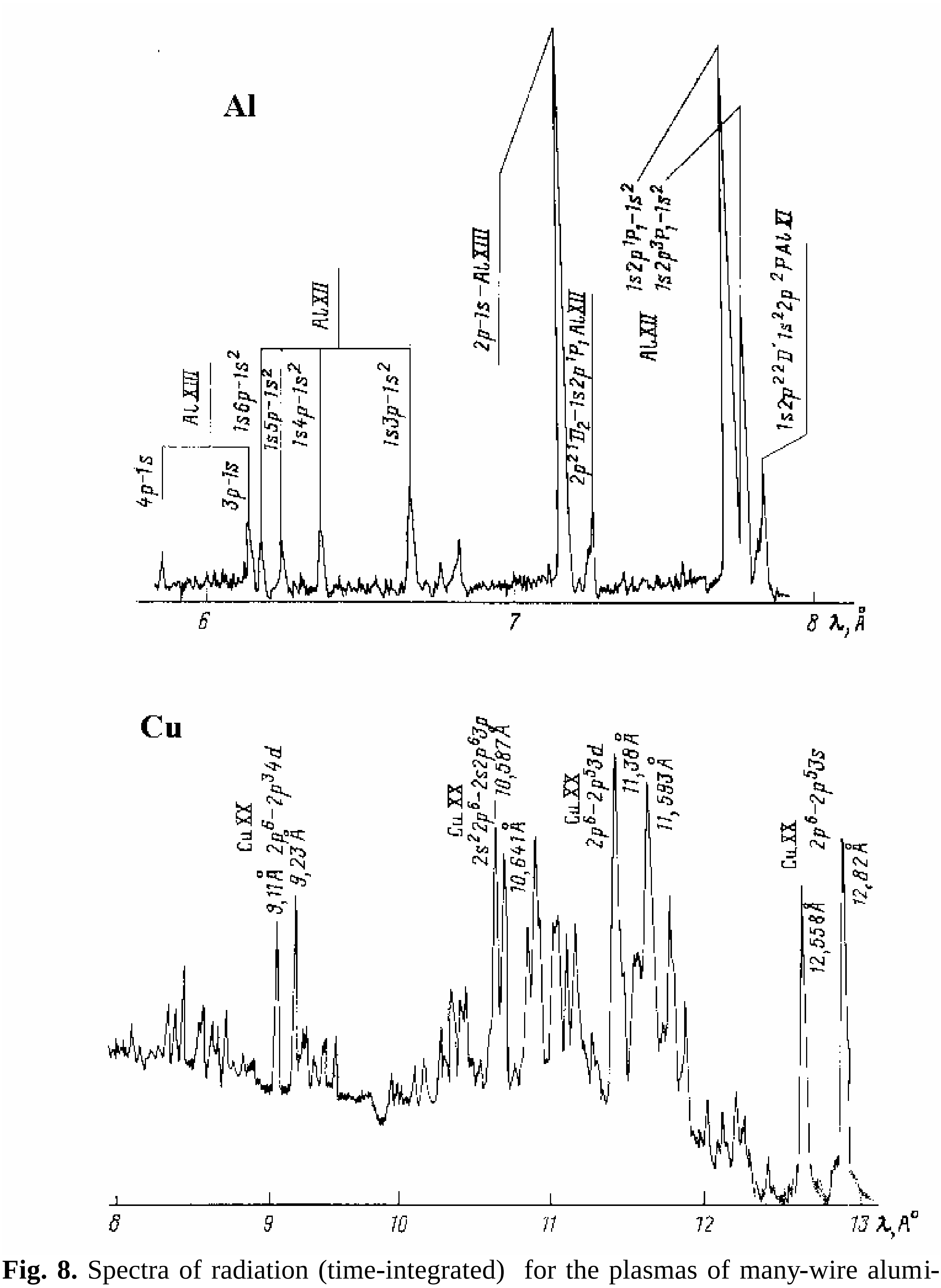


Fig. 8. Spectra of radiation (time-integrated) for the plasmas of many-wire aluminum (above) and copper (below) liners.

On the "Saturn" generator with a large current (7 MA) the output of *K*-radiation from *Al* plasma exceeded 30 kJ. At an essentially more powerful accelerator " Z " the efficiency of *K*-radiation generation is maximal for the plasma of such matter as titanium (Z=22) with the charge larger than the aluminum charge (Z=13). The highest temperature is reached due to the shock mechanism of heating the plasma with the linear weight of 2 mg/cm accelerated up to $(7?9)\cdot 10^7$ cm/s. As a result there is formed a Z-pinch with the diameter ~2 mm. In the experiments the radiation energy in *K*-lines *Ti* (4.8 keV) makes 75-125 kJ, the total output of the radiation energy being 1.2 MJ. The estimation of temperature of Z-pinch plasma gives T_e ~ 2.7-3.2 keV.

The plasma temperature about 0.8-1.2 keV was also obtained with generator "Angara-5-1 " [20] in the experiments with a so-called composite Z-pinch, in which the plasma *Ar* shell collapsed onto a foam-like agar $(C_9O_5H_{12})_n$ core with a 30% additive of *KCl*. The spectrum of radiation of such composite Z-pinch is shown in Fig.9. Measurements of intensities of the resonant transitions of H- and He - like ions of *K* and *Cl* ($h?$=3.51 keV) and the intercombination transition *1s2p* ($^3P_1$)-$1s^2$ ($^1S_0$), as well as the presence of the lines *Cl* [He] ($h?$= 2.95 keV) and *K* [H] ($h?$= 3.51 keV) showed that in the plasma there were the areas with temperature T_e~1 keV and electron density $N_e \sim 2\cdot 10^{21}$ cm^{-3}. This density corresponded to the initial density of foam at the ionization degree typical of the obtained temperature. As shown in [21], the mentioned high temperature is reached at the contact boundary of the core plasma and the flying *Ar* plasma due to heating in a shock wave.

The experiments performed with "Angara - 5-1" and "Z" facilities have shown, that *K*-radiation is generated in a nonequilibrium plasma of middle ions such as *Al-Ti.* Such plasma may be described only with the use of complete radiative-collisional models, taking into account the radiation and Doppler shift of the lines due to the motion of compressed plasma.

For heavier ions, such as *Xe, Mo*, and *W* at the generator " Angara - 5-1 " [17,22,23] and *W* at the accelerator " Z "[24,25], the temperature and hardness of radiation of plasma are much less than for the plasma of middle ions. However, the total radiation power and the integrated output of energy are much higher. For example, at " Angara - 5-1 " generator the energy of radiation of tungsten plasma reached 150 kJ, while for aluminum plasma it did not exceed 80 kJ, and at the accelerator " Z " the energy of radiation of a tungsten liner reached 2 MJ at a record power ~200 TW [24]. In the experiments with double multi-wire liners ("nested wire array ") due to compression of plasma at intermediate collision of liners there was reached radiation power of 280 TW and the total energy of 1.8 MJ. Figure 10 illustrates the spectrum of radiation of tungsten plasma in the experiments with "Z" facility [25]. The temperature of plasma reaches ~200 eV for "Angara - 5-1" and ~360 eV for "Z". The spectra represent the sets of clusters with enormous number of overlapped lines making de facto a continuous spectrum. Theoretical analysis of

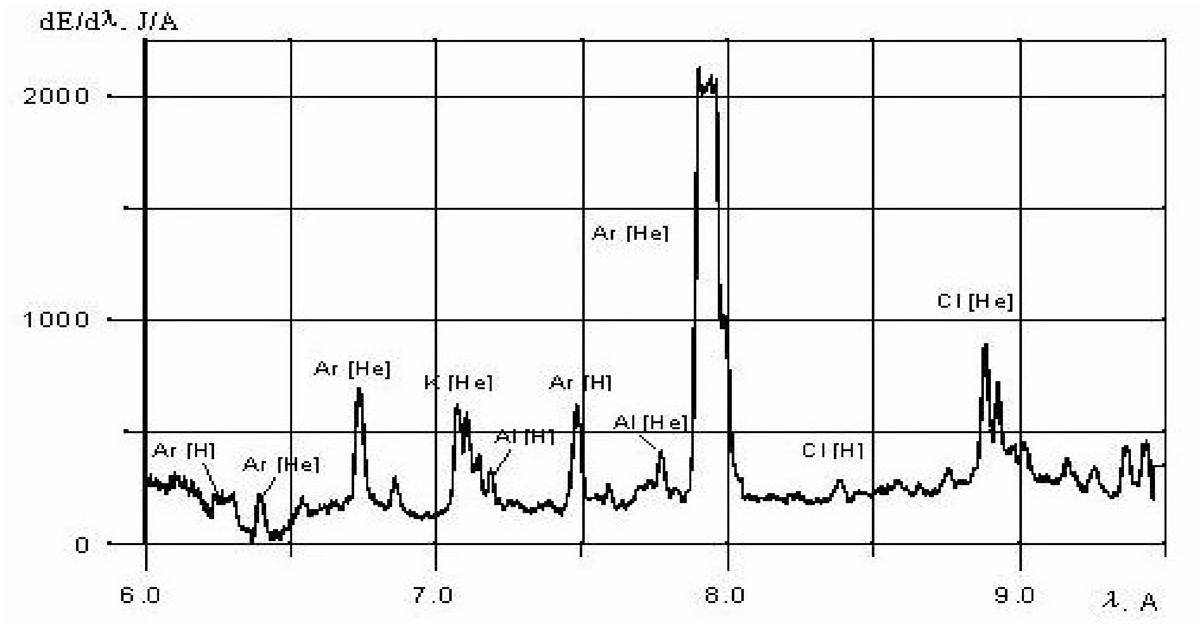


Fig. 9. Time-integrated spectrum of the line emission obtained at "Angara - 5-1" facility. The external shell: hollow *Ar* jet; internal loading: the cylinder of foam (55 ?g / cm) with an additive of *KCl* (30% over the weight). Radiation (*Al* [H] - and [He] - like ions) from the cathode is observed also.

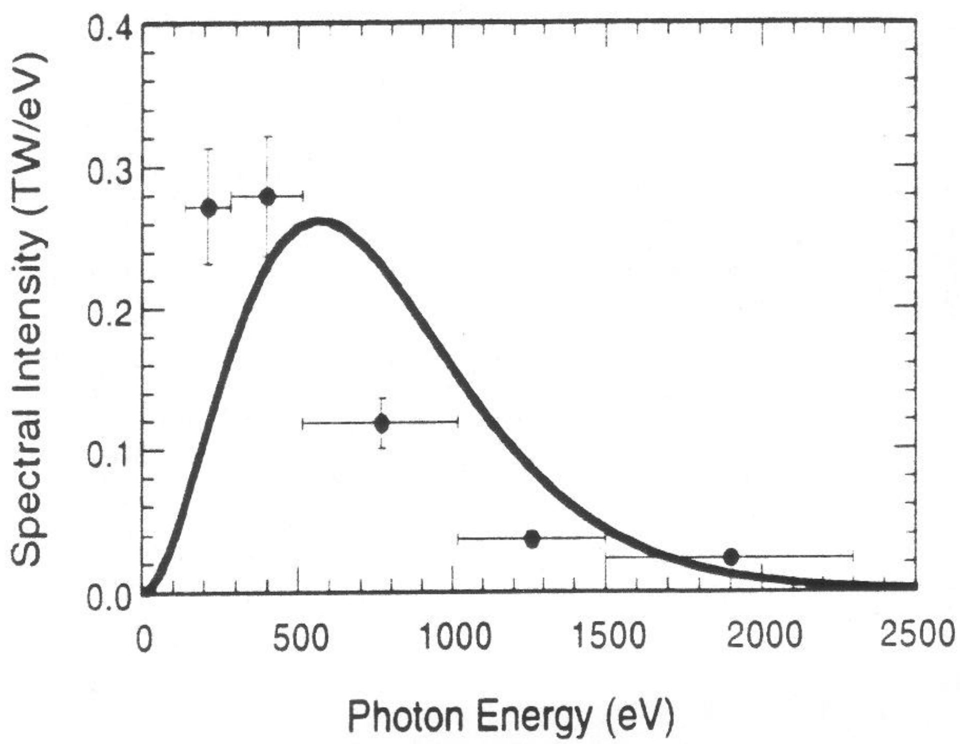


Fig. 10. Spectral data compared with 200 eV Planckian spectrum obtained with accelerator "Z" under compression of multi-wire tungsten constructions.

experiments performed with "Z" [10,11] has shown that plasma of heavy ions is not in local thermodynamic equilibrium with the radiation. The density of radiation energy reaches ~3% from the Planck radiation energy, however, even such a rather low radiation reabsorption changes essentially the state of plasma due to high rates of the photoprocesses (photo-excitation and photoionization).

Intensive radiation of Z-pinches of multicharged ions plasma are used for studying the physics of high density of energy, the equation of a state [28], the degree of plasma non-equilibrium [29], as well as for experimental modeling of the target dynamics in inertial laser fusion based on indirect irradiation [25].

In experiments with "Z" accelerator the energy of x-ray radiation of a tungsten pinch is re-radiated onto the target in the cavity with gold covering to obtain the Plank-like isotropic radiation. The spectrum of such radiation is given in [25]; the intensity of radiation corresponds to "black radiation" with the temperature T_r ~140 eV (so-called "brightness temperature ").

The energy of radiation received by the target considerably grows if the target is placed in the cavity of "the double liner" [30] (named "dynamic hohlraum" [31]) for the capability to keep energy of the radiation arising at the impact of liners). A series of experiments performed with generator " Angara - 5-1 " [17,32,33] and accelerator "Z" [34,35] with " the double liner " ("dynamic hohlraum") have shown that thermal x-ray radiation was generated at the moment of the liner impact, was kept inside the liners, and, due to this, was essentially amplified. At the same time, the experiments with generator "Angara - 5-1 " have revealed that, despite of an increase of the radiative flux, the radiation is not Planckian, and under conditions of experiment [17,32,33] is not in LTE with plasma. The measured "brightness temperature" of radiation ~84 eV (corresponding to intensity of a Planck spectrum) is much lower than the "radiation spectral temperature" of ~130 eV (calculated from the structure of a spectrum).

In the experiments performed at "Z" facility [34,35] under an increase of the current due to a much greater weight and, accordingly, greater optical density of the external liner the brightness and spectral temperatures of radiation turn to be essentially closer. The aperture of radiation intensity at the cover of internal plastic liner with small density was measured, and it constituted 13 TW; the pulses had duration about 4 ns through 2.4 mm. The external liner was made of tungsten. In the experiments with "dynamic hohlraum" made at accelerator "Z" the outstanding results were obtained. The brightness temperature of radiation at the target was above 215 eV [34], and the energy absorbed by a 1.7 mm spherical target exceeded 20 kJ [35]. These results exceed all the results obtained earlier for indirect laser irradiation.

2.2. X-pinches

An interesting source of soft x-ray radiation in the wavelengths range of 0.2-10 A is X-pinch plasma produced by electrodynamic explosion of a conductor in the form of thin wires (two or more) crossed in one point. The most extensive and detailed investigations of X-pinch plasma, including the radiative processes, are being carried out at Cornell University with "XP" facility (the current up to 500 kA; pulse duration, 100 ns, impedance, 0.5 Ohm) (see, for example, [13] - [16]). The X-pinches have been investigated with the help of the wires of the diameter 7.5 - 50 microns made of various metals (*Mg, Al, Ti, Ni, Cu, Nb, Mo, Pd, Ag, Ta, W* etc.). Spectral study of radiation was carried out with the help of crystal spectrographs. Registration of spectra with the time resolution was performed with the use of a streak-camera. The experiments were supported by 2D-MHD calculations.

Basing on the experimental data and its comparison with the results of numerical calculations, one can make the following basic conclusions about the properties of radiative processes in X-pinch plasma. Basing on the character of the radiative processes, the evolution of X-pinch plasma can be divided into three stages. Figure 11 (see [13]) shows an example of the radiation spectra of plasma produced by *Mo* wires and measured at various time moments. These spectra illustrate the radiation evolution with time. The first stage (duration about 10-50 ns) is the formation of a waist at the point of crossing of the wires. At this stage the spectrum of radiation is continuous, but at the end of this stage, during the waist cumulation to the axis and formation of a hot point, the radiation in the lines starts to play more and more dominant role.

Duration of the second stage of evolution of X-pinch plasma (stage of the existence of a hot point) is 10-20 ps. At this stage the peak of radiation in a continuous spectrum (the maximum of a corresponding Planck spectrum falls within the interval of 1-5 keV) corresponds to the conditions of plasma with the highest electron density $N_e > 10^{23}$ cm^{-3} when the temperature is 0.5?1 keV. The plasma maximum temperature of 2?4 keV is reached later, but the plasma density to this moment turns to be below $\sim 10^{23}$ cm^{-3}. At the stage of existence of a hot point, the radiative pressure becomes comparable to the thermal pressure of plasma. Furthermore, the rate of radiative losses exceeds the rate of the joule heating of plasma. Therefore, it is possible to assume that the character of the process of cumulative formation of the hot point is close to the phenomenon of "a radiative collapse". For example, the numerical calculations for X-pinch from two *Mo* wires off the diameter of 10 microns give for radiation energy the value about 0.1-0.2 J. If duration of this stage is 10?20 ps than the radiation power makes 10-20 GW. The corresponding intensity of radiation in the hot point turns to be $\sim 10^{17}$?10^{18} W/cm^2.

At the stage of existence of a hot point the radiation of continuous and linear spectra has a thermal origin, but after several nanoseconds in the linear spectrum of

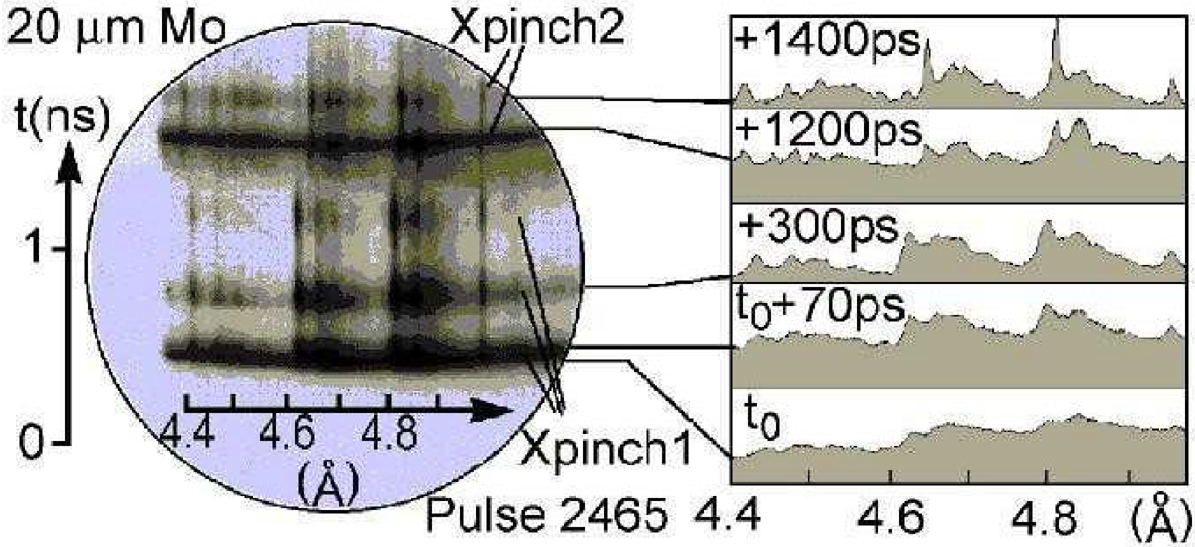


Fig. 11. The spectrogram and spectral structures of radiation of *Mo* plasma in X-pinch [13].

radiation there occur the clearly seen typical transitions with the energy ~20 keV. The occurrence of the lines of characteristic radiation corresponds to the stage of wire-break as a result of explosion of a hot point, and testifies the generation of the beams of accelerated electrons in the residual plasma. The mentioned above energies of the characteristic transitions found in the experiment from the spectra of radiation, allow one to estimate the kinetic energy of accelerated fast electrons at the level of 100 keV.

Thus, an interesting and important feature of Z-pinch as a source of x-ray radiation lies in the fact that temporal dynamics of this dot source of high brightness allows one to investigate the time evolution of a spectral composition from a continuous spectrum to the linear one and the characteristic spectra as well, and to connect it with time evolution of temperature, density and the size of the plasma.

2.3. Capillary discharges

Recently an interest to the creation of electro-discharge sources of radiation (Z-pinch, capillary discharge, plasma focus) in the field of vacuum UV and a soft x-ray spectrum has considerably increased. This interest is appreciably connected with an application of such radiation in lithography. A great number of the specialized symposia are held, and lots of papers are published. Now the major part of investigations is performed in the wavelength range of 135 A, where the ions *Xe X-XI* and *SnVII-XI* are considered to be the most effective radiators. Figure 12 demonstrates the typical temporal xenon spectra obtained in a microsecond capillary discharge [36] in the range 70-150 A. In Figure 13 the time-integrated spectra of *Kr* and *Xe* within the a range of 95-225 A are shown, which have been also obtained in a capillary discharge. More detailed xenon spectrum in the range of 70-170 A, obtained in a dense plasma focus [37], is demonstrated in Figure 14.

The density of plasma in the capillary discharge or plasma focus is rather small (N_i ~10^{16}?10^{17} cm^{-3}), therefore, as a whole the pinch plasma is practically transparent, and the radiation reabsorption takes place only in the strongest lines. Theoretical calculation [38] for collisional-radiative model show that the temperature of such plasma makes 30-50 eV.

3. Generation of nonequilibrium x-ray radiation in quasi-closed geometry

A typical feature of plasma produced in a spherical box under irradiation of its internal surface by powerful laser radiation is its non-equilibrium and non-stationary. Therefore, the radiation X-ray spectrum generated inside the box also differs strongly from the equilibrium Planck spectrum. Accurate calculation of spectral-temporal characteristics of the radiation filling the inner volume of the cavity and interacting with the placed inside target demands the calculation of spectral coefficients of absorption and luminosity of non-equilibrium and non-stationary plasma. This can be completely realized only at numerical modeling of all the processes occurring in plasma: the absorption of powerful laser radiation in hot plasma, the motion of non-equilibrium plasma, the transfer of energy by electrons and ions, the electron-ion relaxation, the generation and transport of non-equilibrium x-ray radiation, the ionization kinetics of plasma, etc.

In the experiments with "ISKRA-5" facility the target represents a spherical copper cavity of the diameter of 1.3?4 mm and its internal was covered by a thin (~1 micron) layer of gold. This layer served as converter of the laser radiation of "ISKRA-5" facility (wavelength 1.315 microns; pulse energy, 8?10 kJ; pulse duration, 0.3?0.5 ns) which was injected into the box through 6 holes and irradiated its internal surface. Typical feature of such a converter is multiple scattering of laser radiation inside the cavity at the wavelength ?=1.315 μm (the operation wavelength of "ISKRA-5" facility). The absorption coefficient of laser radiation (LR) by *Au* plasma does not exceed 30%. Due to this reason the average light exposure of the cavity walls by laser radiation is essentially smoothened. The laser corona formed as a result of laser radiation absorption by *Au* plasma (electron temperature, ~ 3?4 keV; the density ~ 10^{-3} g/cm^{-3}) is a source of initial non-equilibrium x-ray radiation (XR). This radiation, being absorbed by more dense and cold layers of *Au* plasma, forms an x-ray corona (electron temperature ~ 0.2 keV; density, ~0.2?0.5 g/cm^3) which transforms the spectrum of initial X-ray radiation into the Planck one with the temperature about 150 eV.

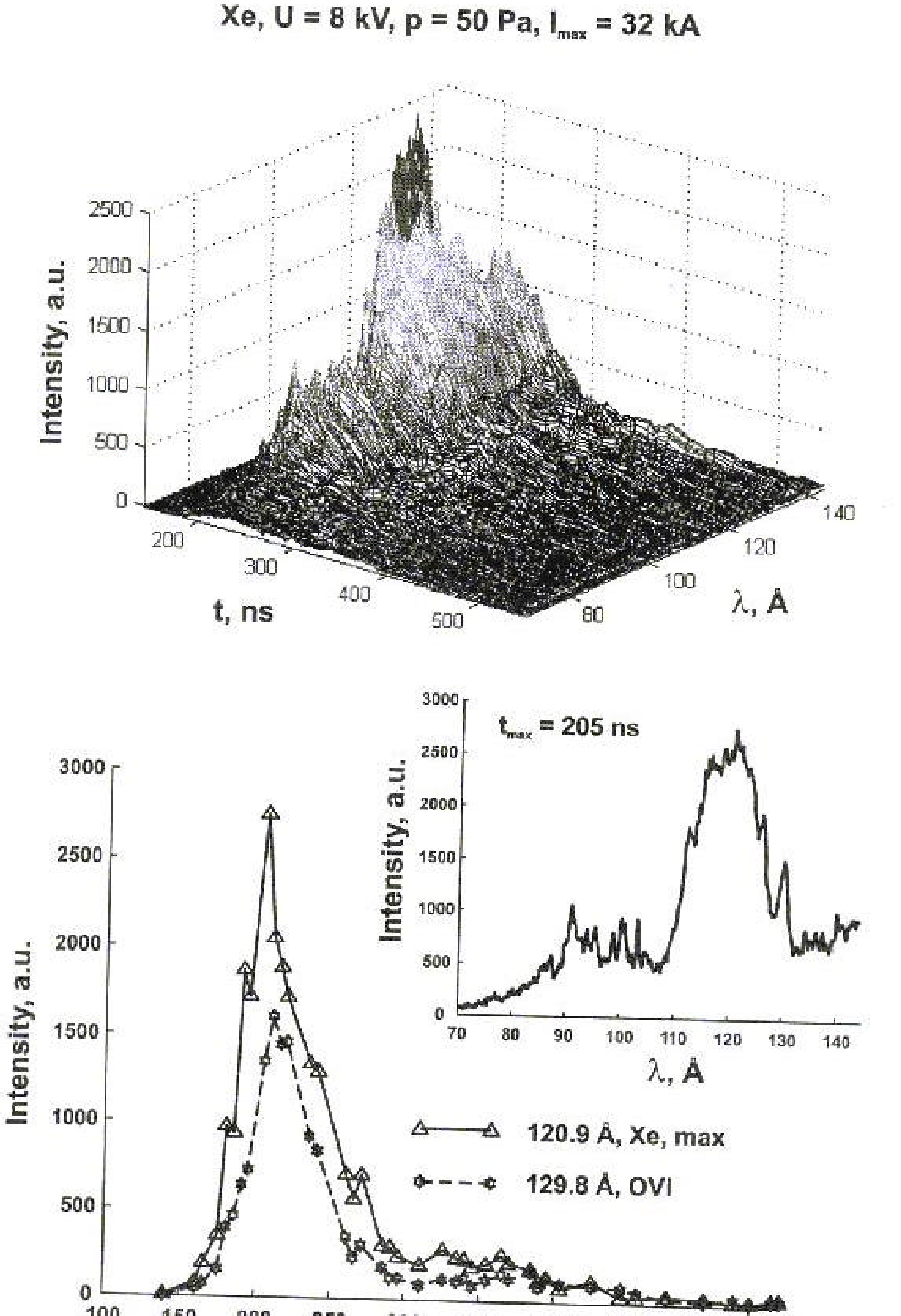


Fig. 12. Time-dependent spectra of a microsecond *Xe* capillary discharge, and the spectrum of *Xe* at the moment of maximum radiation at t=205 ns in the line 120.9 A.

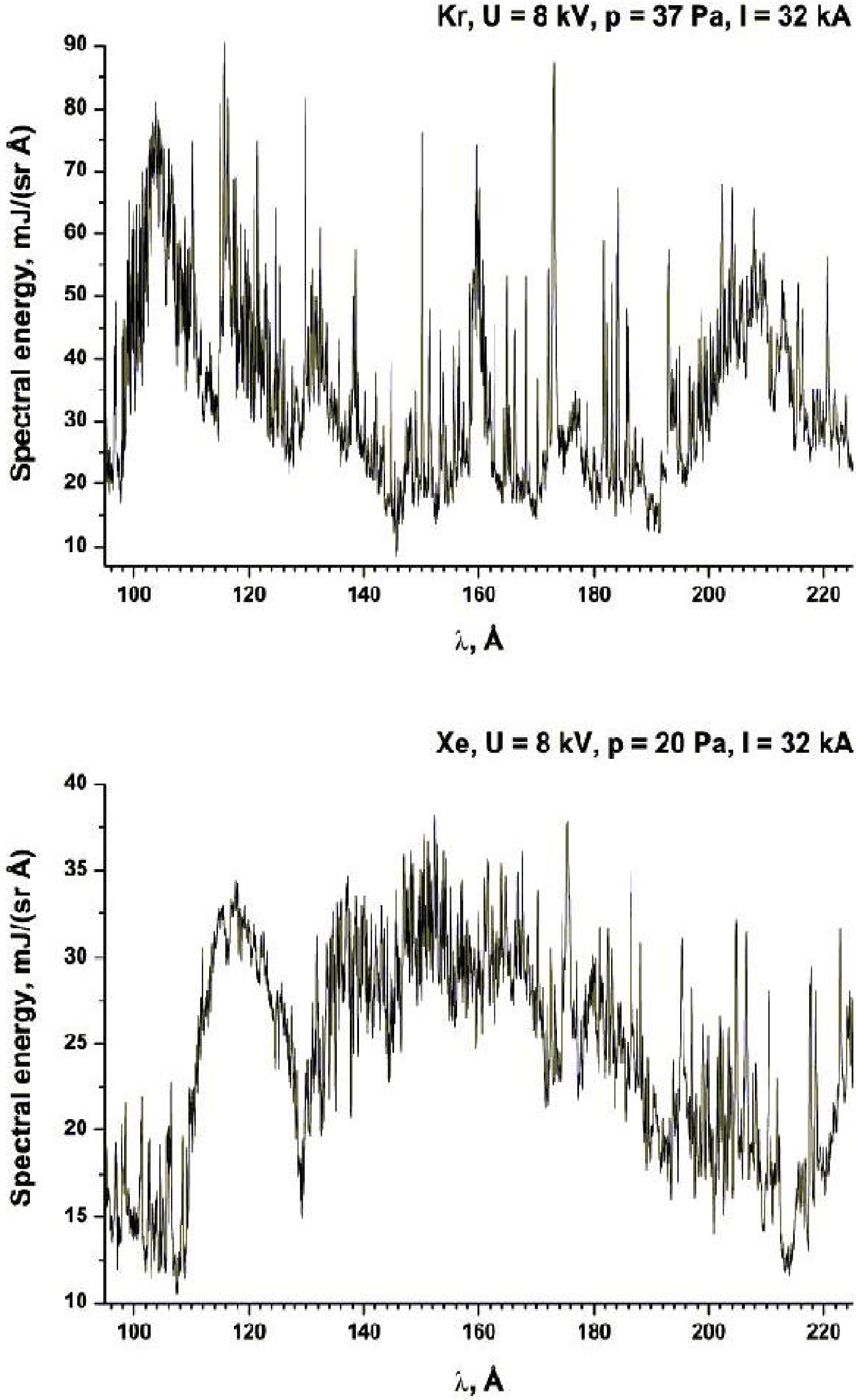


Fig. 13. Spectra of *Kr* and *Xe* (time-integrated) in the range of 95-225 A in a micro-second capillary discharge.

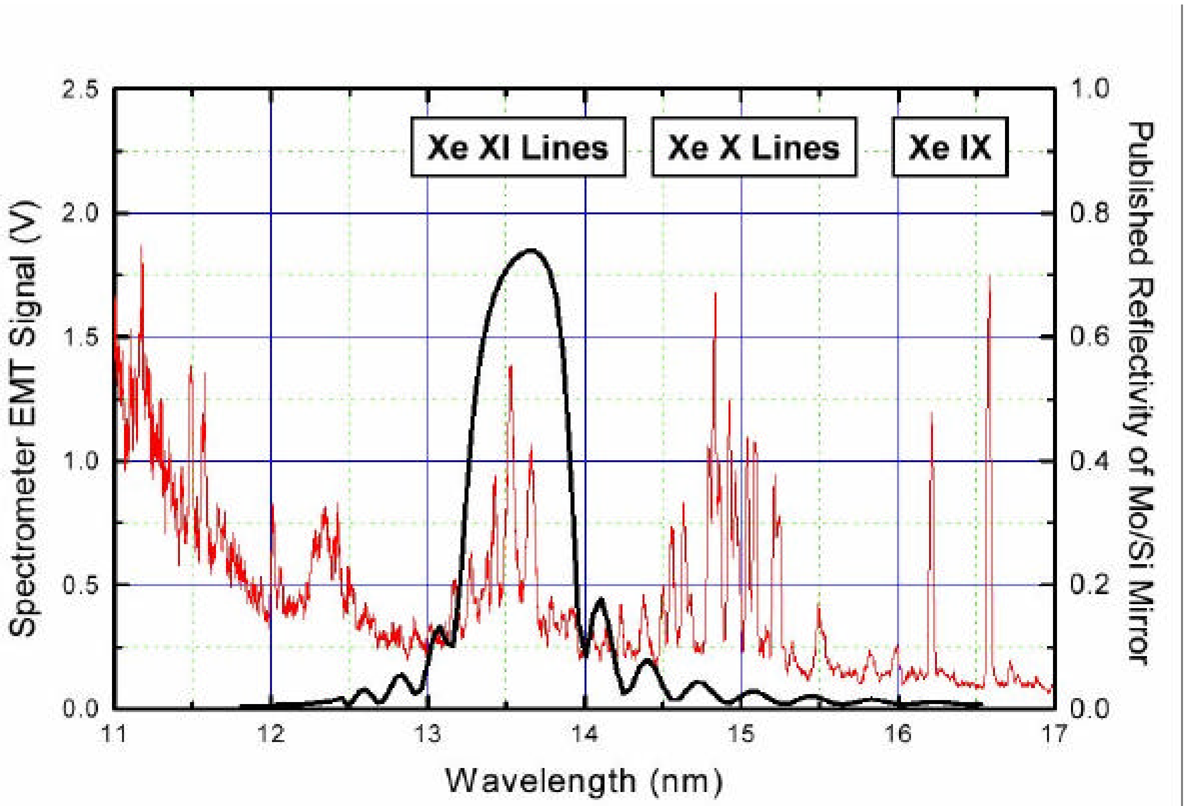


Fig. 14. Spectrum of *Xe* linear radiation obtained in the experiments with plasma focus (time-integrated). The curve of reflecting capability of Mo/Si mirror is also given.

Registration of X-ray emission spectrum [44-46] generated by the cavity walls has shown that the spectrum is a nonequilibrium one (see Fig. 15) [45]. Absolute measurements of the energy of x-ray radiation have shown that the x-ray flux irradiating the surface of a glass capsule corresponds to the effective temperature of 160-170 eV (Fig. 16).

To study the formation of resonant x-ray radiation in non-equilibrium optically thick plasma at "ISKRA-5" facility we used another design of the target - thin-layer spherical target (TLST) in which the internal shell made of elements with middle Z is completely heated by the laser radiation injected into the target, and the external shell made of the elements with small Z is transparent for resonant x-ray radiation produced inside [47]. The transparency of external shell of TLST and high informativity of x-ray spectra allows one to investigate in detail the kinetic and gas-dynamic processes in high-temperature multicharged plasma of the target. The numerical and theoretical analysis has shown that, using the "ISKRA-5" facility, it is possible to investigate the conversion of laser radiation into x-ray radiation and accumulation of quanta of resonant radiation He_a with the energy of $h?$~6-8 keV, the optical thickness of the target plasma in resonant lines being t_a~50-100 paths and

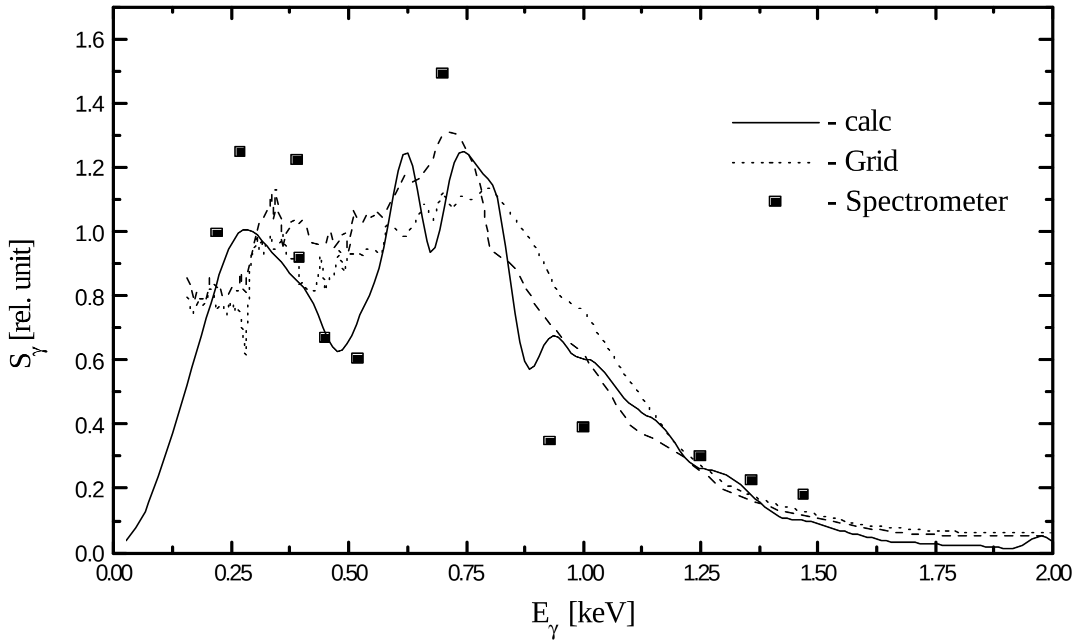


Fig. 15. Registration of the shape of a spectrum of x-ray radiation in the cavity of 2 mm in diameter with the help of diffraction-grating spectrograph (dotted curves) [45] and an X-ray mirror spectrometer (small squares) [46] and comparison with one-dimensional calculation (solid curve).

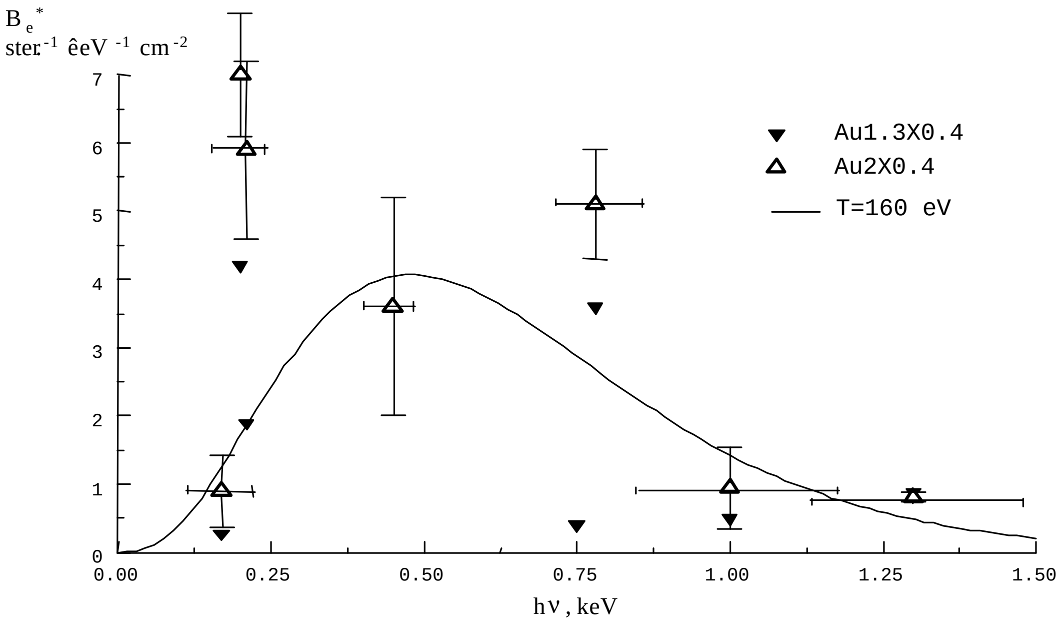


Fig. 16. Results of measurement of *Au* spectra with a spectrometer on vacuum - x-ray diodes for the cavities with diameter of 1.3 (black triangles) and 2 mm (light triangles) and 0.4 mm holes for laser radiation injection.

the plasma temperature about 3?4 keV. High temperature of plasma in TLST is reached due to the laser corona plasma cumulation in the center of a target.

Experiments on conversion of the laser radiation into x-ray using a new type of targets allows to investigate the generation of resonant x-ray radiation with the energy of quanta >7 keV in optically thick plasma of the elements with large Z within the interval of plasma temperature of ~3?4 keV, and expand the field of experiments on non-equilibrium kinetics of multicharged plasmas, necessary for verification of numerical techniques and models of non-equilibrium plasma.

Conclusion.

As shown in the paper, the effects of non-equilibrium are rather essential for radiative plasma. Complicated non-stationary character of behavior of the laser and discharge plasma and its non-equilibrium require for the description of such a plasma a complete collisional-radiative model accounting for the radiation transfer and reabsorption effects. Further development of the methods of modeling is hindered, especially for multicharged ions, by the absence of the necessary atomic data (or their insufficient accuracy).

One should note the following. The radiation spectra of plasma produced by ultrashort laser pulse are simple enough for the analysis (since they are optically transparent), although they demand to take into account the duration of plasma luminescence (and the changes in the parameters of plasma by this time) and reabsorption in the lines. The analysis of spectra of H-and He-like ions requires the information on the presence of a prepulse, which can essentially change the parameters of plasma. In the problems of indirect irradiation of targets one can face the effects associated with the difference in the temperatures of the emitting plasma (wall) and the heating radiation. In this paper an example of the analysis of experiments made with "ISKRA-5" facility is given.

Experiments with pulsed facilities (Z-pinches, capillary discharges) showed the variety of experimental situations and problems. Dynamics of Z-pinches is known and the problem concerns an adequate description of radiation of complicated multicomponent plasma. The main problem for X-pinches is the development of plasma dynamics models during the attainment of a stage of high density.

For the problem of reaching the maximal integrated output of radiation it is necessary to note a possibility connected with the investigation of plasma of small density with an addition of impurity of high-Z elements. In some cases the modeling of spectra behavior depending on the target structure and design, reveals a feasibility to control the spectral structure and power characteristics of radiation by special design of the target without changing the power and other characteristics of the experimental facility and laser pulse.

The collected spectra can be the basis of test problems destined for verification of various theoretical models of plasma radiation.

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