High-resolution x-ray diagnostics of high-temperature plasma with picosecond time resolution

P. V. Nickles, M. P. Kalashnikov, and M. Schnuerer
M. Born Institute, Berlin, Germany

B. A. Bryunetkin, I. Yu. Skobelev, and A. Ya. Faenov
State Science Center "All-Russia Scientific-Research Institute of Engineering Physics and Radio Electronic Measurements," 141570 Mendeleeva, Moscow Region, Russia

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X-Ray spectral diagnostics of plasma, produced on the surface of solid targets by two successive nano- and picosecond pulses following one another with an interval of 1.2 ns, was performed with high time resolution (down to 2 ps) and high spectral resolution (up to 5×10^3). The heating and the increase in the density of the preplasma, produced by the nanosecond pulse as a result of the action of a short (1-ps) intense pulse, was observed. The plasma parameters were determined at different stages of heating. © *1995 American Institute of Physics.*

X-Ray spectral methods of diagnostics[1] are widely used for investigating hot plasma produced under laboratory conditions—inertial-confinement fusion,[2] tokamaks,[3] x-ray lasers,[4] interaction of ultrashort laser pulses with matter,[5] high-current pinches,[6] heavy-ion drivers,[7] and so on—and astrophysical plasma (Ref. 8). Since two-dimensional detectors (photographic film, CCD array, etc.) are used to measure the spectra and since one coordinate must be the wavelength, the other coordinate can be either a spatial coordinate (spatially resolved recording of the spectra) or time coordinate (time-resolved measurement of the spectra). The choice between spatial and temporal resolution is determined by the peculiarities of the specific physical problem and by existing technical possibilities. Spatial resolution is easier to achieve technically. This has been done in most of the previous x-ray spectral analyses (see, for example, the review in Ref. 9). It should be noted, however, that in many cases (for example, expanding laser plasma) the existence of spatial resolution makes it possible to obtain an idea about the time evolution of the plasma.

In some physical problems, however, time resolution is required. An example is a nonstationary x-ray laser with two pump pulses.[10,11] Here the parameters of the plasma, which occupies nearly the same spatial region, are strongly time-dependent and it is impossible to determine from the time-integrated spectrograms their values at the onset of lasing and, therefore, the mechanism for the production of the inverted medium. Another example is investigation of satellite structures in the emission spectra of multiply charged ions. In this case different satellites are excited at different times by different elementary processes. Some excitation mechanisms are effective only under rather exotic conditions[12] (for example, plasma with a high temperature and density but low degree of ionization), which can be realized in plasma only for a short time, and it is extremely

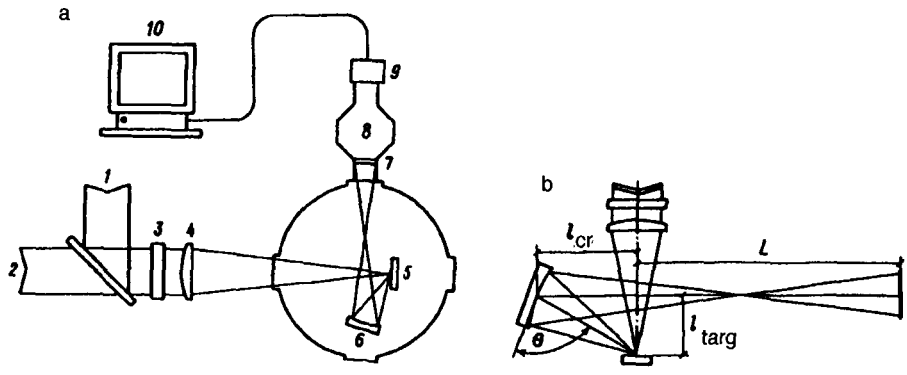

FIG. 1. Experimental arrangement: a) 1 — Nanosecond pulse; 2 – picosecond pulse; 3, 4 — cylindrical lenses; 5 — target (MgTi); 6 — mica crystal curved over a sphere with radius $R = 186$ mm; 7 — entrance slit of the streak camera; 8 — Kentech streak camera; 9 — CCD array; 10 — information analysis and processing system. b) Optical scheme for focusing the spectrum on the entrance slit of the streak camera. Mg target: $\theta = 67.3°$, $l_{cr} = 41.9$ mm, $L = 518$ mm; Ti target: $\theta = 75.9°$, $l_{cr} = 54$ mm, $l_{\min} = 100$ mm; $L = 518$ mm.

difficult or impossible to investigate their role on the basis of the time-averaged spectra.

Our objective in this letter is to demonstrate the possibility of performing high-resolution ($\lambda/\Delta\lambda \sim 5 \times 10^3$) x-ray diagnostics of high-temperature plasma with picosecond time resolution on the basis of the technique of spherically curved crystals.[9] The direct diagnostics problem consisted of investigating a plasma medium produced by two laser pulses which are delayed with respect to one another.

The experiments were conducted on the laser setup at the M. Born Institute. This setup (described in greater detail in Ref. 13) consists of a hybrid two-channel laser, whose master oscillator and first (cavity) amplifier are constructed on the basis of Ti:Sa active elements; the other amplification cascades are built on the basis of Nd-glass rods. A train of 150-fs pulses from the master oscillator is stretched by means of a diffraction-grating telescopic stretcher to a single-pulse duration of ~1 ns, after which an individual pulse is cut out of the train with the help of a Pockels cell and injected into the cavity amplifier. After the cavity amplifier, the pulse is divided in half by amplitude and the two beams are amplified in parallel channels. At the exit of the laser one of the amplified pulses is compressed to ~1 ps by means of a diffraction-grating compressor. This scheme makes it possible to obtain at the exit either a single pulse with the parameters 1 ps, 3 J or 1.2 ns, 6 J or two such pulses (nano- and picosecond) delayed with respect to one another. In our experiments the delay between the first nanosecond pulse and, subsequent picosecond pulse was equal to 1.2 ns.

The experimental arrangement is shown in Fig. 1. The laser radiation (*1, 2*) was focused onto the surface of a flat massive target (*5*) with the aid of an objective consisting of two cylindrical lenses with crossed generatrices (*3, 4*) into either a 20-μm diameter spot (magnesium target) or a 5×0.02-mm strip (titanium target). In the first case we recorded the spectral range 9.15–9.35 Å , which contains the resonance (R) and intercombination (I) lines of the He-like ion MgXI and their dielectronic satellites, which are due to transitions in Li-like MgX and in the second case we measured the spectral range

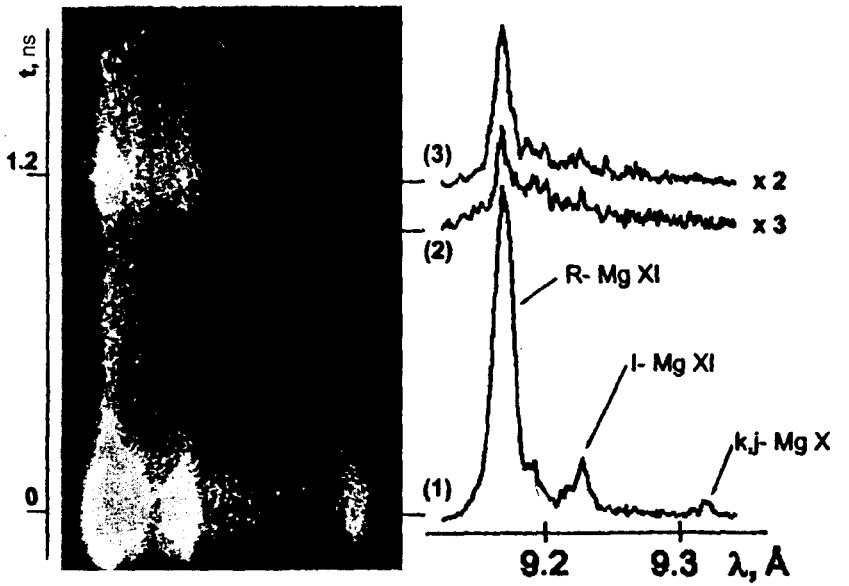

FIG. 2. Time scans of the emission spectrum of a magnesium plasma heated with two pulses. The densitometer traces (1), (3), and (2) correspond to the maximum of the first nanosecond heating pulse, the maximum of the second heating pulse, and the moment before the arrival of the second pulse, respectively. The vertical scale for curves 2 and 3 is magnified by factors of 3 and 2, respectively.

19–19.6 Å, which contains the $4D$-line ($4d-2p$ transition) of the Ne-like TiXIII, its dielectronic satellites, and some lines which are due to 3–2 transitions in O-like TiXV. In each case the dispersing element consisted of a mica crystal with a large 48×15-mm aperture curved over a spherical surface with radius $R=186$ mm (*6*).

The mica has a double interplanar distance $2d\simeq 19.9$ Å and reflects well not only in the first order but also in several higher orders,[14] which makes it possible to cover easily the above-indicated ranges with use of one crystal. Previous crystallographic investigations showed that the spherical curving of the mica with such small radii does not produce any appreciable changes in the width of the reflection curve and in the integral reflection coefficient compared with a flat crystal.[15] The crystal with $R=186$ mm was positioned so as to focus radiation with wavelength in the spectral ranges 9.15–9.35 Å or 19.0–19.6 Å with spectral resolution $\lambda/\Delta\lambda$ up to 5×10^3 on a 30×0.1-mm entrance slit (*7*) of an x-ray streak camera (*8*). The total distance from the source to the crystal and from the crystal to the entrance slit of the streak camera was equal to ~800 mm. A time scan of the spectrum at the exit of the streak camera was recorded with use of a CCD array (*9*) with dimensions of 384×576 pixels. The signal from the CCD array was fed into an image processing system (*10*).

In the experiments with time resolution it is necessary to record in one frame two processes separated by a time interval of 1.2 ns: 1) heating of the target and production of a preplasma by a nanosecond pulse and 2) formation of a nonstationary medium by a picosecond pulse. Consequently, at first we did not work with the fastest scans, so that for

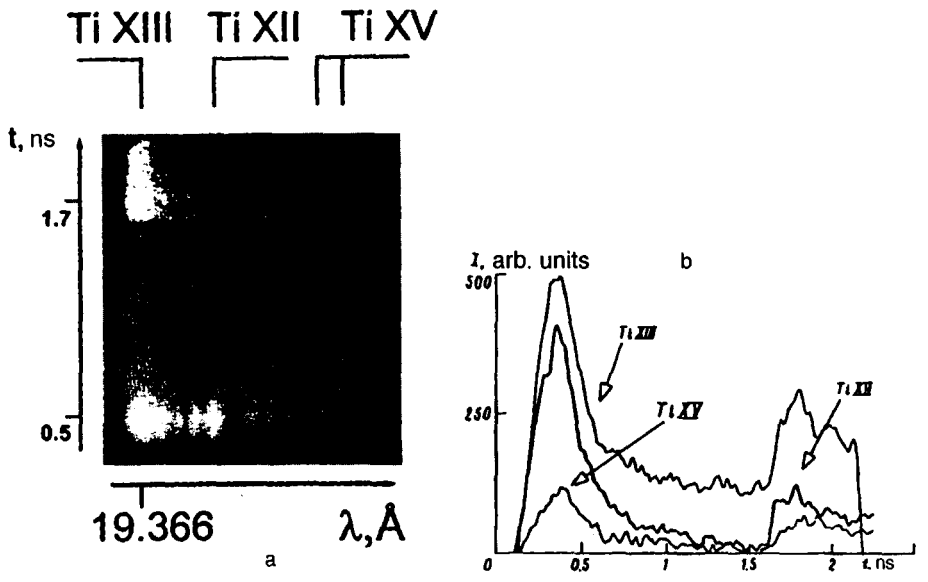

FIG. 3. a) Time scan of the emission spectrum of a titanium plasma heated with two pulses. b) Time dependence of the intensities of the lines of TiXII, TiXIII, and TiXV ions. The position of the maximum of the first heating pulse corresponds to $t \simeq 0.5$ ns.

a 0.1-mm-wide entrance slit of the streak camera the corresponding time resolution was equal to 15 ps. However, the signal level was quite high, and in subsequent experiments the limiting time resolution of 2 ps for the type of streak camera employed (Kentech) was achieved only with a short heating pulse. The spatial resolution in the direction of the linear focus (perpendicular to the plane of the figure) was determined by the width of the entrance slit (0.1 mm) and by the magnification of the x-ray optical scheme in the vertical plane[16] ($\sigma \simeq 5$) and was equal to ~ 20 μm. This resolution was essentially equal to the limiting resolution determined by aberrations of the obliquely incident radiation on the spherical surface.

The time scans of the x-ray spectra of the radiation from magnesium and titanium plasma for the case of two-pulse heating are shown in Figs. 2 and 3.

In the case of the magnesium plasma the spectrograms which we obtained make it possible to determine its parameters at different times by using the now standard x-ray-spectral methods (see, for example, Ref. 1); specifically, from the ratio of the intensities of the resonance and intercombination lines of MgXI ions (electron-density diagnostics) and from the ratio of the intensities of a resonance line and its dielectronic satellites (electron-temperature diagnostics). The results obtained in this manner are presented in Table I for three times corresponding to the maximum of the first heating pulse ($t=0$), the maximum of the second heating pulse ($t=1.2$ ns), and immediately before the arrival of the second pulse ($t=1.1$ ns) (see also Fig. 2).

Qualitatively identical results are also obtained from the spectrograms of the radiation from the titanium plasma. For example, from the measured curves (see Fig. 3b) of

TABLE I. Parameters of a magnesium plasma in an experiment with two-pulse heating.

	Intensity ratios			
t, ns	I_R/I_l	$I_{k,j}/I_R$	T_e, eV	N_e, cm^{-3}
0	5.8	0.04	580	10^{20}
1.1	2	–	–	2×10^{19}
1.2	4.6	0.054	480	7×10^{19}

the intensities of the $4D$ line of Ne-like TiXIII and its dielectric satellite, which is due to a transition in Na-like TiXII, we find that during the action of the second heating pulse the plasma temperature becomes even higher than at the point at which the first pulse peaks, since in this time range the intensity ratio I(TiXII)/I(TiXIII)$\simeq$0.41 is much smaller than the value 0.82 corresponding to the moment of formation of the preplasma, and the indicated intensity ratio is a decreasing function of the electron temperature. The large increase in the intensities of the lines of O-like TiXV indicates that at this time the temperature is substantially higher. It is important that the increase in the intensities of these lines in the region $t>1.6$ ns occurs much more slowly (over a time $\simeq$100 ps) than for the TiXIII lines. This means that the second picosecond heating pulse produces a plasma with nonequilibrium ionization (the degree of ionization corresponds to $T_e^i<T_e$), and this ionization equilibrium lasts for at least several tens of picoseconds. We note that, as follows from the calculations in Refs. 10 and 11, these conditions are necessary for the formation of the high-gain active medium of a nonstationary x-ray laser. We shall publish quantitative estimates of the parameters of a titanium plasma after we perform detailed calculations of the complete set of atomic constants for the ions TiXII–TiXV.

In summary, in the present paper we have presented the first results of x-ray spectral analysis of the time dependences of the parameters of a plasma produced by two laser pulses of different durations. The experimental results qualitatively confirm the mechanism, proposed and realized in Refs. 10 and 11, for the production of an effective active medium for short-wavelength lasers. We underscore the fact that the possibility of obtaining time scans of the emission spectra of a plasma with the required (and very high) spectral resolution $\lambda/\Delta\lambda\simeq5000$ and with a signal-to-noise ratio suitable for quantitative analysis was attributed to the use of an extremely high-power x-ray spectrograph with a dispersing element which is curved over a spherical surface.

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