X-ray radiation spectra of laser targets in experiments on SOKOL-P facility

A.V. Potapov, E.A. Loboda, V.A. Pronin, V.Yu. Politov, L.V. Antonova

VNIITF, Snezhinsk, PO BOX 245, Russia

The development of powerful ultrashort optical lasers with peak energy fluxes above 10^{17} W/cm^2 opened new possibilities for creation and investigation of the high- temperature plasma at solid-state density. Such plasma may be sufficiently uniform in space within some picoseconds from the irradiation start, while gas dynamics flows are too small. It is of great interest for the researches of spectral opacities in laboratory conditions. The experimental information on opacities could be obtained in this case directly from the plasma X-ray spectra measurements, which urgency is dictated, first of all, by the need for calibration of complex physical- mathematical models. Opacities value calculated by different models may disagree with each other up to several times [1].

At VNIITF such researches are carried out at the SOKOL-P laser facility [2] built by the standard scheme of chirp pulse amplification. Nominal power of the facility is 5 – 10 TW at the laser energy of 5 – 8 J on a target and the pulse duration of 0.8 – 3 ps. The contrast of the main laser pulse relative to the pre-pulse exceeds 10^9.

The first stage of the researches was devoted to the elaboration of spectral measurement techniques and experimental estimation of temperatures typical for picosecond laser plasma. Two types of targets were irradiated: massive uniform plates and thin multilayer targets with a buried layer being the main emittor (multilayer design was chosen to supress expanding of the plasma generating X-ray radiation by the external facings matter). The aluminum was used as a diagnosed matter of the massive plate and the burried layer because of its rather simple and well studied atomic structure.

The X-ray radiation spectra of the targets integrated over time were recorded with the use of two different spectrometers. First of all, the broadband spectrum of laser plasma was measured within a spectral range from 1 to ~ 17 keV by a seven-channel semiconductor spectrometer applying the "grey filters" technique. Each detector of the spectrometer was covered with a beryllium or aluminum foil of proper thickness that allowed for selection of the different spectral ranges. The thickness of four filters designed for passing through the soft quanta with energies less than 10 keV was 2 – 35 mg/cm^2. The filters for more hard spectral range were 100 to ~ 700 mg/cm^2 thick.

Additionally, lines spectra of H-, He-like ions of aluminum were recorded for quanta energies ε =1.4 - 2.5 keV by the focusing Gamoshy spectrograph with crystal dispersing element placed at an observation angle of 25^0 to the target surface.

A series of numerical calculations of radiative gas dynamics [3], level-by-level ionic kinetics [4] and radiation transfer has been carried out to interpret the recorded X-ray spectra for massive and multilayer targets irradiated by the picoseconds pulse of the Nd-laser 1-st harmonic. The parameters of targets geometry and irradiation pulse, which was focused into the spot of about 30 – 40μm diameter with peak energy flux $q_0 \sim (5\text{-}8)\cdot 10^{17}$ W/cm^2, were the initial data for calculations. The thickness of polyethylene facings and buried aluminum layer of multilayer targets were 2.2 μm and 4 μm, respectively.

It is to note that at irradiation fluxes over 10^{17} W/cm^2 no more than 10% of the picosecond pulse energy is transformed into the internal energy of plasma [5]. Moreover, the measurements of X-ray radiation hard quanta show that almost 30% of absorbed energy is spent to accelerate the fast particles – electrons and ions. To take these effects into account in gas dynamics calculations the laser absorption coefficient as a fitting parameter, varied in physically valid limits $\eta \le 0.1$, was introduced into the physical model.

The simulated basic value was the spectral intensity of X-ray radiation $I(\varepsilon,\theta_0,t)$ leaving the target under observation angle. Using this intensity the spectral radiation energy distribution and electrical charges induced in each i-th spectrometer detector was calculated by the following formulas:

$$\frac{d^2E_{XR}}{d\varepsilon\, d\Omega} = S_{XR}\cdot \sin\theta_0 \int dt\, I(\varepsilon,\theta_0,t) \qquad Q_{th,i} = \Omega_i F_i \int d\varepsilon \frac{d^2E_{XR}}{d\varepsilon\, d\Omega}\cdot f_i(\varepsilon)$$

where S_{XR} – the square of X-ray radiation yield being approximately equal to the focusing square ~ $8\cdot 10^{-6}$ cm^2, Ω_i –solid angle of observation of the i-th detector, $f_i(\varepsilon)$ - normalized spectral function of this detector describing the spectral range of its susceptibility, F_i – maximum value of the susceptibility estimated as $(3 – 4)\cdot 10^{-17}$ Q/keV.

Simulated spectra are compared with the experimental ones in fig. 1 (a,b) for massive and multilayer targets within the quanta energies range of 0 – 8 keV. These dependences demonstrate that the main part of massive target X-ray radiation is formed by the photorecombination processes in H-, He-like ions of aluminum, whereas radiation yield from multilayer target is defined by the same processes in H-like carbon. As a consequence, the X-ray radiation of multilayer target is almost ten times less intensive. Effective temperature of the X-ray spectra is estimated in both cases as ~ 0.8 keV that is in reasonable agreement with the experimental results.

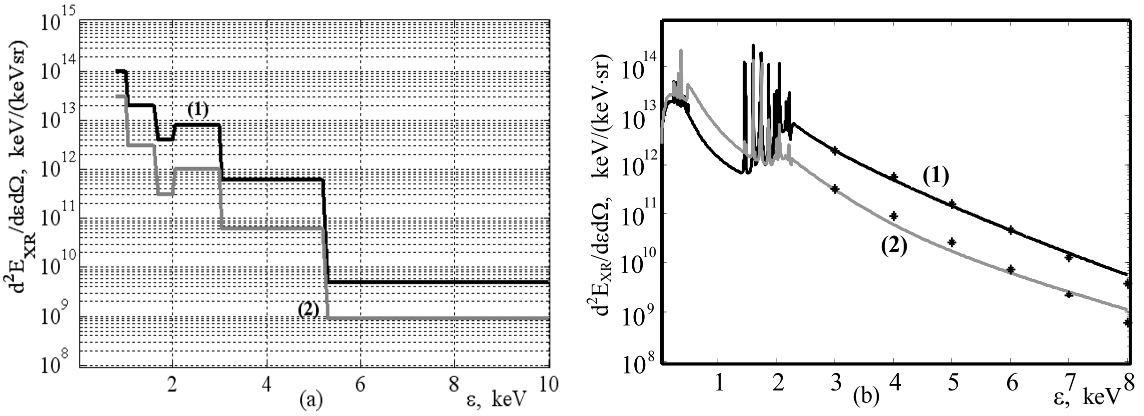

Fig.1. Experimental (a) and simulated (b) spectral distributions of X-ray radiation energy for massive aluminum (1) and multilayer (2) targets; symbol '*' means exponential function with electron temperature T_e = 0.8 keV.

The electrical charges were calculated for real characteristics of the spectrometer detectors - measured spectral functions $f_i(\varepsilon)$ and known solid angles Ω_i which vary for different i = 1...7 from $8{\cdot}10^{-6}$ sr to $4{\cdot}10^{-4}$ sr. When calculating, the $Q_{th,i}$ values were compared with the experimental charges depending on laser absorption efficiency. For η ~ 0.05 – 0.07 the signals of the first five detectors recording the soft X-ray radiation quanta with energies less than 10 keV are well reproduced numerically both for massive and multilayer targets. On the contrary, simulation of the electrical charges induced by more hard quanta with energies ~ 17 keV did not give any agreement. The reason is that the model does not consider the fast electrons bremmstrahlung, which influences dominatingly on signals of hard quanta detectors.

In the frame of simulation technique described briefly, the spectra of H-, He-like ions of aluminum have been calculated as well. For the massive and multilayer targets and η=0.05 these spectra are plotted in fig. 2 (a,b). Their comparison with the experimental spectra shows that calculated intensities of the most strong resonance lines Ly_α, Ly_β, He_α, He_β are close qualitatively and even quantitatively to measured values to within 100%. Especially good coincidence takes place for the massive target. For the multilayer target the situation is worse.

The attempt to increase the laser absorption efficiency by 2 – 3 times resulted in significant change of the ratios of resonance lines intensities. The lines of H- like ions become strongly dominating in the spectra that is not registered experimentally. Hence, one can conclude that the distribution of X-ray radiation intensity among lines of multi-charged ions is a sensible indicator for details of laser pulse absorption and its efficiency value.

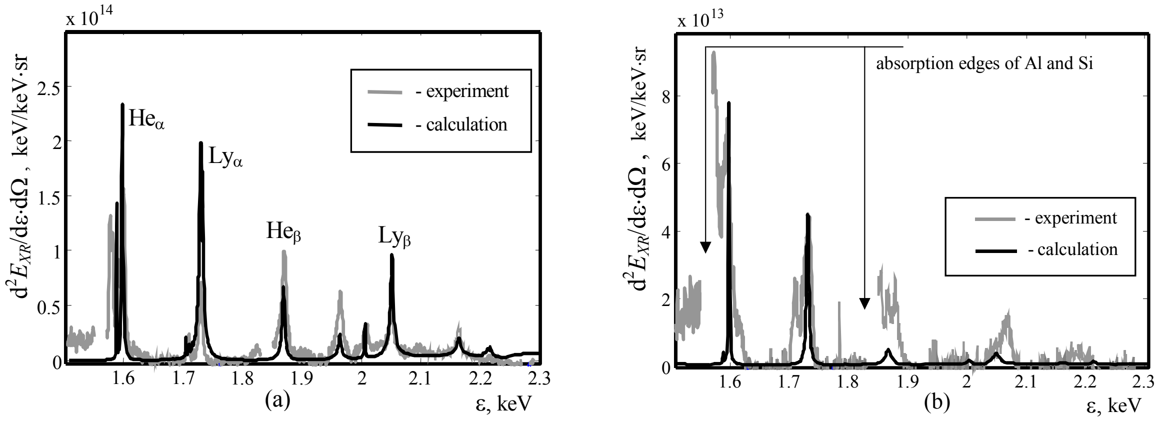

Fig. 2. X-ray radiation spectra in resonance lines of H-, He- like ions of aluminum for massive (a) and multilayer (b) targets.

As to the lines widths, they contain a lot of information about parameters and evolution of plasma as well. But for this information could be extracted and numerically analyzed, the lines shapes should be refined from the apparatus broadening being the main broadening mechanism of experimental spectra. Here, we do not concern such a problem.

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