X-ray diagnostics for investigation of nanosecond laser plasma

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Abstract. In this paper, the object of study is a laser plasma produced by nanosecond (~ 2.2 ns) laser low coherence radiation interacted with different solid targets. In the irradiation of target by a laser pulse with intensity of ~ 10^{12} - 10^{14} W/cm², the temperature of the formed plasma can be up to a few keV, and the maximum emissivity falls on the X-ray spectrum region. Developed X-ray diagnostics complex allows one to study of luminosity distribution of plasmas with high spatial, spectral and temporal resolution.

1. Introduction
The study of plasma sources with a typical lifetime of a few nanoseconds and a maximum emissivity attributable to X-ray and VUV regions is an interesting and actual issue. Currently, the sources of short-wave radiation ( VUV and X-ray spectral range) represent considerable interest as a manipulator of light with a wavelength comparable to atomic dimensions [1], and also in research on controlled thermonuclear fusion , in particular LTF [2, 3]. In these cases laser-plasma light sources are promising, they have a fairly compact dimensions, allow to work in a wide range of spectrum and intensity.

Investigation of the properties of laser-plasma sources requires the development of reliable methods of diagnosis. Comprehensive diagnostics of spatial, angular, temporal and spectral characteristics of the plasma source in X-ray, as well as in the soft X-ray and VUV, allow to obtain information about the efficacy and mechanisms of absorption of laser energy, the distribution of the plasma in space, as well as the role and nature of various nonlinear processes developing in the interaction of radiation with plasma.

The aim of the presented work is creating a diagnostic system for the detection of radiation from a laser plasma in X-ray and VUV spectral ranges, the experimental investigation of laser-target interaction, and the analysis of the experimental data.

2. Experimental setup
The laser-matter interaction experiments have been performed on the "Kanal-2" laser facility [4] LPI of RAS. Experimental facility includes Nd-laser, amplification system for the laser radiation and the vacuum chamber with a set of diagnostic equipment.

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Diagnostic system for the studying of the plasma X-ray consists of the following channels used in the experiments:

- pinhole camera for obtaining the plasma image in the own X-ray radiation ($\lambda \leq 9$ Å);
- Schwarzschild objective [5] for obtaining the plasma image in the own VUV radiation (180 – 200 Å);
- diagnostic channel for registration of continuous X-ray spectra, based on stepwise attenuator consisting of 13 beryllium filters;
- two channels on the basis of Johann spectrograph with a spherical crystal and grazing incidence spectrograph (GIS) for registration of line X-ray radiation spectra [6];
- channel for registration of the time evolution of plasma X-ray radiation;
- channel based on the mass spectrometer;
- calorimetric system for plasma and laser energy characteristics measuring.

Laser beam parameters such as energy, pulse duration and spectral composition also have been registered. The size of the focal spot of the heating radiation at the surface of the target was ~ 170 $\mu$m. Laser energy was 1-6 J.

The targets have been irradiated by one laser beam. Foils of Gd, Al, and alloy of Gd+Al (with containing 10 % Gd) have been used as the targets. Gd is interested as radiation source candidate based on “single line” or “single radiating ion”, and has strong arrays radiating close to 6.6 – 6.7 nm.

3. Experimental results

For heating radiation wavelength $\lambda_0=1060$ nm, and all types of the studied targets value of the critical density is several mg/cm$^3$. According to the conditions of the experiment the target with supercritical density have been irradiated. But in the interaction processes near target surface plasma cloud is formed with areas of supercritical, critical and subcritical densities.

In the study of X-ray pulse time-base with the electron energy $\geq 1500$ eV it was established that there is a formation of hot plasma. The existence time of hot plasma of targets is order of the laser pulse duration, and the hard component X-ray tracks changes in the electron temperature of the plasma [7].

Images of plasma have been obtained in hard X-ray spectral range $\lambda \leq 9$Å, and VUV spectral range $\Delta \lambda=180-200$ Å.

From the obtained images of the plasma in the hard X-ray emission it was found that gadolinium, aluminium targets is characterized by a spatial-limited emission region, that size approximately correspond to the focal spot. And this emission region is hot plasma.

Using the diagnostic channel based on a Schwarzschild objective, we studied images of laser plasma in VUV spectral range $\Delta \lambda=180-200$ Å (Figure 1). A comparison of images of the aluminium, gadolinium plasma, and the alloy of aluminium and gadolinium plasma showed that the emission targets containing the gadolinium has heterogeneity (as a “jets”), while the aluminium target emission more homogeneity over the spatial coordinates. And the radiation intensity of aluminium target is less than the radiation intensity of the gadolinium target and alloy aluminium with gadolinium at similar laser energy.
Figure 1. Images of laser plasma VUV spectral range \( \Delta \lambda = 180-200 \text{ Å} \).

- a – Gd target, laser energy 2.5 J;
- b – Al target, laser energy 2.2 J;
- c – alloy Gd+Al, laser energy 2 J.

Plasma images in VUV spectral range are also characterized by the presence of area with intense emission (“core”) with dimensions close to the focal spot. From the Figure 1 one can see that VUV radiation of plasma is propagated along the surface of the target. And the emission regions in the transverse direction relative to the direction of laser beam propagation have dimensions exceeding the size of the focal spot in several times (3-4).

The results on the ion composition for the gadolinium target are presented on Figure 2. One can see that laser plasma with multiply charged ions, the degree of ionization \( Z=21 \) has been formed at small laser energy of 2 J, and the laser intensity \( 3.5 \times 10^{12} \text{ W/cm}^2 \).

Figure 2. Ions of Gd target laser plasma.

X-ray spectra of multiply charged ions in the 10-200 Å for gadolinium targets have been registered, also the dependence of the intensity of X-ray spectra on the laser pulse energy and its duration have been obtained. One can see that the output intensity of X-ray increases with the intensity of the laser pulse. Furthermore, the output of the plasma X-ray radiation decreases with increasing laser pulse duration. The electron temperature of gadolinium plasma estimates of ~100 eV at an energy of heating laser radiation 6 J.
4. Conclusion
The realized diagnostic system enables to research of X-ray laser plasma: to study the spectrum of X-ray radiation in a wide range (1-400 Å), the spatial distribution of the laser plasma emitting regions in various spectral ranges (VUV 180-200 Å, the hard X-ray \(\leq 9\) Å), to determine the temporal behaviour of the plasma X-ray pulse with respect to the heating laser pulse, electron temperature of the plasma, and its ion composition.

The experiments on the interaction of nanosecond laser radiation with solid targets of Gd, Al and alloy of Gd+Al have been performed. It was found that the spatial distribution of hard X-rays have a spatial area of intense radiation localized near the focal spot, but the spatial distribution in VUV range have the total size of plasma emitting area exceeds the size of the focal spot. Studying of X-ray spectra and ion composition of created plasma is indicated on formation of multiply-charged plasma with electron temperature is 100eV, it is theoretical temperature needed for excitation of Gd ions radiating at 6.6-6.7 nm.

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