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Emission characteristics of a laser-plasma source of extreme ultraviolet radiation with thin-film targets

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The radiation spectra in the soft X-ray and extreme ultraviolet wavelength ranges of thin-film ($0.15\,\mu$m) targets made of light materials (Si, C, Be) were studied when excited by a Nd:YAG laser pulse with a duration of 5.2 ns focused to an intensity of $\sim 10^{12}$ W/cm^2. Line spectra of BeIII, BeIV, CV, and SiV ions were recorded using a spectrometer based on a multilayer X-ray mirror. A comparison with the spectra of bulk solid-state targets of the same materials is carried out. In all cases, there was a decrease in the intensity of the lines of the soft X-ray spectrum of film targets compared to monolithic ones; the decrease was, depending on the material, from several tens of percent to several times, with more than an order of magnitude less mass of the vaporized substance.

Keywords: SXR and EUV radiation, thin films, laser plasma.

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Introduction

The interaction of laser radiation with thin films is studied mainly using petawatt power level lasers. This is attributable to the interest in the problem of acceleration of charged particles in the electric field accompanying the laser pulse [1,2] — in appropriate experiments, the laser pulse should be able to propagate through the target. A substance that interacts with a high-intensity laser pulse usually becomes a source of X-ray radiation. The simplest generation mechanism is the deceleration mechanism, since the oscillatory energy of an electron is sufficient to emit fairly rigid optical quanta. The deceleration mechanism implies a wide, decreasing with increasing quantum energy, radiation spectrum without any pronounced features. The interaction region can be a source of not only deceleration radiation, but also of characteristic radiation. The characteristic radiation has pronounced spectral peaks, the type of which is determined by the composition, concentration and temperature of the resulting plasma, and the shells of atoms can be excited both due to collisions with electrons and due to the absorption of high-energy deceleration quanta [3]. At the same time, there are also more efficient laser-plasma mechanisms for generating X-rays, mainly associated with the collective movement of charged particles caused by an acutely focused laser pulse. X-ray generation from a betatron source [4–7] and during the interaction of a laser pulse with capillaries [8,9] is associated with collective mechanisms.

The studies of the creation and effect of extreme light fields on matter began to develop actively with the advent of super-powerful (petawatt) laser complexes at the end of the last century. The largest number of papers are devoted to the problem of acceleration of charged particles up to energies measured in gigaelectronvolts [10–13]. This state of affairs is connected with the urgent task of developing accelerator technology based on new physical principles, which will dramatically increase the availability of accelerated particle beams and short-wave radiation, which are in demand for medical and technological applications. In recent years, a large number of publications addressing the use of betatron radiation arising from the interaction of petawatt pulses with matter for medical X-ray diagnostics have been released [14–16]. A rather rigid X-ray radiation with energies from units to tens of kiloelectronvolts was observed in these papers with a narrow directivity and femtosecond duration; gas jets or gas-filled cells were used as laser targets. Studies of the interaction of petawatt laser radiation with targets in the form of foils have been conducted for quite a long time [17,18]. The thickness of the foils in the mentioned works ranges from one to hundreds of micrometers and the generation of sufficiently hard characteristic radiation with quantum energies of more than 1 keV is being studied, however, there is practically no work on the study of soft X-ray (SXR) and extreme ultraviolet (EUV) radiation from foils when exposed to nanosecond lasers. Such radiation should be observed at lower radiation intensities on the target, it is also of interest for a large number of practical applications (microscopy in the spectral region of the water transparency window, EUV nanolithography, fluorescence analysis of light elements, metrological tasks). Radiation in the SXR region was observed in a number of studies when focusing laser pulses on solid-state [19] and gas targets [20]. In this case, both the generation of high harmonics of the laser frequency [21] and the characteristic radiation [22–24] could be observed. The spectra of EUV radiation released in case of the interaction of laser plasma from a solid-state target with a gas jet were studied in paper [25]. A constructive version of the target in the form of a gas-filled capsule with a film wall destroyed by a laser pulse can be manufactured and studied on the basis of thin films. Capsule targets can be used, for example, in experiments aimed at finding ways to improve the efficiency of laser-plasma EUV sources for lithography, in which the emitting plasma is formed when the laser is focused in a gaseous medium, in particular, in xenon.

One of the reasons for the lack of studies of the spectra of film targets in the SXR and EUV ranges is the difficulty in manufacturing a significant number of targets with a thickness significantly less than 1 μm. There are no publications on the study of SXR and EUV radiation in case of the exposure of thin-film targets (thickness less than 1 μm) to laser, while there is interest in understanding the process of laser generation of X-rays with a decrease in the thickness of the laser target. An intense radiation from an extremely thin Al target was shown for the first time in our previous paper [26], only 30% inferior in intensity to radiation from a massive target, with more than an order of magnitude less total mass of vaporized material.

The study of the generation of SXR and EUV radiation during laser excitation of thin-film targets from other light elements such as Be, Si, C was continued to obtain new experimental data for the development of models of the interaction of laser radiation with condensed matter. The convenience of using light elements is attributable to the fact that they have a small number of characteristic lines emitted in these areas of the spectrum. The resulting spectra are simple to interpret.

1. Experiment and results obtained

The study was carried out on an experimental bench with a laser-plasma source, described in detail in [27]. A massive solid-state or film target was inserted in the vacuum chamber of targets in the area of acute focusing (a spot with a diameter of about 60 μm) of an Nd:YAG laser with a pulse energy of 0.8 J and a pulse duration of 5.2 ns. The radiation spectrum was recorded using a mirror spectrometer [27] (Fig. 1).

The spectrometer operates in three ranges: 3–6, 6–11 and 11–17 nm, which are changed by changing the dispersion element of the spectrometer — multilayer X-ray mirror. A solid-state target was studied at the first stage. First, a coarse scanning was performed with a step along the angle of incidence of radiation on the mirror 2°, which corresponded to a step along the wavelength of the order of 0.2 nm for all three ranges. The registered bright lines were registered with a smaller step, the angles of rotation of the mirror were determined, for which intensity maxima were observed. The corresponding spectra for the three materials are shown in Fig. 2.

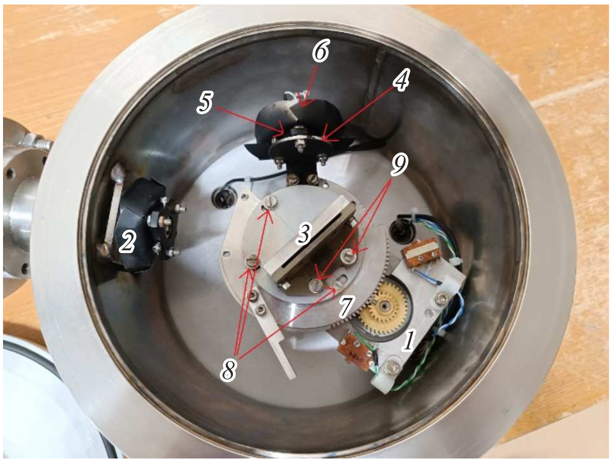

Figure 1. Spectrometer photo: *1* – stepper motor, *2* — input film filter, *3* —X-ray mirror, *4* — diaphragm, *5* — detector film filter, *6* — detector, *7* — goniometer, *8,9* — screws for changing the mirror.

The emission spectra acquired are in good agreement with the available literature data on the wavelengths of transitions in multicharged ions of elements used by us as targets [28,29]. The brightest lines in the silicon spectrum are SiV lines with wavelengths of 11.8 and 11.9 nm (they are not resolved by a mirror spectrometer). CV carbon lines, according to [28], pertain to the wavelengths 3.34, 3.50, 4.03 and 4.07 nm. Some systematic shift of the peaks in the recorded spectra relative to these values is probably attributable to the inaccuracy of the spectral calibration of the Cr/Sc mirror used in the measurement range with a graphite target. The peaks in the beryllium spectrum correspond to the lines of BeIII and BeIV ions with wavelengths of 7.7 and 10 nm [29].

Samples with a thickness of 0.15 μm were made from Be, Si and C to study the radiation spectra of film targets, which structurally comprised films glued to a supporting grid with a cell size of 3×3 mm. The grid was supposed to localize the damage to the film within one cell with each laser pulse. The outer diameter of the frame of the support grid is 35 mm, working diameter is 25 mm. Figure 3 shows a photograph of two thin-film targets — before and after the experiment.

The film target was placed in place of a massive solid-state target, the spectrometer was adjusted to the peaks of the lines defined in the previous step. A series of shots were made with the same laser parameters as for a solid-state target, the results were averaged. The ratios of the line signals recorded from the massive and thin-film targets are

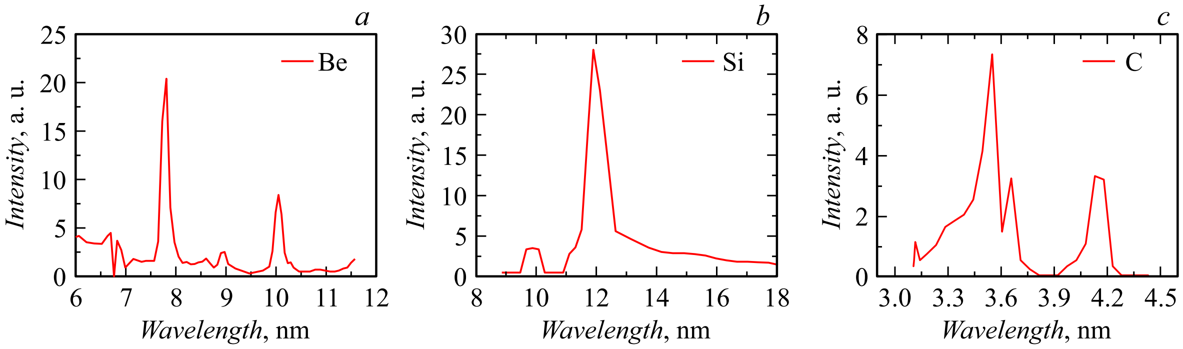

Figure 2. Emission spectra of massive materials in case of the laser excitation: *a* —beryllium, *b* —silicon, *c* — carbon.

Relative intensities of spectral lines of massive and film targets

Material	Wavelength, nm	Intensity, rel. u.	
		Massive	Film
Al [26]	13.1	4.5±0.3	3.5±0.3
	16.2	2.9±0.2	2.1±0.2
Be	7.7	20±0.1	9.6±0.3
	10.0	8.4±0.2	4.6±0.3
Si	12.0	4.2±0.3	3.8±0.3
C	3.6	3.3±0.2	1.3±0.1
	4.1	7.3±0.2	1.6±0.2

presented in the table. The results for Al are taken from previous study [26].

As can be seen, there is a noticeably lower signal of emission lines compared to the signal from a massive material for all the thin-film targets studied in this work. This difference is most pronounced for beryllium and, especially, for carbon, whose spectra are more rigid. At the same time, attention is also drawn to the fact that in the carbon spectra, the ratio of line intensities indicates a higher plasma temperature of the thin-film target, despite a much weaker emission intensity in general. We associate the qualitatively observed features with the dual role of the target as a source of matter for the formation of radiating plasma. On the one hand, a massive target is capable of delivering a substance in almost unlimited quantities, which increases the total output of SXR and EUV radiation. On the other hand, this is also an obstacle to heating the plasma to higher temperatures. In the case of using a thin-film target, the deficiency of the substance is more noticeable the smaller the atomic number of the material used, since lighter ions fly away from the laser focus area at a higher thermal velocity.

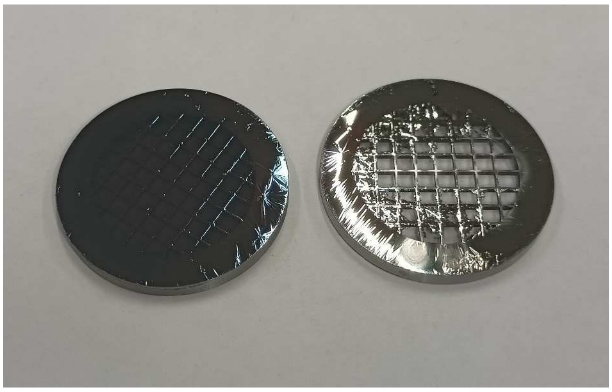

Figure 3. Photo of film targets on a support grid (before and after the experiment).

Conclusion

The use of thin-film targets to create sources of SXR and EUV radiation, along with existing types of targets, has certain prospects. However, it is hardly to be expected that thin-film laser targets will be broadly applied for creating sources of SXR and EUV radiation with high average power as the types of targets traditionally used in these tasks such as massive solid-state, gas-jet, drip targets, etc. This is due to the significant labor costs that would be required to manufacture a large number of film elements. Nevertheless, laser-plasma experiments with thin films are, in our opinion, of undoubted interest as a source of experimental data for testing and developing mathematical models describing the dynamics of plasma, which is created by a powerful laser pulse and emits in the SXR range. As shown in this paper, the emission spectra of plasma for targets of submicron thicknesses can differ quite significantly from the spectra of the array; the degree of difference depends, in particular, on the material. For light materials (Be and C), the intensity decrease was two or more times, while for heavier materials (Al and Si), the decrease is several tens of percent with more than an order of magnitude less mass of the vaporized substance.

The potential of using thin-film, including capsule, targets in research using petawatt-power lasers seems to us practically inexhaustible. Thin films are an alternative to foamed and porous targets often used to limit the amount of matter interacting with the laser pulse, while providing a richer choice of materials. It is possible to hope that it will be possible to form a region of hot plasma in the form of a flat „cake “under certain conditions of laser exposure to a thin film, and this opens up prospects for conducting experiments to enhance SXR radiation in recombining plasma, in which a beam of a significant aperture is amplified in the geometry „lumen “. Capsule targets are interesting as a possible replacement for gas cells, often used with petawatt lasers in schemes for generating high harmonics and laser-plasma acceleration of charged particles.

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Conflict of interest

The authors declare that they have no conflict of interest.

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