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Results of experiments for the study of the directional pattern of laser plasma-scattered radiation on the „Iskra-5“ unit

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The Iskra-5 unit was used to study dependence of directivity of laser plasma-scattered radiation on the power density of laser radiation with the wavelength of 1.315 μm on a target and on sizes of a focal spot and its form. It is shown that with the power density from $2 \cdot 10^{13}$ to $2 \cdot 10^{14}$ W/cm^2 the integral (in 4π) scattering loss is ~ 50 % of the pumping energy with various forms of the focal spot and its sizes within the range from 0.2 to 14 mm. At the same time, the nature of the directional pattern substantially depends on radiation intensity, the form and sizes of the focal spot and directions of a polarization vector.

Keywords: directional pattern, nonlinear scattering, photopaper, laser plasma.

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Introduction

A role of the nonlinear processes in laser-plasma interactions has been widely studied recently in many laboratories of the world. This interest is due to the fact that a number of the nonlinear process occurring in the laser plasma leads to negative consequences with substantial complication of achievability of effective ignition in experiments related to laser-thermonuclear synthesis [1,2]. These consequence may include nonlinear scattering of laser radiation by the plasma, which results in losses of laser radiation and danger of compression asymmetry for the capsule with $D-T$-mixture.

The processes of nonlinear scattering of radiation by the laser plasma have been already studied for more than 50 years, but there is still no quantitative match between the theory and the experiment [2]. It seems to be attributable to the following conditions. First of all, radiation scattering in the heterogeneous plasma is simultaneously contributed by several mechanisms and each of them has its own specific features and has different directional patterns. Secondly, most radiation receivers used have no required spatial and angular selection.Thirdly, the experimental research is difficult due to the fact that when interacting with the plasma laser radiation is partly transformed into a wideband frequency spectrum including harmonics and sub-harmonics of heating radiation and combination of plasma frequencies with laser radiation [2]. It results in necessitated use of photodetector with a wideband spectral range.

Despite previous wide theoretic research, the researchers mainly focused on studying stimulated Brillouin scattering related to interaction of laser radiation (LR) with an ion-sound wave and resulting in scattering of laser radiation back to the focusing optics and on stimulated Raman scattering (SRS) backwards [1,2], which occurs due to LR interaction with the plasma waves and results in energy scattering in the form of radiation. First of all, this is due to experimental difficulty of measurements of scattered energy sidewards. At the same time, the results of the works [1,2] show that side scattering of large magnitude can appear around the angles 45°−90° when the diameter of the focal spot is bigger than the longitudinal (along the direction of heating radiation) size of the plasma.

Extensive experimental material and its theoretical analysis made in the 90's of the last century (its results are given in the review [3]) is obtained based on using relatively low-energy laser units with short (sub-nanosecond) duration of pulses and point beam focusing of laser radiation into the focal spots of the diameter 50−100 μm. At the same time, the longitudinal and transverse sizes of the formed plasma do not exceed 150−200 λ, where λ — the pumping wavelength. With these values of the plasma scale, the nonlinear processes in conditions of convective instability do not create quite intensive fluxes of scattered radiation in side (within the angles above 45°) directions [1,4].

In case of LR point beam focusing, i.e. when the longitudinal size of the plasma exceeds the focal size of the beam, the least threshold for development of nonlinear scattering is in a inverse direction to the laser beam, since the major part of scattering goes back. It makes it possible to record backward-scattered radiation by means of an available focusing system, thereby simplifying the experimental setup. In this case, radiation going sidewards is usually recorded using a small number of photodetectors installed at the angle 30°−45° to the optical axle. When laser radiation obliquely falls to a target, energy of mirrored radiation is also measured.

Generally, the directional patterns of scattered radiation are determined using calorimeters or photoelectron appliances, which are installed in certain places inside an interaction chamber [5,6]. In order to increase the angular range of recording, it is propose in [1,7] to use fiber light guides designed to output scattered radiation out of the interaction chamber to the photodetectors. Even using a quite large number of these detectors, it is impossible to obtain a scattering pattern in the wideband range of the angles with high spatial resolution. As mentioned in [1], in order to obtain a more detailed scattering pattern within the wideband angle range, it is necessary to use a dedicated interaction chamber, which contains a large number of the light guides (at least 200). When a limited number of the photodetectors is used for evaluating omnidirectionally-scattered radiation energy, the obtained results are extrapolated by 4π [6], considering that it is scattered isotropically in accordance with the Lambert law. It may not correspond to the nonlinear scattering pattern as observed in some works [8–10]. It has been previously reported in [9]. If an indicatrix of scattered radiation is substantially anisotropic, then this approach to determination of a value of scattered energy may result in significant errors and incorrect understanding of the physics of laser-plasma processes.

With increase in power of the laser units and with increase in the LR duration to $3-10$ ns, in the conditions of focusing into the spots of a millimeter size, conditions arise for intensive scattering of laser radiation sidewards [8,9] including within the angles $75^\circ-90^\circ$. The most complicated scattering pattern is formed when there is some nonlinear processes in the plasma with quite high power density of the laser pulse. In order to understand them, it is highly important to know the directional pattern of scattered radiation, which can be taken to judge scattering mechanisms and locations of their origin in the plasma.

The aim of the present study is to determine the directional pattern of radiation scattered from the laser plasma and to evaluate energy losses for scattering by means of a procedure described in the works [9,11].

1. Measurement procedure

Nonlinear scattering has been experimentally measured on the Iskra-5 unit using an iodine laser [12] at the wavelength of $1.315\,\mu$m with targets made of different materials (copper, zinc, germanium) at the different sizes of the focal spots.

The spatial pattern of scattering of radiation from the plasma in the solid angle $\sim 4\pi$ has been built using exposed and developed photopaper (PP) [9,11]. It can be used to record radiation within the wideband frequency range from UVto IR with the threshold energy density of 0.05 J/cm^2 which is required to form a visible burn. In order to quantitatively determine the scattered energy in various directions, PP sensitivity has been calibrated. A procedure for calibrating PP sensitivity is described in the work [11], which has shown that the dynamic range of energy density recording is 10 with the radiation duration of ~ 1 ns.

The spatial resolution of the procedure is determined by a PP quality for the samples used and it is 100 strokes per one millimeter. This method of recording of scattered radiation is also advantageous in that it is insensitive to interference, simple and available for use.

The quite large transverse size of the plasma was obtained while providing the LR power density over $\sim 10^{12}$ W/cm^2 (which is the threshold power density to get the nonlinear processes for $\lambda = 1.315\,\mu$m) by using focusing of laser radiation on the target as a narrow string (line) with the length of $2-14$ mm and the widths of $170-200\,\mu$m. With radiation energy of $150-200$ J at the wavelength of $\lambda = 1.315\,\mu$m and in the pulse of duration of 350 ps, it could achieve the requried LR power density.

In order to model experiments related to the laser-thermonuclear synthesis, with LR duration of several nanoseconds, in use, the Iskra-5 unit having laser pulse's duration of 0.4 ns has provided a pre-pulse ahead of the main pulse by $2-7$ ns. It is done to provide a spatial scale of plasma transformation along the laser radiation direction.

The optical setup of the experiments for studying nonlinear scattering is shown in Fig. 1. The interaction chamber *7* was a cylinder of the diameter of 500 mm and the length of 1100 mm. Its residual-gas pressure did not exceed 10^{-2} Pa. The focal spot was formed as a line by combining the spherical *4* and the cylindrical *5* lenses. The required line length was specified by changing the distance between them. By rotating the cylindrical lens around an axis, the line direction can be changed. In the experiments done, a polarization vector was perpendicular to the line direction.

The flat plat *2* was placed in front of the reflecting mirror *3* to obtain the pre-pulse. The target *9* was glass plates of the sizes 10×20 mm and thickness of 2 mm, whose surface was coated with a layer of copper (germanium or zinc) of the thickness of $1.5-2\,\mu$m. The target was placed in the interaction chamber on a special suspension designed to exactly adjust in the position and in the angle. At the same time, the target plane in relation to the beam was installed vertically and rotated by 3.5° to the right (from the target) in order to avoid incidence of the reflected beam into the amplifier. The scattered energy going sidewards and into the focusing optics was measured using the calorimeters *10* and PP *8*.

The spectral composition of radiation running along the line was measured using a prism spectrograph and a diffraction grating spectrograph *12*. After interacting with the spectral device *12*, the scattered radiation was focused by the lens *13* to the photopaper *14* to leave a burn thereon.

The PP *8* was laid on an internal surface of the cylinder of the diameter of 190 mm and the length of 200 mm. In order to output radiation running along the line, the cylinder and the PP were perforated.

A typical pattern of scattering of radiation sidewards as obtained in the experiments with the pre-pulse and the line of the length of 14 mm, at the power density $(2-5) \cdot 10^{13}$ W/cm^2 is shown on Fig. 2.

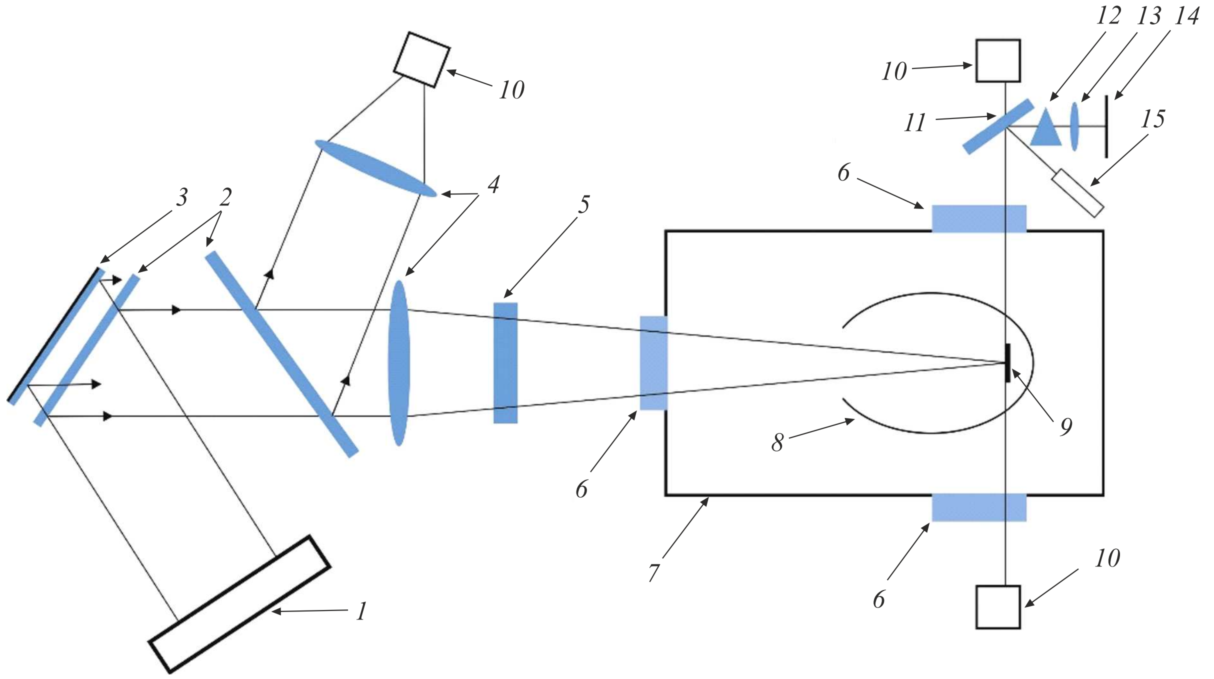

Figure 1. Optical setup for measurements (plan view): *1* — Laser pulse generator; *2* — Flat glass plates; *3* — Mirror; *4* — Spherical lenses; *5* — Cylindrical lens; *6* — Chamber windows; *7* — Interaction chamber; *8, 14* — PP; *9* — Target; *10* — Calorimeters; *11* — Optical wedge; *12* — Prism; *13* — Focusing lens; *15* — Photodiode.

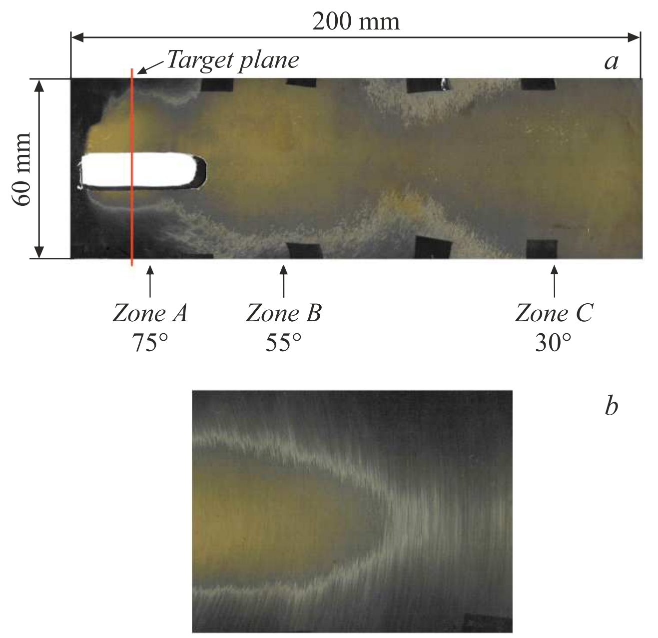

Figure 2. Burns on the photopaper: *a* — the nature of radiation distribution on the left (from the target) part of the screen in the experiments with the line of the length of 14 mm; *b* — distribution of radiation as narrow radial bands.

As it is clear from Fig. 2, *a*, along the line (the area *A*) radiation running within the angles 75°–90° to the optical axis at the distance of 100 mm makes a uniform burn on the PP as a spot of the size of $\sim$ 30 mm. In the area *B* with the angle $\sim$ 55° to the optical axis the radiation distribution is of a linear nature in the form of narrow radial bands, whose curvature radius is determined by their distance to the axial line along the line. The appearance of the radial bands in the area *B* is shown in Fig. 2, *b*. No radial band is visible in Fig. 2, *a*, as they merge into a single burn due to high intensity of scattered radiation. At the angles below 40° in the area *C* the distribution is uniform.

The directivity is quite clear at the angles $\sim$ 30°, 55° and 75°–90° in the horizontal plane in an angular distribution of scattered radiation. Vertically, the angular size of scattered radiation depends on the line length and when it is 14 mm this size is $\sim$ 15°. With decrease in the line length to 2 mm, the scattering angle in a vertical direction increases to 25°.

In its nature, the scattering pattern of Fig. 2 was not substantially changed with decrease of the line length within the range from 14 to 3 mm. However, with decrease of the line length, there was reduction of a burn force in the areas *A* and *B*. The pattern of scattered radiation was qualitatively changed with decrease of the line length to 2 mm, when there was a closure of all the burn zones. With the line length of 1.5 mm and its width 0.5 mm, there was radiation in direction perpendicular to the line and the scattering pattern became more uniform in the horizontal plane within the angles from 45° to 70°, but it was still far away from the Lambert law.

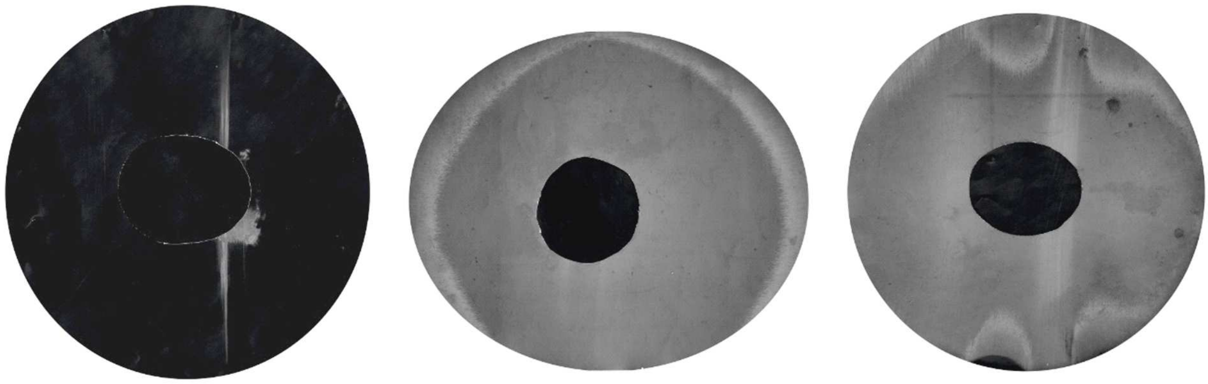

Figure 3. Burn pictures on the PP in a plane perpendicular to the laser beam at the various power density on the target.

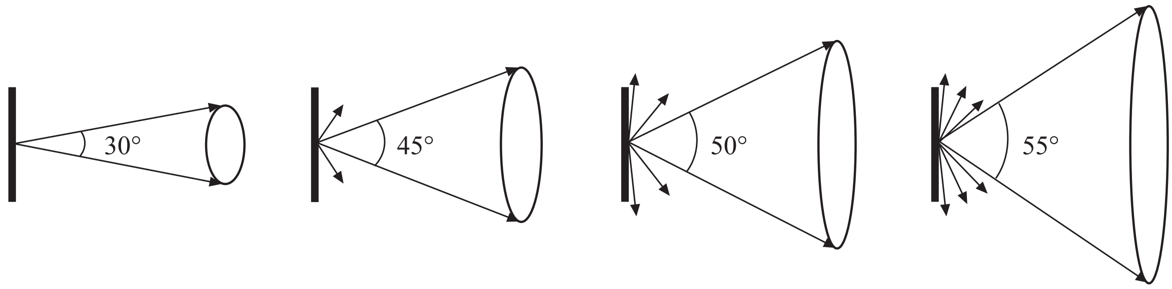

Figure 4. Dynamics of changing of the directional pattern of scattered radiation with increase of the LR power density at the line length of 14 mm.

With the LR power density above $2 \cdot 10^{12}$ W/cm^2 , there was clearly the recorded burn from conical radiation scattered back to the focusing system as shown in Fig. 3.

As it is clear from Fig. 3, the threshold LR power density with the wavelength of 1.315 μm, which is required for occurrence of backward nonlinear scattering, is $1.4 \cdot 10^{12}$ W/cm^2. With the power density above $2 \cdot 10^{12}$ W/cm^2, the directional pattern of plasma-backward scattering radiation becomes conical and the angle size of this cone increases from 30° to 55° with increase of the LR power density from $2 \cdot 10^{12}$ to $2 \cdot 10^{13}$ W/cm^2 on the target.

The nature of the directional pattern of scattering in the horizontal plane at the constant pre-pulse delay depends on the LR power density and the dynamics of its changing is shown in Fig. 4. It shall be noted that the above pattern of the scattering dynamics corresponds to the experiments with the line length of 14 mm. With decrease of the line length, the threshold of occurrence of sideward scattering within the angles 75°–90° increases. Thus, with the line length of 8 mm the sideward scattering occurs when the LR power density is above $1.2 \cdot 10^{13}$ W/cm^2, while at the line length of 14 mm tis threshold is $9 \cdot 10^{12}$ W/cm^2. With decrease of the line length to 3.5 mm, the sideward radiation occurs when the LR power density is $4 \cdot 10^{13}$ W/cm^2. As noted above, the threshold of occurrence of backward conical scattering does not depend on the sizes and the form of the focal spot and corresponds to $2 \cdot 10^{12}$ W/cm^2.

It shall be also noted that the nature of directional pattern of scattered radiation substantially depends on mutual directivity of the line and the polarization vector. In the conditions of the experiments on the Iskra-5 unit, the polarization vector was always vertical so when the line was horizontal, their directions were mutually perpendicular. In this case, the main portion of sideward scattered radiation propagated in the horizontal plane perpendicular to the polarization vector. When the line was along the vertical direction, sidewards scattered radiation also propagated perpendicular to the polarization vector. The experiments done show that the nature of the scattering pattern is mainly influenced by a direction of the polarization vector rather than the line position. The result obtained confirms conclusions of the work [10], which also shows that the sideward scattering is perpendicular to the plane of laser polarization.

Schematically, the directions (directivity)of scattered radiation in the horizontal plane when LR is focused into the horizontal line of the length 14 mm, with the available prepulse and with the power density above 10^{13} W/cm^2 are (is) shown in Fig. 5.

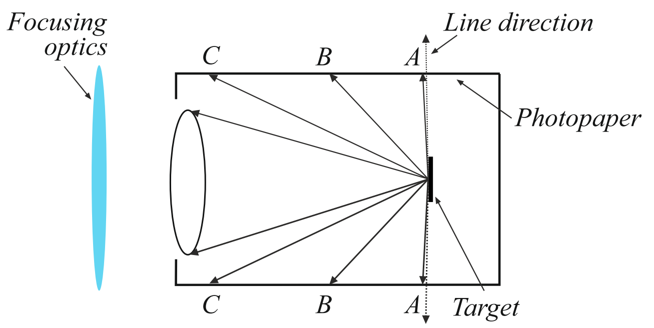

Figure 5. Main directions of radiation scattering in the horizontal plane.

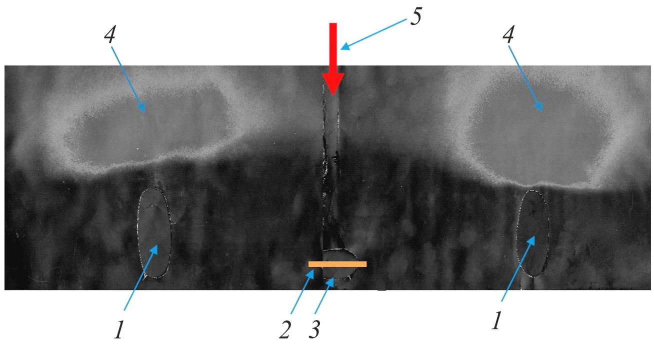

Figure 6. Unrolled picture of the burns on the PP laid on the internal surface of the cylinder when focusing of laser radiation into the round spot: *1* — the openings for outputting scattered radiation within the angles 75°–90°; *2* — the flat target; *3* — the openings for target suspension; *4* — the burns in the area *B*; *5* — the direction of LR propagation.

When LR is focused into the round spot of the diameter of 0.2 mm, without the pre-pulse and at the power density of $\sim 10^{15}$ W/cm^2 , there was the picture of the burns on the PP as shown in Fig. 6. An opening in the middle of the lower part of the PP image is designed for insertion of a target holder, while the left and right openings are designed to output scattered radiation running along the line to the calorimeters. The sideward scattering is in the plane which is perpendicular to the polarization vector and is directed at the angle of $\sim 50°$. Quite intensive conical scattering is also backward towards the focusing optics (Fig. 3).

Using the method of scanning the burn obtained on the PP and based on the results of calibration of its sensitivity to light radiation [11], the amount of energy scattered in various directions has been determined. As the results of the experiments have shown in the conditions of the developed nonlinear processes, with the LR power density above $2 \cdot 10^{13}$ W/cm^2 the scattered energy of radiation into the area*A* is $\sim 10\,\%$ of the pumping energy, so into the area *B* $\sim 5\,\%$, and so into the area *C* $\sim 5\,\%$. Taking into account that the scattering proceeded symmetrical in relation to the laser beam, the total sideward scattering is $\sim 40\,\%$. Towards the focusing optics the scattering was $\sim 10\,\%$. With the power density below $2 \cdot 10^{13}$ W/cm^2, an energy portion scattered sidewards is reduced, while the backward radiation increases. The obtained scattering in 4π, equal to 50 % corresponds to the results of the works [9–11,13–16], which give close values of the losses for scattering in the laser-plasma experiments.

2. Spectrum of scattered radiation within the angles 75°–90°

The experiments done have examined a spectrum of radiation occurring within the angles 75°–90°. Use of the spectrometric equipment in these conditions is featured by present high-intensive radiation propagating along the line. When radiation was focused into an entrance slit of the spectrometer, an optical breakdown and slit destruction took place. In order to exclude this phenomenon, the spectrograph was without the entrance slit. Then, the spectral resolution of the device was determined by a ratio of the size of the plasma formation to a distance from the prism to the target by angular dispersion of the prism. Within the studied range of the spectrum, the resolution of the measurement system is ~ 20. References for calibrating the spectrometer scale were lasers with the wavelengths 532 and 633 nm. Due to high intensity of sideward radiation the spectrum was recorded by means of the PP placed in the plane of image of the lens downward of the prism, as shown in Fig. 1.

The experimentally obtained spectrum of radiation of the copper target is shown in Fig. 7. It is evident from the figure that in the direction of the angles 75°–90° the spectrum of scattered radiation is within the range from 875 to 1025 nm, which is defined by the SRS process [2] resulting in occurrence of a combination of the frequencies of the plasma and the light wave.

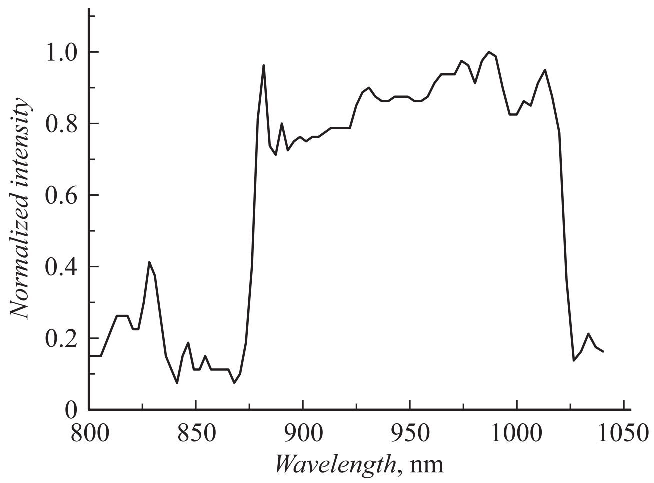

Figure 7. Spectrum of plasma-scattered radiation from the copper target within the angles 75°–90°.

3. Analysis of the scattering pattern

The results of the performed experiments indicate a substantially anisotropic nature of scattering radiation, which is far away from the Lambert law. The analysis of the burns on the PP allows to make a number of conclusions on the nature of the nonlinear radiation scattering:

1) availability of quite pronounced angular directivity of the scattering pattern both in vertical and horizontal directions, which depends on the LR power density and the form of the focal spot;

2) in the area *A* the burn picture is a round spot having the diameter of ~ 30 mm at the distance of 100 mm to the target, as it is clear in Fig. 2, and it did not vary substantially with decrease of the line lengths within the range from 14 to 3 mm;

3) in the area *B* the burn picture consists of narrow ($\sim 10\,\mu$m) radial bands, whose radius increases as we move away from the area *A*;

4) in the area *C* the burn picture is of a uniform nature and its vertical size increases as we move away from the area *A* and *B*.

Towards the focusing optics, the directional pattern of scattered radiation is conical and has a clearly outline border. The sizes of the cone and its form heavily depend on the power density of heating radiation on the target and on a line direction as it is shown in Fig. 3.

With focusing of laser radiation into the round spot of the diameter of 0.2 mm with the power density of $\sim 10^{15}$ W/cm^2 and without the pre-pulse, sideward scattered radiation within the angles $75°-90°$ was not recorded within limits of sensitivity of the photodetectors used. The main portion of scattered radiation was directed to the right and to the left at the angle of $45°-50°$ in the plane perpendicular to the polarization vector. For comparison, in the experiment with focusing into the horizontal line of the length 2 mm and the width of 0.3 mm with the LR power density of $3 \cdot 10^{13}$ W/cm^2 we observed quite strong sideward radiation towards the line.

The greatest interest in the LR scattering pattern under consideration with focusing into the line is availability of quite intensive radiation directed along the target plane. As noted above, based on the readings of the calorimeters designed to record radiation along the line, in the target plate within the angular sector $75°-90°$ with the line length of 14 mm and with the pre-pulse, energy of up to 40 J is radiated to both sides with the pumping energy of 200 J. Assuming that the duration of scattered pulses is ~ 100 ps, then at the distance of 15–20 cm to the target the average intensity of radiation reaches $\sim 10^{10}-10^{11}$ W/cm^2 which can result in destruction of the optical elements. This phenomenon was repeatedly observed in the experiments done, when a mirror surface of the mirrors with an aluminum coating (which were outside the interaction chamber at the distance of 55 cm to the target) was destroyed, so was the surface of two diffraction gratings used in the spectrometer. Besides, in the experiment with focusing into the line of the length of 7 mm, with the LR intensity of $2.4 \cdot 10^{13}$ W/cm^2, there was local destruction of the glass surface of the prism both at its input of radiation and the output thereof.

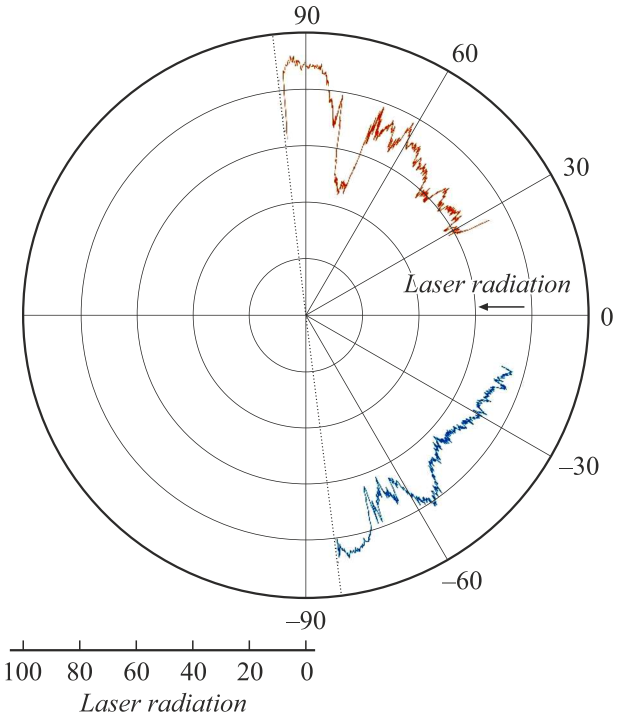

Figure 8. Appearance of the directional pattern of scattered radiation in the horizontal surface as resulted from scanning the burns on the photopaper.

Fig. 8 shows an integral directional pattern of scattered radiation in the horizontal plate when focusing into the line of the length of 14 mm to the LR target with the power density of $3 \cdot 10^{13}$ W/cm^2 and with the pre-pulse available, which is obtained by scanning brightness of the burns on the PP in the horizontal plane. The burn brightness is given in relative units. The given directional pattern is rotated about an axis of the laser beam by 7° counterclockwise due to inclination of the target in the horizontal plane. It should be noted that the experimentally obtained directional patterns of radiation from the plasma qualitatively correspond to the scattering pattern of radiation as obtained in the work [10].

A specific nature of the directional pattern (observed in the experiments with LR focusing into the line) that is characterized by availability of the areas *A*, *B* and *C* may indicate presence of scattering of laser radiation on a diffraction structure. This hypothesis put forward more that 10 years ago in the work [9] is confirmed, for example, in the works [17,18], which have experimentally detect appearance of the diffraction grating in the plasma. A mechanism of formation of the spatial periodical structure similar to the Bragg one [19] in the laser plasma is related to exposure of electrons to the electromagnetic field of the standing wave which is formed due to superposition of the incident and reflected pumping waves from the critical layer. Under the ponderomotive forces, the refractive index of the optical medium is modulated with formation of the structure with a period equal to the wavelength. At the same time, regardless of the form of the focal spot, due to Bragg scattering there is radiation being formed on the produced diffraction structure, which runs backwards as a cone, as it is shown in Fig. 3.

Conclusion

It can be concluded within the framework of the performed studies that when focusing of LR of the wavelength of $1.315\,\mu$m into the horizontal stroke (line) of the length above 3 mm with the radiation power density above $\sim 10^{13}$ W/cm^2 the process of laser-plasma interaction includes intensive sideward scattering of radiation within the angles $45^\circ-90^\circ$, which takes away up to 40 % of the laser energy. Radiation which is scattered backwards as a cone with the angle of $30^\circ-60^\circ$ takes away ~ 10 % of the pumping energy.

The LR power density required for occurrence of sideward scattering depends on the line length and reduces with increase of its length. Thus, with the line length of 3 mm sideward scattering occurs with the LR power density above $3 \cdot 10^{13}$ W/cm^2, so does at the line length of 14 mm with the LR power density of $9 \cdot 10^{12}$ W/cm^2. At the same time, the sideward scattering is symmetrical in the horizontal plane.

In all the cases of target irradiation realized in the work, the indicatrix of radiation scattered from the plasma is substantially anisotropic.

Conflict of interest

The authors declare that they have no conflict of interest.

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