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INTERACTION OF PARTIALLY COHERENT LASER RADIATION WITH MATTER

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ABSTRACT

A new approach to the problem of IFE laser driver based on generation and amplification of radiation with controllable coherence proposed and realized at P.N.Lebedev Physical Institute of the RAS had initiated the studies of an interaction efficiency of a partially coherent radiation with matter.

Recent results of experiments carried out with the aim to study of the physical processes in targets under illumination by the laser with controllable coherence of radiation are presented and discussed, especially such important laser-matter interaction phenomena as absorption and scattering of laser radiation, the laser radiation harmonic generation, X-ray generation, crater formation and plasma expansion under laser pulse, conversion of laser radiation by means of nonlinear crystals, influence of coherence degree on the processes mentioned above.

1. INTRODUCTION

A new approach to the problem of a laser thermonuclear electric station on the basis of a hybrid reactor with a laser ignition was proposed in [1-3]. The essence of that approach was to use a laser-driver irradiated target as a thermonuclear source of neutrons in order to initiate energy yield in a subcritical blanket, which envelopes the target. As a fissionable material for the blanket one could use uranium 238, plutonium, or just natural uranium. Speaking about a hybrid fusion-fission reactor it is necessary to underline that its main advantage as a subcritical blanket is a high (practically absolute) degree of safety because the accidents connected with chain fission reactions are exclude at all in such type of reactor.

Today it seems that an electric power station with hybrid fusion-fission reactor is the only real way for development of new energetic.

A high energy gain of a two-cascade blanket amplification, by 3000-5000 times, allows one to re-consider the earlier used approaches to a development of a laser-driver. Such a high gain makes it possible to reduce sharply the requirements to energy output of thermonuclear reactions in the laser plasma, and as a consequence, to the laser-driver power, and to the homogeneity of the target irradiation. It becomes possible to use slightly compressed targets. This not only simplifies the target design, but allows the use of a small number of beams for the target irradiation (even two-beam schemes may be suffice).

In [4-6] it was proposed to apply lasers with a controllable function of mutual coherency (or with quasi-thermal parameters of the radiation) as the basis for high-power laser systems to be used in power stations.

The paper summarizes results of experiments carried out with the aim to study of both the features of laser with controllable coherence of radiation (CCR laser) and the physical processes in targets under the CCR laser radiation.

2. LASER WITH CONTROLLABLE COHERENCE OF RADIATION (CCR LASER)

At N.G.Basov Institute of Quantum Radiophysics of P.N.Lebedev Physical Institute of RAS, a project of a laser facility is being realized, which is aimed at constructing a CCR laser. The goals of the project are to determine ultimate characteristics of such a laser and to start a development of a laser driver for a hybrid fusion-fission reactor.

At present, a first module of the CCR laser has be made. The parameters of this module are listed in Table 1.

Table 1

Master oscillator		Linear cascade amplifier	
Output aperture	6 mm	Output aperture	60 mm
Pulse duration	40 ns	Pulse duration	2,5 ns
Radiation energy	0.7 J	Radiation energy	up to 300 J
Divergence	$1,1\cdot10^{-2}$	Divergence	$1,4\cdot10^{-3}$

Optical scheme of the master oscillator, of the system of formation of spatial-temporal characteristics of laser radiation, and of the amplify system is shown on Figure 1 (disc amplifier element 9 with output aperture 100 mm is now under development).

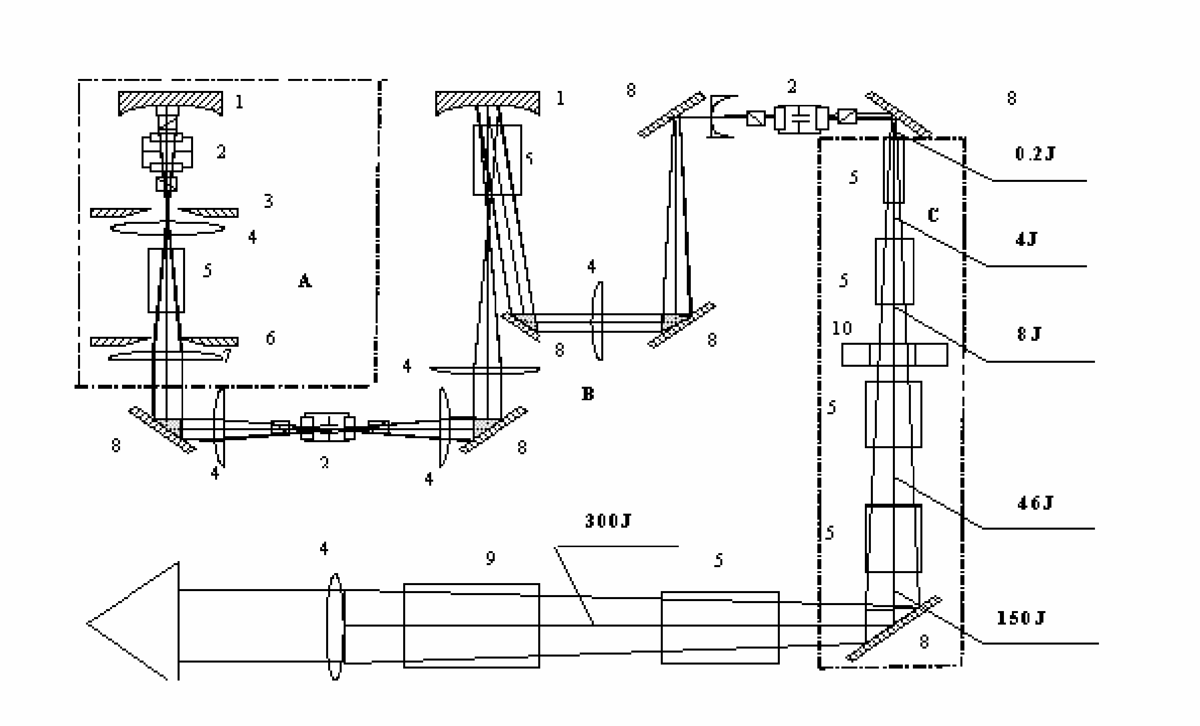


Figure 1. Optical scheme of the master oscillator (A), of the system of formation of spatial-temporal characteristics of laser radiation (B), and of the amplify system (C):

1 - spherical mirror, 2 - Kerr shutter, 3 - forming diaphragm, 4 - lens, 5 - active element, 6 - output diaphragm, 7 - output mirror of the resonator, 8 - rotatable mirror, 9 – disk active element, 10 – Faraday rotator.

The performed studies demonstrate that the CCR laser has a number of advantages as compared to conventional schemes of lasers.

The radiation coherency control allows us to use physical properties of laser light to form the required distribution of laser radiation and to exclude the undesirable phenomena leading to laser beam breaking.

The scheme of formation of the master oscillator pulse permits us to provide the required spatial and temporal coherence of the radiation pulse and to control the coherence of the laser beams used in the ICF experiments without violation of a laser-target matching, and to control the laser radiation intensity distribution in a lens focus. Design of the master oscillator permits one to change divergence of the output radiation within $2 \cdot 10^{-2}$ - $3 \cdot 10^{-3}$ by means of changing the value of the forming diaphragm. By changing the transmittance shape and profile of the forming diaphragm one can control the angular distribution of the output radiation.

The coherence degree affects very strongly the self-focusing process, especially the small-scale self-focusing. In the case of a low coherence radiation the picture of interaction is non-constant both in time and in space, and the interference picture is formed only within the coherence dimension. Therefore, a decrease in the coherence level leads to an increase in a threshold of small-scaled self-focusing, and due to this to its suppression without using of spatial filtration.

The problem of the speckle formation, that is irremovable by conventional methods of linear optics, may also be solved easily with the help of CCR lasers. The coherence control gives a possibility to smooth a speckle structure of the field at a target, because the lesser the time of a stationary interference pattern, the lesser the probability of development of all kinds of instabilities leading either to a pre-heating of target, or to breaking of stability of the target compression. So it is possible to have very high level of homogeneity of irradiation of a target without using traditional correcting systems (such as phase plates, adaptive optics and etc.).

The controllable coherence can have a pronounced effect on the active medium gain in the saturation regime, where practically all the cascade amplifiers are effective. Such an increase in the laser pulse efficiency is very important from the viewpoint of optimization of the laser facility architecture, it determines the quantity and aperture of the output cascades, which are necessary for achievement of the required laser energy, and the efficiency of the laser facility as a whole.

One more advantage of the lasers with controllable radiation coherence is a simplification of requirements to optical elements that are used. The absence of spatial filters between successive amplification cascades, the feasibility of using the elongated active elements with high gain, the absence of complex optical devices for a laser beam wavefront corrections all these allow to significantly simplify a laser scheme and to decrease the total number of optical elements used in the amplifying laser path.

Also the requirements to a precision of manufacture of optical elements and to room hygiene can be reduced.

The system of formation of the spatial-temporal characteristics of the laser radiation provides for the given pulse duration, radiation contrast, and the level of energy required for loading of the cascade pre-amplifiers. The possibility to control the coherence of the laser beams used in the ICF experiments without violation of a laser-target matching and to control the laser radiation intensity distribution in a lens focus is also demonstrated.

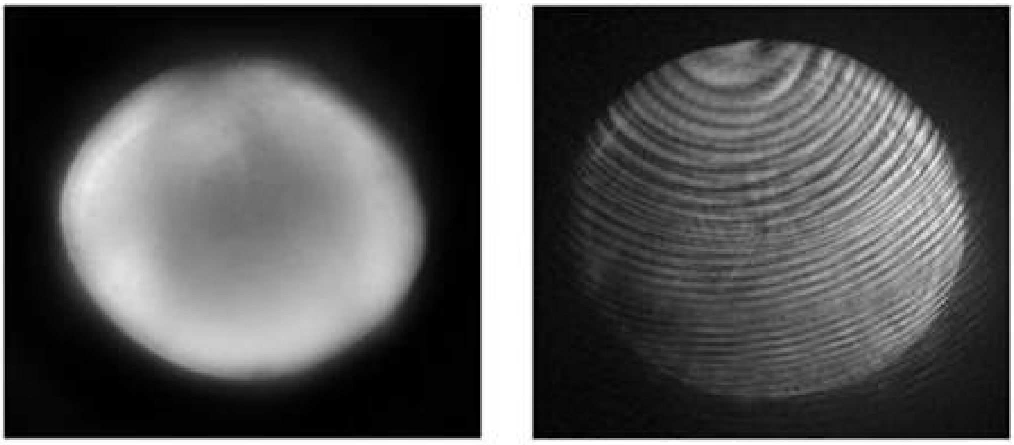


Figure 2. Laser intensity distribution (left – radiation of CCR laser, right – radiation of single-mode YAG laser).

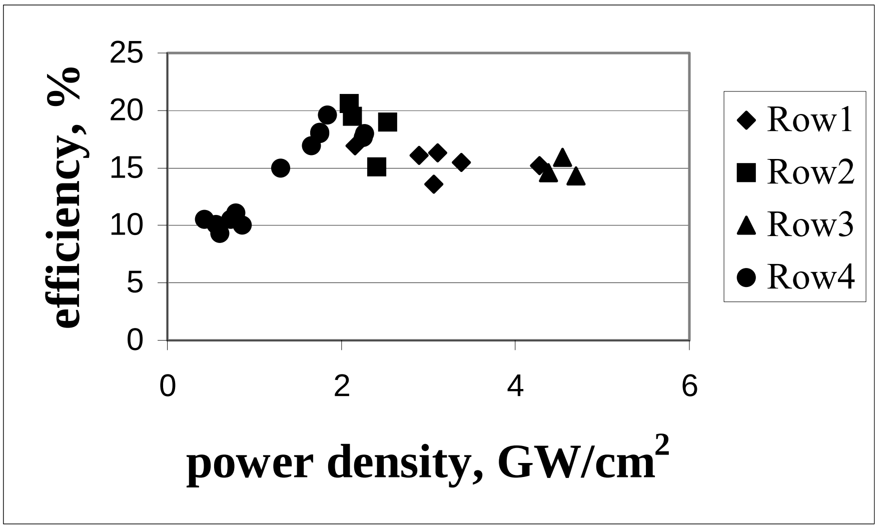
All above-mentioned advantages of laser with controllable coherence lead to conclude the cost of output laser energy unit is reduced by several times in comparison with conventional schemes of laser driver.

Figure 2 illustrates possibilities of controlling spatial-angular characteristics of the CCR laser radiation. Comparison of CCR laser intensity distribution (left) with intensity distribution of a single-mode YAG laser (right) makes it possible to conclude that in the case of CCR laser the intensity distribution is smooth, and no diffraction or interference phenomena take place.

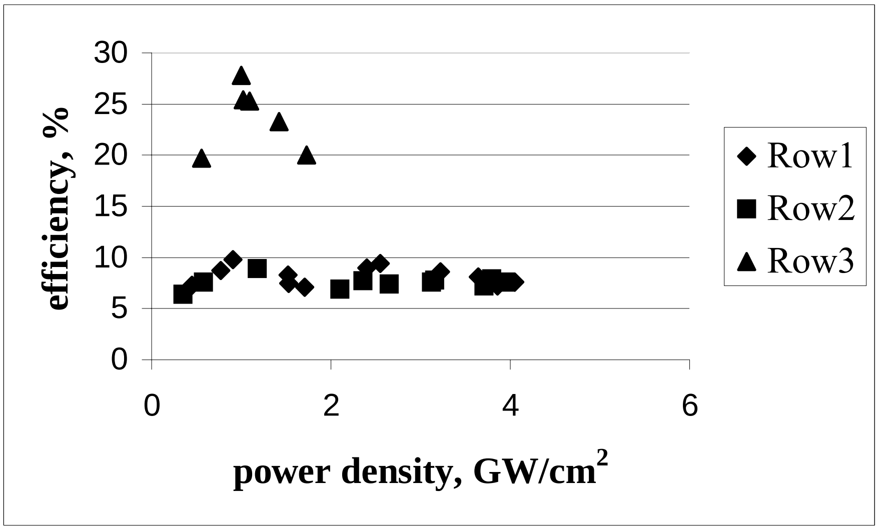
The aim of the experimental studies, the results of which are reported below, was the efficiency of conversion of a high-power neodymium laser radiation with controllable laser beam coherence into the second harmonic by a nonlinear crystal. They were performed with respect to the type of a nonlinear crystal, length of the crystal, the radiation polarization degree, and the degree of the temporal and spatial coherence in the range of laser powers from 0.5 to 10 GW/cm^2.

The efficiency of conversion of a weakly polarized radiation by the oee-type KDP crystal was studied at two values of the linewidths, ~ 3 Å and ~ 30 Å. The measurement results are represented in Figure 3a, which illustrates the dependence of the incident radiation harmonic conversion efficiency on the crystal load for these two linewidths. As seen, the maximum of coefficient of the incident radiation conversion into the second-harmonic is achieved of ~ 20% at 2 GW/cm^2 load on a crystal, and then the efficiency slowly decreases as the load increases. No considerable influence of the Linewidth value on the conversion efficiency is observed.

The angular distribution of the second harmonic is more than twice as narrower than pumping wave radiation pattern. This result agrees well with angular width of the synchronism for the used crystal. In the near field the radiation field distribution is close to the distribution of a supergaussian beam type. The radiation power density is practically constant both at the fundamental and second-harmonic frequencies by a beam aperture, no small-scale perturbations are present, and no diffraction bands are observed.



3a



3b

Figure 3a. Dependence of the conversion efficiency on the oee-type 40-mm long KDP crystal load for different diameters of a forming diaphragm d_f (Row 1 – d_f = 3 mm, $\Delta\lambda \approx 3$ Å, Row 2 – d_f = 5 mm, $\Delta\lambda \approx 3$ Å, Row 3 – d_f = 8 mm, $\Delta\lambda \approx 3$ Å, Row 4 - $\Delta\lambda \approx 30$ Å).

Figure 3b. Dependence of the conversion efficiency on the ooe-type KDP crystal versus the pump load. (Row 1 – 15 mm-long crystal, non-polarized radiation, Row 2 – 19 mm-long crystal, non-polarized radiation, Row 3 – 19 mm-long crystal, polarized radiation).

Figure 3b is illustrated dependence of the conversion efficiency from the polarization degree. As seen, in the case of the non-polarized pump radiation the conversion efficiency for KDP crystal of ooe type and 15 mm length does not practically change within a wide range of laser power densities from 0.5 to 5 GW/cm^2, and does not exceed 9%. The same results were obtained when using the KDP crystal of ooe type and 19 mm length, under similar conditions of the crystal irradiation. It easy to see from Figure 3b that the increasing of the pump polarization degree leads to the increasing of the conversion efficiency up to the value 30%.

3. INTERACTION OF CCR LASER WITH MATTER

To investigate an efficiency of interaction of a CCR laser radiation with matter there were carried out a lot of experiments. Under these experiments the plane target made of various materials (Cu, Al, Ti, Fe, Be, Mg, Ta, and other) is illuminated by the CCR laser radiation.

The investigation results on light scattering are shown in Figures 4, 5.

It is possible to see from Figure 4 that practically all incident energy is absorbed by arising plasma. Reflection coefficient is very small and does not exceed 1 %. As to angular distribution of the scattering radiation it may be seen from Figure 5 that the radiation with wavelength 1.06 μm is concentrated in a cone with the cone angle 40º, but the scattering of the radiation with wave length 0.53 μm is practically diffusive. The observed high absorption of CCR laser radiation leads to effective plasma heating, and according X-ray measurements (see Figure 6) the plasma temperature may achieve 500 eV.

Simultaneously we recorded the generation of harmonics $(3/2)\omega_0$, $2\omega_0$, and $(5/2)\omega_0$ of laser frequency ω_0 (see Figure 7).

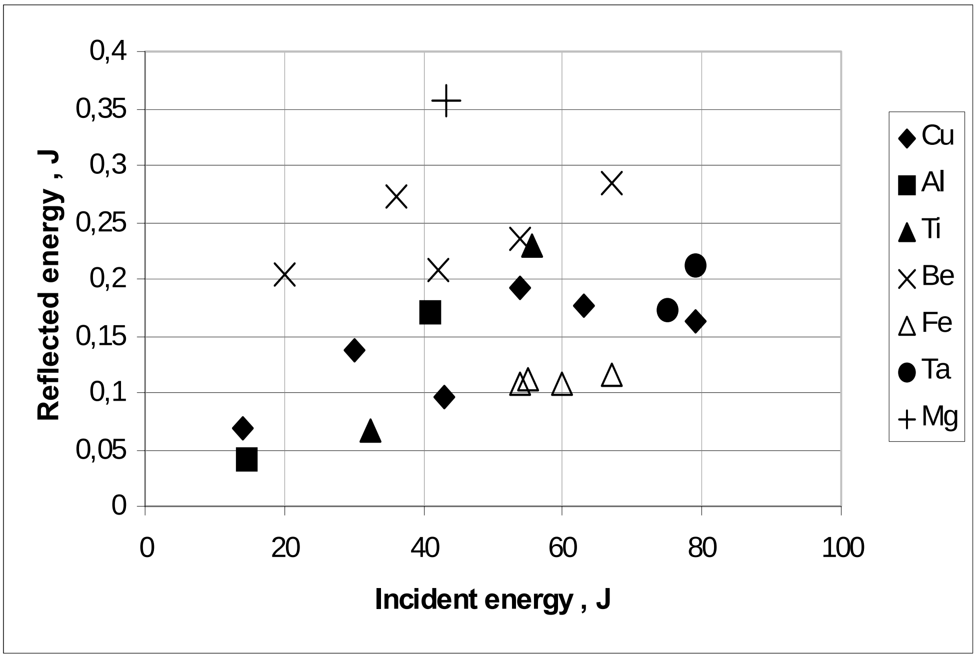


Figure 4. Dependence of energy reflected into aperture of focusing lens on the incident laser energy.

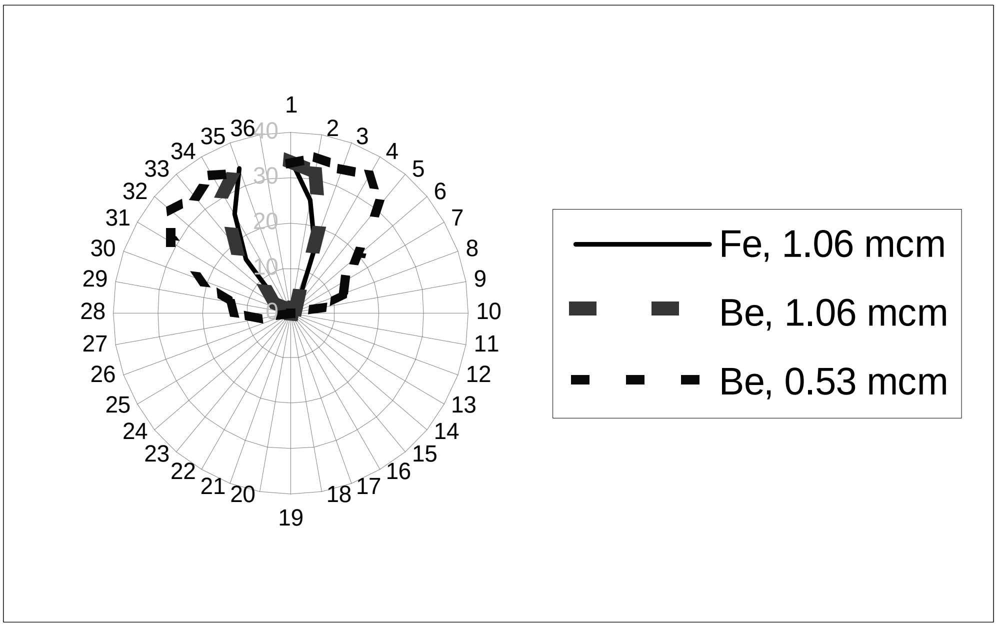


Figure 5. Angular distribution of radiation scattered at the fundamental frequency (1.06 μm) and the second harmonic frequency (0.53 μm).

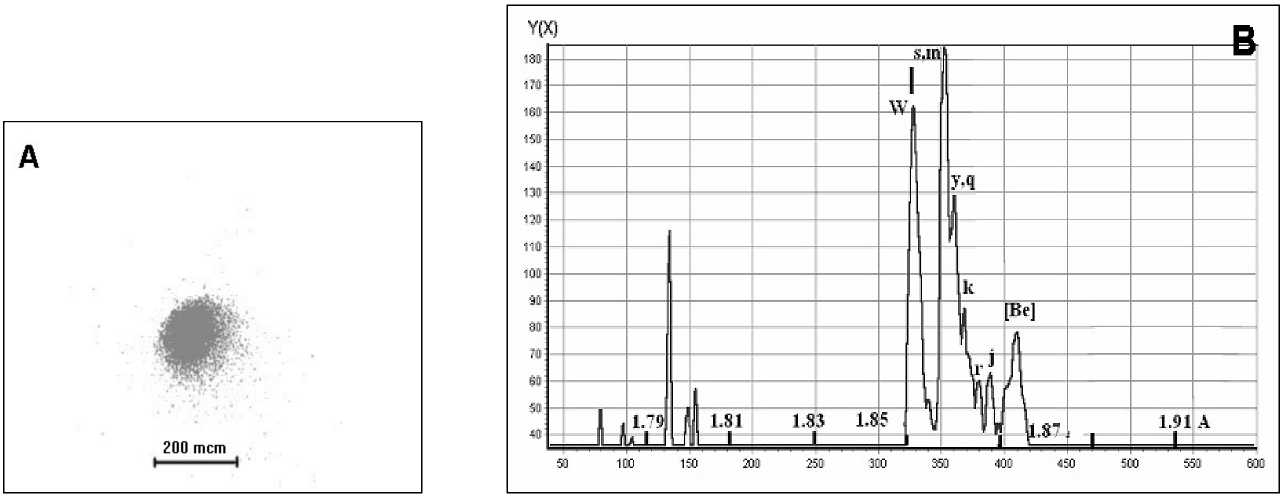


Figure 6. A - Image of laser plasma in X-ray radiation received by means of pinhole camera with apertures 14 μm. B - X-ray spectrum of laser plasma radiation from Fe target. Density power of heating laser radiation ~ $2{\cdot}10^{14}$ W/cm^2, $T_e \sim 300$ eV.

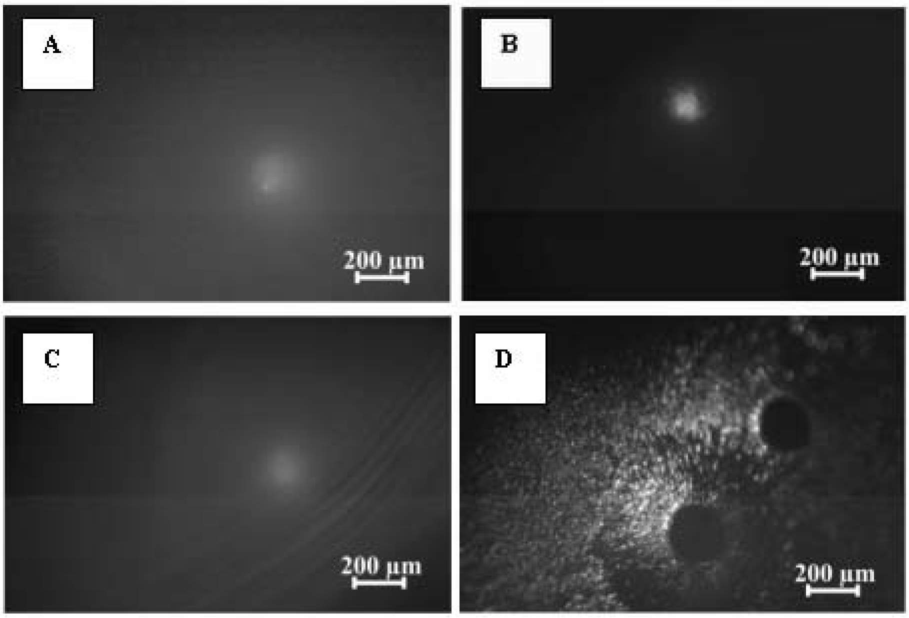


Figure 7. Images of laser plasma in $(3/2)\omega_0$ (C), $2\omega_0$ (D), and $(5/2)\omega_0$ (B) radiation, correspondingly ((A) – craters in Cu target, density power of heating laser radiation ~ $2{\cdot}10^{14}$ W/cm^2, $T_e \sim 300$ eV).

Results concerning of $2\omega_0$ harmonic generation are shown in Figure 8. It may be seen that the generation of second harmonics originates from space region with size about 180 μm (laser beam spot on target – $d_{sp} \approx 180$ μm), spectrum of this harmonic has complicate form, and with time a line of $2\omega_0$ harmonic shifts to the blue side. This means that during a laser pulse the velocity of expanding plasma is increasing.

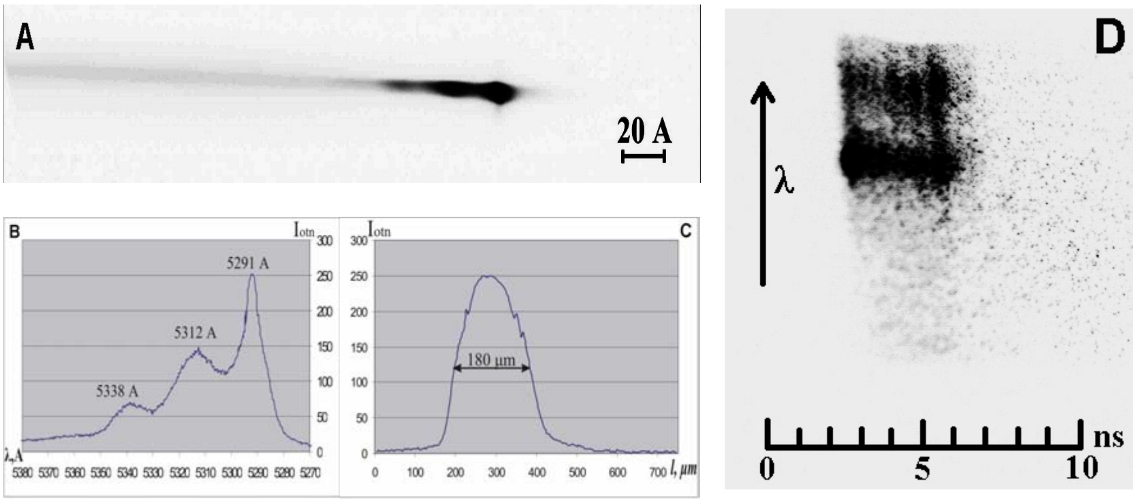


Figure 8. The second harmonic generation. A – spectrum of $2\omega_0$, B – spectral distribution, C – spatial distribution, D – time-resolved spectrum of $2\omega_0$.

The carried out experiments on the harmonic generation have shown that the recorded scattered radiation and the harmonics are a very effective method to measure the local parameters of plasma such as a plasma velocity and plasma temperature. The investigation of the harmonic radiation spatial distribution may also be an attractive method to analyze the spatial distribution of an incident laser beam in a plasma, and therefore to determine the efficiency of a laser-plasma interaction. For example, an observed very smooth spatial distribution of a second harmonic clearly indicates a high degree of a spatial distribution uniformity of the incident laser beam near a critical density plane.

4. CONCLUSIONS

The performed studies demonstrate that the laser based on generation and amplification of radiation with controllable coherence (CCR laser) has a number of advantages as compared to conventional schemes of lasers.

The experiments on a triggered laser module justified the validity of the proposed principles of designing CCR laser. The possibility of suppression of small-scale self-focusing of a laser beam without application of a spatial filtration and smoothing of a speckle structure of the field at the target lead to a very high level of homogeneity of irradiation of a target without using traditional correcting systems (such as phase plates, adaptive optics and etc.). The feasibility of the laser beam coherence control without breaking the laser-target system matching and the laser intensity distribution control has been demonstrated.

CCR laser radiation may be effectively transformed by KDP crystal into second harmonic, and the intensity distribution of this harmonic is also very smooth and has no speckles. An efficiency of such a conversion may achieve 30-50% depending on the experimental conditions.

Study of such important laser-matter interaction phenomena as absorption and scattering of laser radiation, the laser radiation harmonic generation, X-ray generation, crater formation and plasma expansion under laser pulse has also been shown the effective interaction of CCR laser radiation with matter.

5. ACKNOWLEDGMENTS

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