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Results of experimental investigations on the atomic and nuclear processes going in picosecond laser plasma

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The purpose of our investigation is to verify experimentally the basic results obtained with the magnetoactive laser plasma theory [1]. The experiments were performed on the NEODIM laser setup outlined in Fig.1. The laser setup consists of the following main components: start system, amplification path, compressor, vacuum target chamber, laser radiation diagnostic system, and plasma diagnostic complex.

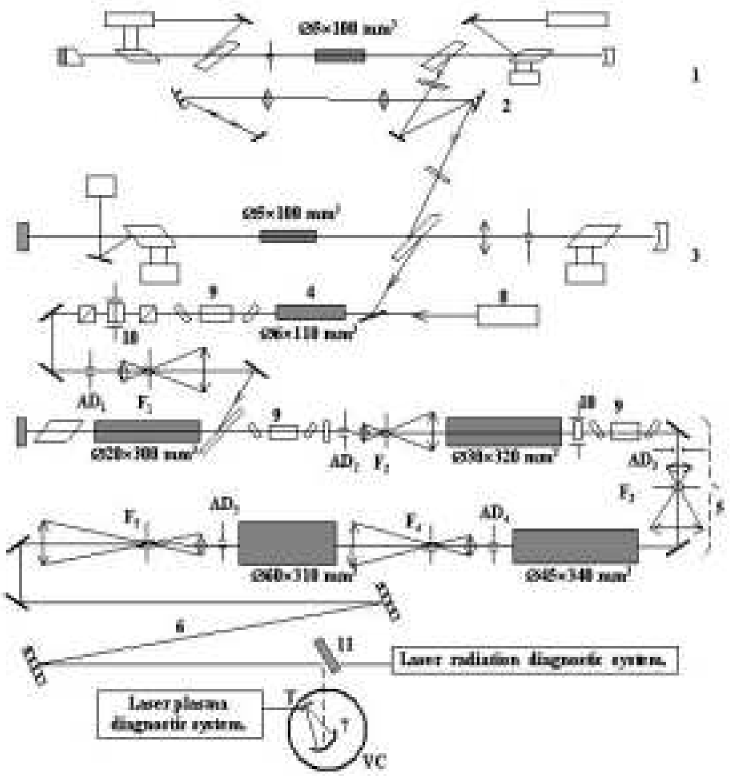

Fig. 1. NEODIM laser setup scheme.

1 – master generator;
2 – stretcher;
3 – regenerative amplifier;
4 – pre-amplifier ∅6×110 mm^3;
5 – amplifying system with four amplifiers;
6 – compressor;
7 – focusing system;
8 – adjustment laser;
9 – Faraday isolators;
10 – Pokkels sells;
11 – mirror;
AD_i – aperture diaphragms;
F_i – vacuum spatial filters;
T – target;
VC – vacuum chamber.

Measurements showed that at the laser setup exit the laser beam with the diameter of 120 mm has the laser pulse energy of up to 12 J at pulse duration of 1.5 picoseconds.

From the laser setup exit, the laser beam goes to the vacuum target chamber where it is focused at the target into a spot 15 μm in diameter with an off-axis parabolic mirror. It provides the intensity of 10^{18} W/cm^2.

For our laser plasma investigations we developed the diagnostic complex which consists of the X-ray spectrographs with spatial resolution; the activation neutron detector; the allwave neutron detectors based on ^{3}He counters; the neutron- and γ-detectors based on stilbene or plastic scintillators; the γ-detector based on NaI(Tl) crystal; and the track detectors.

Our experimental setup is outlined in Fig.2. Using the off-axis parabolic mirror, the laser beam was focused on different targets at 20^0 with respect to the target normal. As a target, we used solid-state plates made of deuterated polyethylene $(CD_2)_n$, 150 to 350 μm thick; plates made of deuterated berillium BeD 500 μm thick; targets based on $(CD_2)_n$ powder with the density of $\rho = 0.1$ g/cm^3; as well as targets made of teflon, berillium, aluminum, magnesium, copper or zinc.

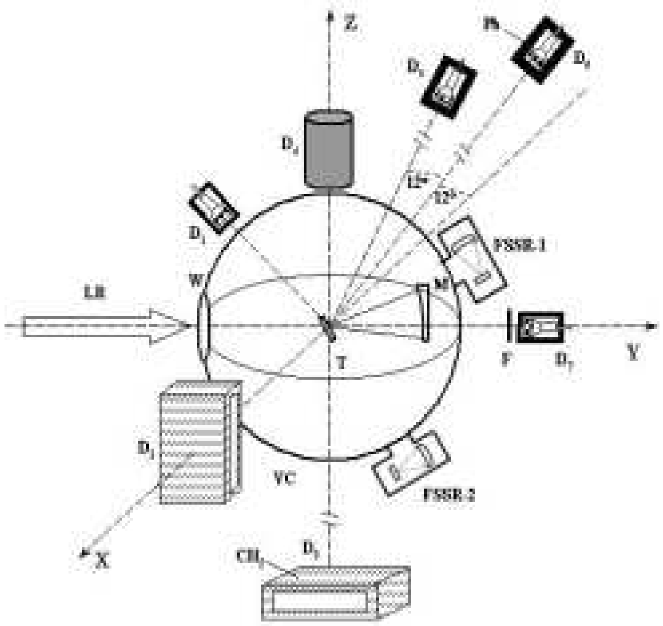

Fig. 2. Experimental setup scheme.
T – target; VC – vacuum chamber; W – vacuum chamber window; M – off-axis parabolic mirror; LR – laser radiation; F – Pb filters; D_1 – scintillation detector based on stylbene $C_{14}H_{12}$ crystal; D_2, D_3 – neutron radiation detectors based on ^{3}He counters; D_4 – highsensitive neutron activation detector; D_5, D_6, D_7 – detectors based on plastic scintillators; FSSR-1, FSSR-2 – X-ray Focusing Spectrographs with Spatial Resolution.
Target T, mirror M and detectors D_1, D_2, D_5, D_6 , FSSR-1, FSSR-2 placed in one plane XY.

Control of laser radiation intensity was made by measurement of hard X-radiation with the detector D_1 based on stilbene crystal. We did not change position of D_1 detector and its lead protection throughout the experiments. To monitor laser plasma neutron radiation, we used two detectors - D_2 and D_3 – based on helium counters, which were placed at 20 cm behind the target (D_2 detector) and at 1 m under the target (D_3 detector). D_2 detector performed neutron radiation monitoring along the laser beam, while D_3 detector – across the laser beam. To determine neutron yield we used highly sensitive activation neutron detector D_4 placed at 25 cm above the target. To estimate neutron energy distribution with the time-of-flight method we used two detectors - D_5 and D_6 – based on plastic scintillators. D_5 detector was placed at 2.8 m from the target, while D_6 detectors – at 4.1 m from the target. Both D_5 and D_6 detectors were placed within lead housings with the walls 10 cm thick to provide protection against γ-radiation from laser plasma.

To estimate the maximum energy of hard X-radiation and the numbers of γ-quanta we used D_7 detector based on plastic scintillator placed at 1 m from the target. In front of the detector we installed lead filters of different thicknesses. Lateral surfaces of D_7 detector were protected with lead protection 1.5 cm thick.

To register plasma X-radiation we used two FSSR spectrographs with spatial resolution.

In Fig.3a we present oscillograms of pulses from the neutron detectors based on helium counters (the upper ray corresponds to D_3 detector digital output, while the lower one – to D_2 digital detector). The data were obtained when detecting neutrons from $(CD_2)_n$ target 350 micrometers thick at laser radiation intensity of 10^{18} W/cm^2.

a) b)

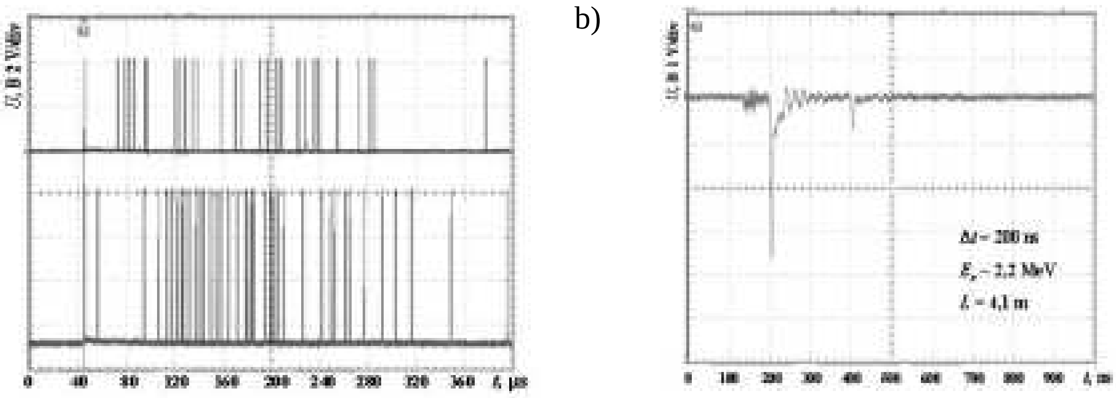

Fig. 3. Experimental oscillograms.

Detection of neutrons and estimation of their energy were made using the time-of-flight method.

Fig. 3b illustrates oscillogram of the signals from the detector based on D_6 plastic scintillator. It can be seen that except for the first pulse caused by γ-detection, there is another one delayed by 200 ns with respect to the first one. The second pulse is associated with detection of neutrons having energy of about 2.2 MeV. These data confirm that the neutrons detected in the experiments are not of thermal nature but result from fusion reaction $D + D \rightarrow n(2.45 MeV) + {}^3He$.

It is interesting to compare our results for neutron yield from laser plasma on solid-state deuterated $(CD_2)_n$ targets with those obtained in other research laboratories. Fig. 4 presents measurements of neutron yield with solid-state deuterated $(CD_2)_n$ targets at different laser pulse intensity and duration (the triangles correspond to lasers with the duration of 50 to 300 femtoseconds, while the circles correspond to lasers of picosecond duration). Our results are indicated with circles N6, 7. It can be seen that in terms of maximum neutron yield on solid-state deuterated $(CD_2)_n$ targets it is preferably to use lasers of picosecond duration. Note as well that the threshold intensity of laser radiation to obtain sufficiently large neutron yield of order of 10^4 per a pulse is about 10^{18} W/cm^2 for femtosecond lasers, while for picosecond lasers – about 10^{17} W/cm^2.

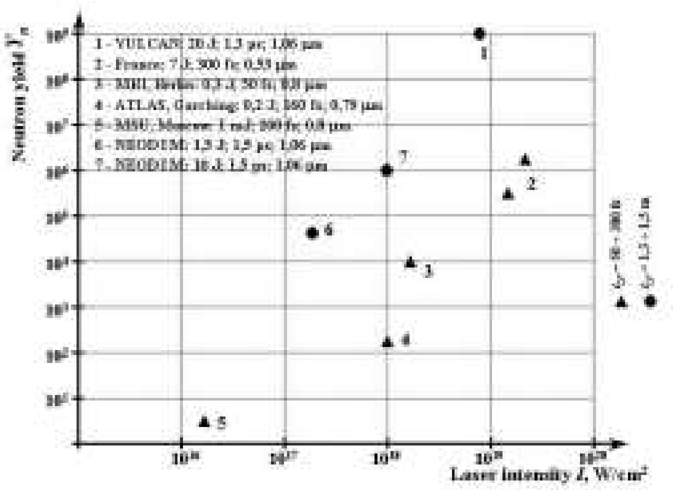

Fig. 4. Measurements of neutron yield.

The fact that picosecond laser plasma has sufficiently high temperature even at laser radiation intensity of order of 10^{17} W/cm^2 is confirmed by our experimental results obtained for detection of fast ions, fast electrons and super-strong magnetic fields.

The summary of our experimental investigations are:

1. Neutron generation in laser plasma has been investigated at intensities from 10^{17} to 10^{18} W/cm^2 with different deuterated targets.
2. Fast ion distribution has been obtained at $I \approx 3{\cdot}10^{17}$ W/cm^2. The part of fast ions having energy higher than 10 KeV is about 20%.
3. Maximum electron energy (cutoff energy) $E_{e,MAX} \approx 650$ KeV has been estimated at $I \approx 3{\cdot}10^{17}$ W/cm^2.
4. Spectral method for local measurement of super-strong magnetic fields in laser plasma has been developed based on registration of F IX ion Ly_α X-ray line satellites. Values of magnetic field intensities has been found to be equal to $B \approx 40$ MG at $I \approx 2{\cdot}10^{17}$ W/cm^2 and $B \approx 60$ MG at $I \approx 3{\cdot}10^{17}$ W/cm^2.
5. Laser plasma diagnostics has been made by Mg and Al ion X-ray spectra with T_e and N_e estimation. Spectrum of highly-excited states has been investigated for N-, O-, F-like ions of Zn XXIV, XXIII, XXI.

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References

1. Belyaev V.S., Pinch-effect in laser-produced plasma, 31st EPS Conference on Plasma Physics, report P2-018.