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SOVIET DEVELOPMENTS IN LASER FUSION

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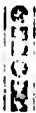
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INTRODUCTION

This is a collection of abstracts on significant Soviet work in laser fusion, dating from approximately 1969 to the present. The material was selected from the Informatics, Inc. serial publication Bibliography of Soviet Laser Developments, and includes articles directly dealing with fusion as well as related studies by authors active in the fusion field. Several abstracts have already appeared in Effects of High Power Lasers, nos. 1 and 2, or in the monthly reports on Selected Material from Soviet Technical Literature, published under this contract in 1972-1973. Items which have appeared as Russian abstracts in the Referativnyy Zhurnal series have as a rule been omitted.

The abstracts are grouped into experimental studies (plasma kinetics, plasma spectroscopy, laser design), and theoretical studies. A comprehensive bibliography and a first-author index are appended.

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1. Plasma Kinetics

Basov, N. G., S. D. Zakharov, O. N.
Krokhin, P. G. Kryukov, Yu. V. Senatskiy,
S. V. Chekalin, A. I. Fedosimov, and M. Ya.
Shchelev. Study of heating a laser plasma
formed by ultrashort laser pulses. KSpF,
no. 8, 1970, 48-52.

An experiment is described on heating an LiD target in vacuo by ultrashort pulses from an Nd glass laser. The nominal pulse width was 10 nsec at a 15 nsec repetition rate; however spikes of the order of 1 or 2 nsec appeared in each pulse, with energies in the range of 0.1 joule. It was attempted to maximize the number of spikes and observe their particular effect on target heating.

Records were made of plasma development by shadow and Schlieren photography, using the second harmonic (0.53 μ) to illuminate the plasma region. An electrooptical converter was also used to register plasma radiation in the visible range and reflected laser radiation; plasma electron temperature was determined from its x-ray emission using a filter technique.

A detailed study of recorded data showed that the heating process was as follows: the initial spike forms a highly luminous region, expanding at 10^6 - 10^7 cm/sec to some 1 or 2×10^{-2} cm. Spikes arriving in the next few nanoseconds do not add significantly to plasma heating, but are strongly scattered; within about 4 nsec the plasma is effectively opaque. Following this the plasma transparency returned and a new portion of plasma is heated in the same manner. Converter data are given showing plasma radiation in the blue-green region as a function of spike occurrence and scattering. Fig. 1 shows examples of incident and reflected radiation to scale. Records of x-ray emission showed that T_e varied between 140-220 ev.

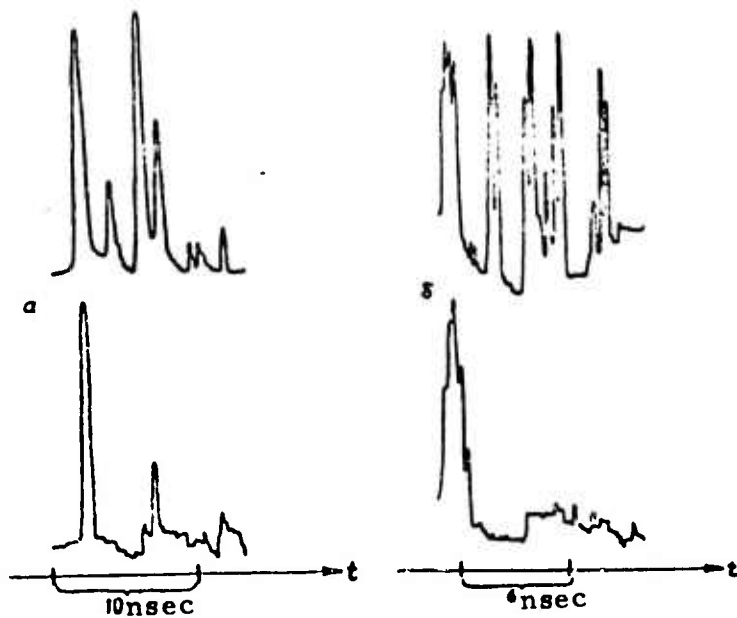


Fig. 1. Photometric records of incident (top) and reflected (bottom) laser radiation for two applied pulses.

It is evident that absorption of laser energy varies in the course of a pulse as the optical thickness of the outer plasma layer changes. Specifically, when laser frequency ω is less than plasma frequency ω_p , most of the incident radiation is reflected; whenever this is not the case, plasma heating to a high temperature can occur. Results indicate that the depth of the target layer converting to plasma is on the order of the laser wavelength.

Basov, N. G., S. D. Zakharov, O. N. Krokhin et al. Studies of plasma formed by ultrashort laser pulses. IN: Sb. Kvantovaya elektronika, no. 1, 1971, 4-28.

This is a review of the work done to date by Basov's group since their first experiments with laser heating of an LiD plasma with

picosecond pulses in 1968. Several of the early experiments with glass lasers are described, together with the techniques of photographing and analyzing the plasma flare. A theoretical discussion of heating and relaxation of electron and ion temperatures is included, which essentially reports the material of the foregoing article by Basov et al.

Dolgov-Savel'yev, G. G., and V. N. Karnyushin.
Injector of lithium hydride particles for laser
plasma experiments. PTE, no. 3, 1970, 220-222.

An electrostatic method for injection of lithium hydride particles into the focal region of a laser is described. A diagram of the injector is shown in Fig. 1. Lithium hydride particles (0.1-0.4 mm) captured

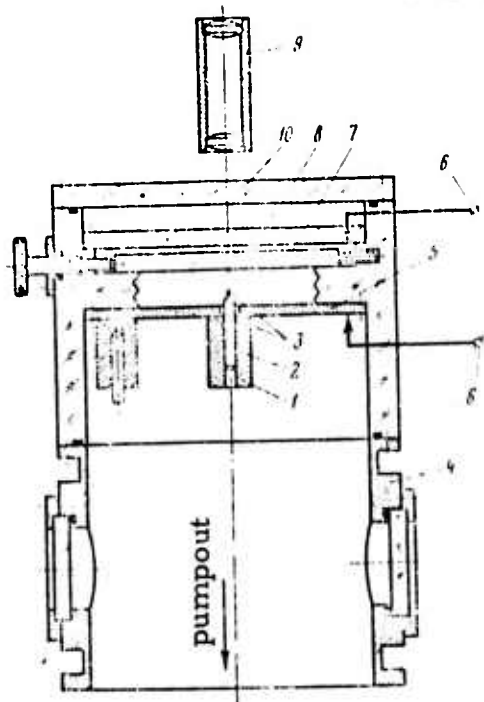


Fig. 1. Diagram of LiH injector.

1- tank, 2- feed rod, 3- LiH particles, 4- vacuum chamber, 5- lower electrode, 6- lead-in, 7- movable plate, 8- upper electrode, 9- microscope, 10- transparent lid.

by a moving feed rod (2) are injected into the space between two electrodes (6 and 8). Subsequently an electrostatic field of 10^3 v/cm is produced and the charged LiH particles are trapped by a flat glass plate (7). After tank (1) is removed the particles are injected into the vacuum chamber (4) by applying a rectangular pulse with amplitude of ~ 30 kV and duration of ~ 0.02 sec. The entire system is evacuated to 10^{-5} torr. The particle trajectory scatter and velocity measured in the center of the vacuum chamber were ~ 0.2 rad and ~ 2.5 m/sec, respectively; their transit distance was 20 cm.

The arrangement used in the laser plasma experiments is shown in Fig. 2. The energy and power of the laser pulse were 3 j and

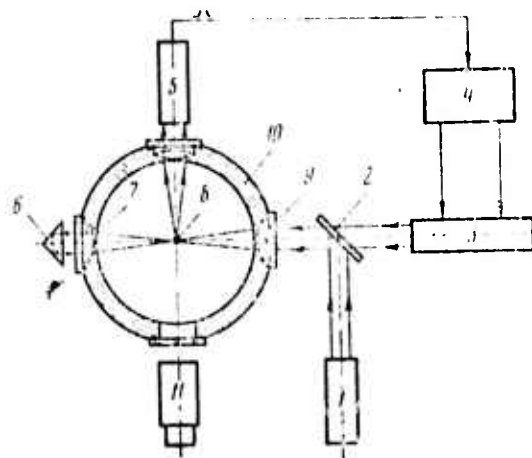


Fig. 2. Experimental diagram.

1- He-Ne laser, 2- glass plate, 3- neodymium glass laser, 4- trigger for pump pulse and Kerr cell, 5- amplifier for photocell, 6- reflector, 7- lens, 8- target, 9- lens, 10- vacuum chamber, 11- image converter.

60 Mw, respectively; focal lengths of lenses = 7 and 9-10 cm; diameter of the gas and neodymium laser beams were 0.5 and 0.8 mm. With this configuration the experimentally determined probability of the hitting a target element was about 30%. A typical record of the laser plasma radiation is given in Fig. 3.

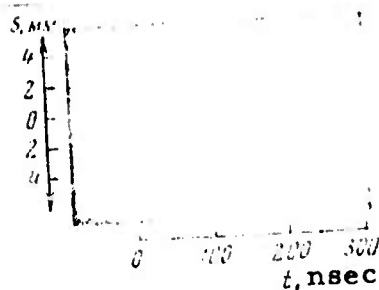


Fig. 3. Record of the laser plasma radiation.

Dolgov-Savel'yev, G. G., V. N. Karnyushin,
and V. T. Sekerin. Investigation of a laser
microplasma in the focus of two laser beams.
IN: ZhETF, v. 58, no. 2, 1970, 535-540.

The properties were studied of a plasma produced by irradiation of a LiH target by two opposed laser beams. The energy, peak power and half-width of the laser pulses were 2.5 j, 150 Mw and 15 nsec, respectively. Focal distances of the lenses were 7-7.5 cm, diameter of the focal spot 6×10^{-2} cm. Targets in the form of a parallelepiped with a height of 0.2 cm and cross-section of $0.6-2 \times 10^{-3}$ cm² were enclosed in a 10^{-5} torr vacuum. The total number of atoms in the focus was $5 \times 10^{18}-10^{19}$. The experiments were conducted with magnetic fields in the center of the chamber of $B = 0$ and $B = 12$ kgs. The experimental setup is shown in Fig. 1. Fig. 2 compares incident and transmitted pulses.

The experiments show that the laser plasma evolved in two stages:

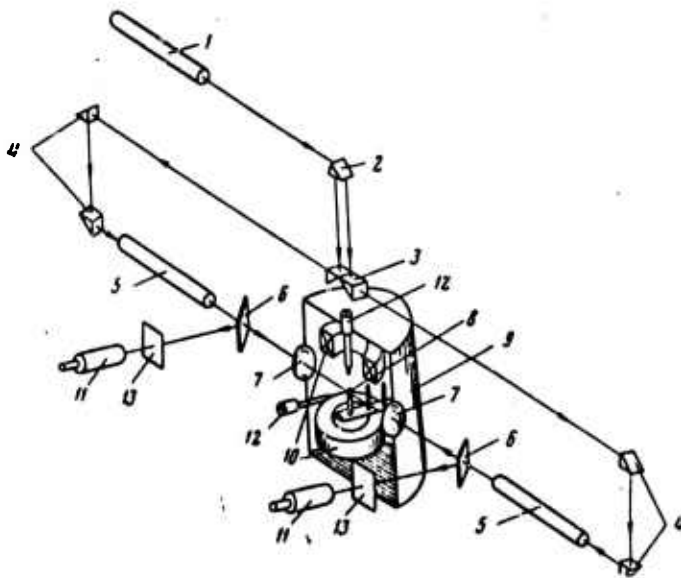


Fig. 1. Dual laser experiment.

1- master laser (Nd glass); 2, 4- deflectors;
 3- splitters; 5- amplifiers; 6- splitters;
 7- lenses; 8- target; 9- vacuum chamber;
 10- coils; 11- photocell; 12, electric probes;
 13- attenuator.

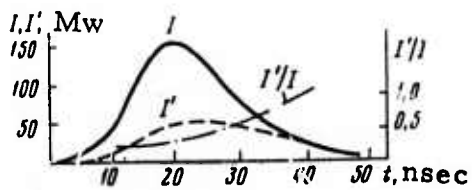


Fig. 2. Intensity of incident I and transmitted I' laser pulse.

First stage. In this stage a bright luminous central zone with a sharp boundary propagating at 2×10^6 cm/sec is observed. The outer layers of the zone absorb laser emission and produce a flux of fast weakly-radiating plasma diffusing with a velocity $\approx 4 \times 10^7$ cm/sec. An external magnetic field does not affect the plasma dynamics in this stage.

Second stage. This stage is characterized by the gas dynamic diffusion of the central zone after the end of the laser pulse. The boundary of the zone becomes less bright, and propagates with a radial velocity of about 6×10^6 cm/sec in the absence of a magnetic field. Applying an external magnetic field causes an order of magnitude drop in radial velocity. The duration of the radiation in the plasma spectral lines increases by a factor of 2-3.

It was also concluded that the plasma develops more symmetrically in the cited case than in the case of a single laser beam.

Generalov, N. A., G. I. Kozlov, and Yu. P. Rayzer. Nonequilibrium states and variation in absorptive capabilities of a plasma from the effect of powerful optical pulses. PMTF, no. 3, 1970, 27-37.

This paper gives an extended analysis of test results reported previously by the authors on laser absorption in plasma (ZhETF Pis'ma, v. 8, no. 3, 1968; ZhETF, v. 56, no. 3, 1969; PMTF, no. 1, 1970). Their experiments have shown that absorptive capacity of a plasma depends on incident beam intensity, and generally will vary in a non-monotonic manner. The analysis investigates the kinetics of heating, ionization and absorption of optical energy for a variety of plasma and laser parameters. A treatment of this sort is considered essential for explaining certain phenomena of interest such as the self-shielding effect of a laser-generated plasma on the solid surface beneath it. The theoretical results agree adequately with the cited experimental findings.

Generalov, N. A., V. P. Zimakov, G. I. Kozlov, V. A. Masyukov, and Yu. P. Rayzer. Continuous hot optical discharge. ZhETF P, v. 11, 1970, 447-449.

The authors claim here the first continuous hot plasma generator, which uses a gas ignited and fed by two different lasers. The plasma region was maintained within the center of an enclosed gas volume, thus becoming the "optical plasmatron" suggested earlier by Rayzer (ZhETF P, v. 11, 1970, 195). The working gas was xenon in a steel vessel at varying pressures up to 10 atm. Initial breakdown was made by a Q-switched CO₂ laser, developing

10 kw, 0.3-1.5 μ s pulses at a 50-250 Hz firing rate. The sustaining laser was a standard Lund 100 type, whose beam intersected the firing beam at right angles; it operated at 100 ma, 150 w, and was focused to a beam diameter of 0.08 mm in the plasma. Maintaining beam intersection and focal points was critical to the experiment, and admittedly complicated the method. However, this technique gives maximum flexibility in ignition frequency and duration, and furthermore does not contaminate the discharge region with electrode debris as is the usual case. The authors maintained a xenon plasma for periods of 10 minutes or more, terminating it only because of heating of the container, which was uncooled. A pressure threshold of 3 atm was determined for plasma generation; plasma shape and location were variable with increasing pressures. From i-r absorption data the plasma temperature was found to be about 14,000^o K. This experiment was a variant of one reported earlier by Bunkin et al (Laser spark in the "slow burning" mode. ZhETF P, v. 9, no. 11, 1969, 609), in which the combustion phenomenon was obtained with a neodymium laser in atmospheric air. Combustion duration on the order of a millisecond was obtained at densities of 10^7 w/cm² under conditions where the density for optical breakdown would have been 10^9 w/cm².

Krasyuk, I. K., P. P. Pashinin, and A. M. Prokhorov. Experimental observation of stimulated Compton absorption of laser emission in a spark. ZhETF P, v. 12, 1970, 439-442.

An experiment is described which was designed to demonstrate the predominance of stimulated Compton absorption of laser energy in a plasma, at sufficiently high beam intensities. The test was based on the theory that the scattered spectrum of laser light passing through a plasma will be generally shifted to longer wavelengths, which is difficult to attribute to other than Compton absorption. The test method is shown in Figure 1.

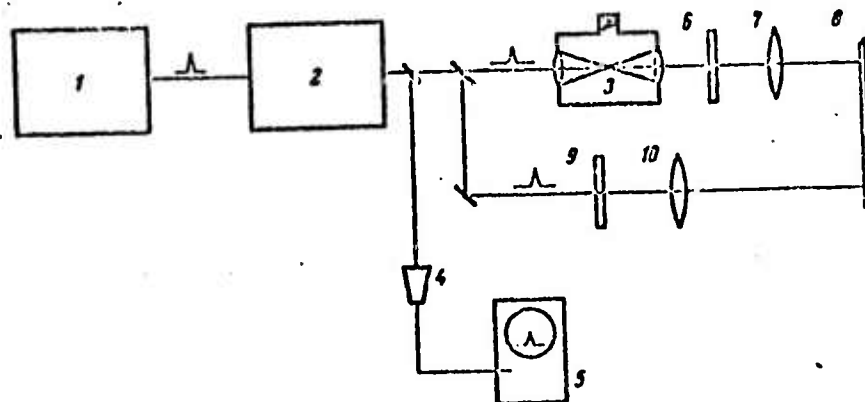


Fig. 1. Compton absorption experiment.

1- ruby laser; 2- amplifier; 3- test vessel
 4- photoelement; 5- CRO; 6, 9- filters;
 7, 10- collimators; 8- spectrograph input.

Amplified picosecond pulses from a ruby laser were focused in a helium vessel (3) to generate a spark; pulse width was 50 ns, with a density at the focal point of $2 \times 10^{14} \text{ w/cm}^2$. The scattered spectrum of the transmitted beam was simultaneously compared to the original pulse spectrum in spectrograph (8). Typical shifts are seen in Figure 2 for helium and for a 150 Å thick aluminum foil target; the mean values of absorption coefficients were found to be $\alpha = 0.26 \times 10^{-2}/\text{cm}$ and $2 \times 10^{-2}/\text{cm}$, respectively. In general the experimental values of α were less than those predicted by theory; however, the results are cited as evidence of the major role played by Compton absorption in this type of laser-plasma interaction.

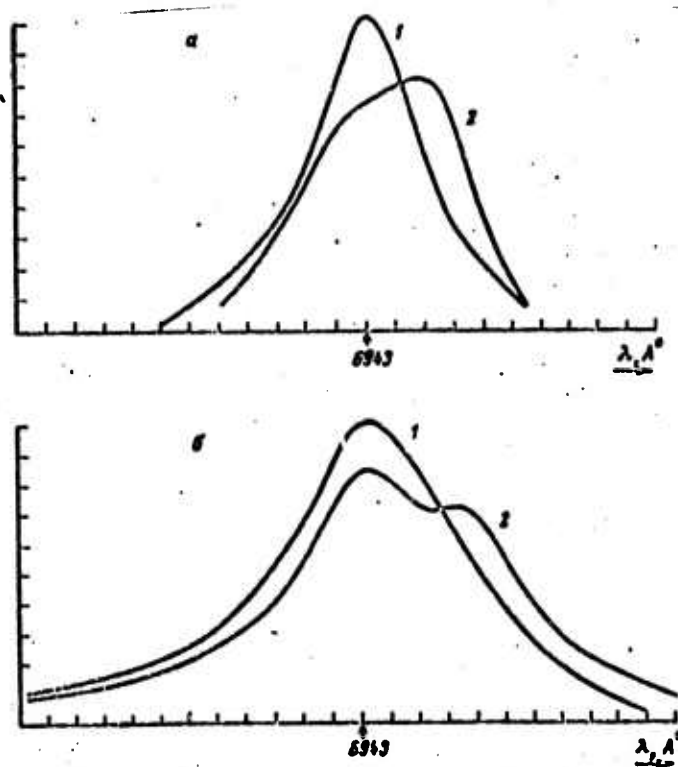


Fig. 2. Spectral shift in a laser plasma.
 a- He plasma; b- Al foil; 1- incident radiation;
 2- transmitted radiation.

Askar'yan, G. A., and V. K. Stepanov.
Simultaneous extended action of a powerful
 optical flux on matter. ZhETF, v. 59, no.
 2, 1970, 366-367.

In optical beam-target or gas breakdown tests the laser beam is typically focused by spherical lenses to the desired spot size. A departure from this is considered here by Askar'yan and Stepanov, where they briefly describe beam-target experiments using a two-dimensional or slit-shaped

incident beam, formed by cylindrical rather than spherical lenses. In the tests cited a Q-switched neodymium laser with a 6 cm cylindrical lens was used to produce an extended optical breakdown in argon and other gases at pressures up to 20 atm; an unswitched laser was also used to form slits in metal targets. An inherent advantage of this method is that the focused beam area attainable with a cylindrical lens is substantially greater than that for a spherical lens -- by a factor of 100 in the cited case. This paper mostly emphasizes the practical arguments for line-focused beams in material processing; however, in the case of line breakdown in gas or on a dielectric surface, it is also pointed out that plasma propagation velocity can exceed light velocity, which suggests a number of interesting theoretical and practical possibilities.

Bunkin, F. V., I. K. Krasnyuk, V. M. Marchenko, P. P. Pashinin, and A. M. Prokhorov. Structural study of a spark generated by a focused picosecond laser pulse in gas. ZhETF, v. 60, no. 4, 1971, 1326-1331.

With reference to an earlier paper by Krasnyuk et al (ZhETF, v. 58, no. 5, 1970, 1606), the authors have conducted further tests to identify particular characteristics of picosecond optical breakdown in air, Ar and N₂ at atmospheric pressure. A ruby laser in the ring configuration of Figure 1 was used, generating pulse trains with individual pulse widths of 20-100 ps. Additional recording equipment was used to get an exact time relationship of spark initiation, propagation and geometry with excitation pulse, lens focal length and focused spot dimensions. Typical photos of spark configuration are given, as well as streak photos of spark development. From the latter it can be seen that, following spark initiation, discrete

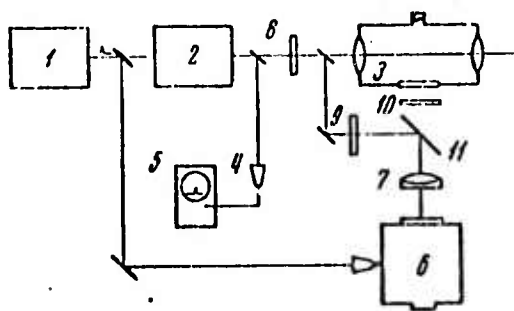


Fig. 1. Gas breakdown experiment.

1- ruby; 2- amplifier; 3- test chamber;
 4- photoelement; 5- oscilloscope; 6- electron-
 optical cameras; 7- lens; 8, 9, 10- filters;
 11- deflector.

subsparks continued to develop up to 160 ps after the end of the laser pulse. The authors note a lower threshold with their long-focus lens that the value reported by Krasnyuk et al at $f = 2$ cm (3.5×10^{12} w/cm² vs 1.5×10^{14} w/cm², respectively). The results confirm that self-focusing is responsible for the discrete spark structure observed.

Kaytmazov, S. D., A. A. Medvedev, and
 A. M. Prokhorov. Effect of a 400 koe magnetic
 field on the plasma of a laser spark. ZhETF P.
 v. 14, 1971, 314-316.

An experiment is briefly described in which the controlling effect is studied of an external magnetic field on the geometry of a laser spark plasma. Two conditions must evidently be met for field control of spark geometry, namely (1) field pressure must exceed gas kinetic pressure in the plasma, and (2) the skin layer should not exceed spark radius, r . This means that the external field must be sufficiently great that on lowering

of plasma pressure to the magnetic pressure level, plasma temperature still remains high enough to preclude diffusion in the external field. The corresponding threshold for field control in the present case was calculated to be on the order of 300 koe. Tests to corroborate this were run at levels up to 500 koe, using a transformer-fed one-turn coil of 0.8 cm dia. instead of the usual capacitor bank. A 100 μ sec field pulse was thus generated, which simplified the requirement of exact synchronization of laser spark and field pulse. Tests were run in ambient air, using a neodymium glass laser at 2--3 j in both giant pulse and spike regimes to produce breakdown. The comparative effect of the field is seen in Fig. 1, where the spark is confined to a cylindrical form with a smooth boundary. In both laser regimes

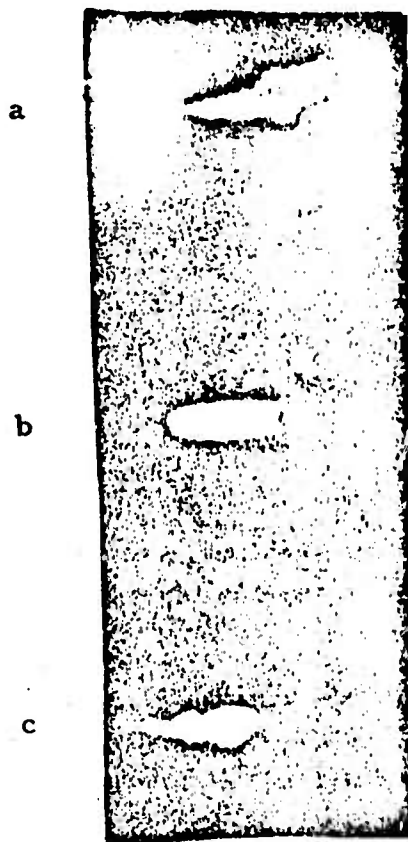


Fig. 1. Field effect on laser spark.
a, c- no applied field; b- field applied.

the field increased spark axial length by about 1.5 times; it follows that this formation should retard plasma cooling. Nominal spark parameters of $r = 0.1$ cm and time constant $\tau = 3 \times 10^{-7}$ sec led to the conclusion that the plasma temperature attained was at least 6×10^5 deg. K.

Kazakov, A. Ye., I. K. Krasnyuk, P. P. Pashinin,
and A. M. Prokhorov. Experimental observation
of laser radiation amplification from the interaction
of opposed laser beams in a plasma. ZhETF P,
v. 14, 1971, 416-418.

Experimental data are briefly discussed on the effects of focusing opposed laser beams in an argon plasma. The test configuration (Fig. 1) used a monopulse laser at 6943 \AA and 20-100 nsec duration, split

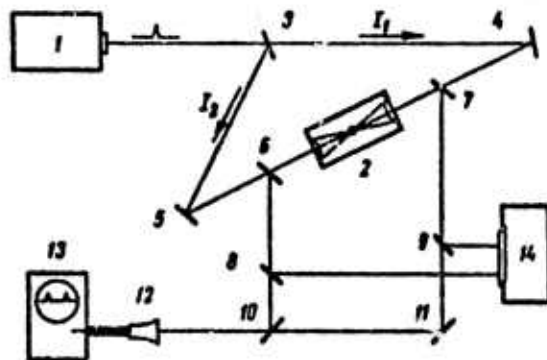


Fig. 1. Colliding beam experiment.

1 - laser; 2 - Ar chamber; 3--11 - splitting,
deflecting optics; 12 - coax; 13 - scope, 0.2
ns resolution; 14 - spectrograph.

and simultaneously focused at $f = 2$ cm through opposite faces of the argon chamber. The optics were assigned such that $I_2 < I_1$ by varying amounts, but both were above breakdown threshold. Records of exit intensities and

spectra of the two pulses showed two distinct effects: the weaker pulse was amplified by the stronger, and also underwent a spectral broadening. These effects were more pronounced with larger initial disparity between I_1 and I_2 intensities. An example given shows I_2 increased by a factor of 1.32, where initially $I_2 = 0.2 I_1$. Stimulated Compton scattering is suggested as the main mechanism for these results, and calculations on this assumption show a good agreement with actual gain figures for the weaker pulse. The spectral change in I_2 is not explained and must be clarified by additional tests.

Aglitskiy, Ye. V., V. A. Boyko, S. M. Zakharov, and G. V. Sklizkov. Determining diffusion rate and electron density profile in a laser plasma from measurements in the vacuum u-v range. KSpF, no. 6, 1971, 3-7.

The authors note that studies of laser fusion demand a knowledge of the gas dynamic parameters of the laser plasma developed. In particular the region with size on the order of the focused laser spot was observed for electron density N_e and flare propagation rate, determined spectrographically. An Nd glass laser was used on a carbon target in vacuo, developing 15 ns pulses at 10 j. A 4x image of the flare was projected via a spherical indium mirror onto the slit of a DFS-29 spectrograph.

Distribution of N_e vs. distance from the target was determined from Stark broadening based on C^{VI} transitions $\lambda_1 = 520.6 \text{ \AA}$ (3-4 transition) and $\lambda_2 = 3434 \text{ \AA}$ (7-8 transition). Averaged results over the beam axis are shown in Fig. 1 for two elapsed times, and corroborate the earlier interferometry curves of Basov.

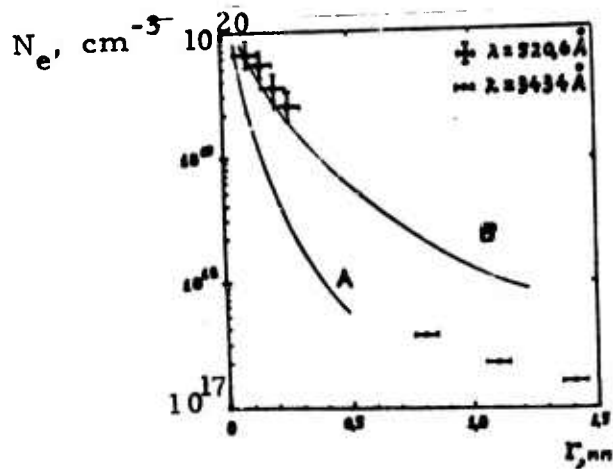


Fig. 1. Electron density profile $N_e(r)$ from Stark broadening of C^{VI} lines. Curves are from Basov et al., FIAN Preprint no. 79, 1970.

A - 10 ns, B - 36 ns after pulse start.

Plasma expansion rate was deduced from Doppler shift in absorption lines, using the resonant doublet of C^{IV} , $\lambda_1 = 1548.2 \text{ \AA}$ and $\lambda_2 = 1550.77 \text{ \AA}$. This spectrographic data together with data of Basov et al (DAN, v. 196, 1970, 1248) was used to get the velocity profile of Fig. 2. It

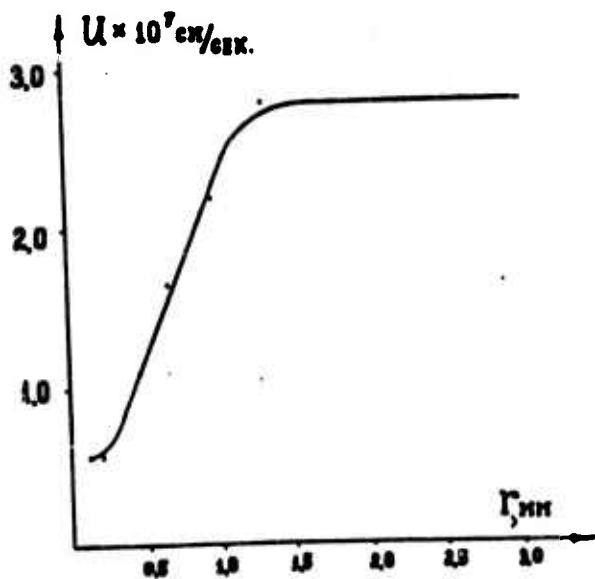


Fig. 2. Velocity profile of gas dynamic plasma motion.

is noted that the acceleration interval occurs over a dimensional range on the order of the focused spot diameter.

Gribkov, V. A., V. Ya. Nikulin, and G. V. Sklizkov. Increased plasma density from the collision of laser flares. *Kratkiye soobshcheniya po fizike*, no. 2, 1971, 45-49.

An experiment is described in which two opposed plasma flares are generated simultaneously to collide with each other. The objective was to measure the thermodynamic properties of the impact region. Figure 1 shows the test arrangement. A neodymium laser beam was split into two opposed beams of 12 ns and 30 j each, and directed onto two slightly offset

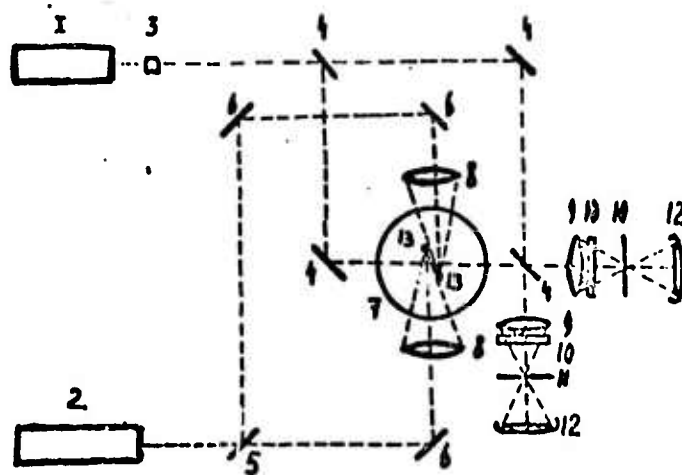


Fig. 1. Colliding plasma experiment.

1 - ruby laser; 2 - Nd laser; 3 - KDP cell;
4 - interferometer mirrors; 5 - splitter;
6 - mirrors; 7 - test vessel; 8, 9 - objectives;
10 - filters; 11 - diaphragms; 12 - photorecorders;
13 - targets.

polyethylene targets, separated by 1 mm, so that the generated plasmas would intersect. A ruby laser was used for high-speed interferometry of the collision region; wavelengths of 0.69 and 0.35 μ were used over an interval of 100 ns following the beam-target pulse generation. With this technique, the contribution of ions to the collision region could be discounted, since in this case the ion component was practically independent of optical frequency. From the combined interferograms it was possible to determine electron density profiles in the collision region, as shown in Figure 2.

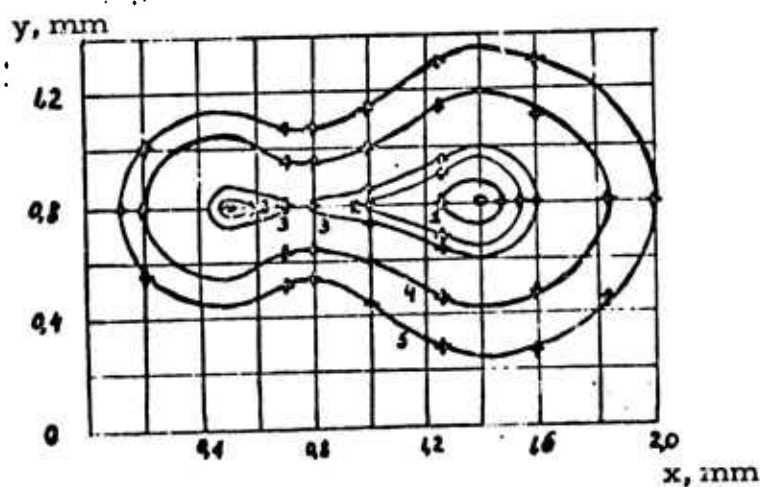


Fig. 2. Electron density profiles from colliding plasmas.

1- $8.8 \times 10^{19}/\text{cm}^3$; 2- $5 \times 10^{19}/\text{cm}^3$; 3- $3.5 \times 10^{19}/\text{cm}^3$;
4- $1 \times 10^{19}/\text{cm}^3$; 5- $5 \times 10^{18}/\text{cm}^3$.

Figure 3 shows an electron density profile in a plane bisecting one target, for the two-beam case as well as for only a single target beam. A sharp increase is clearly evident in the colliding plasma case. The target specimens in this experiment were cubes, 0.2 mm on an edge; the authors suggest that substantially higher densities could be obtained by using cylindrical or spherical targets.

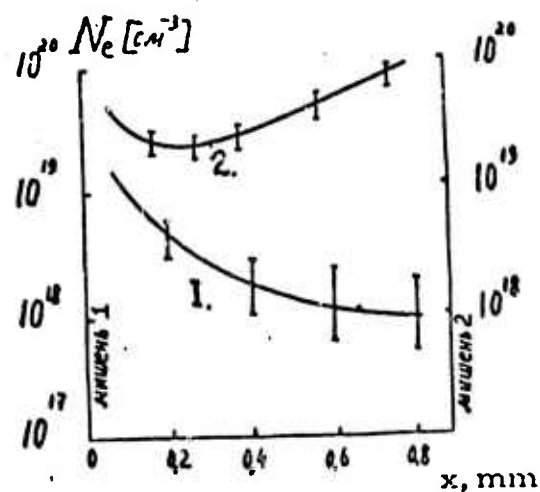


Fig. 3. Electron density for single-beam (1) and colliding (2) plasmas.

Basov, N. G., V. A. Boyko, V. A. Gribkov, S. M. Zakharov, O. N. Krokhin, and G. V. Sklizkov. Gas dynamics of a laser plasma during heat-up. ZhETF, v. 61, no. 1, 1971, 154-161.

The gas dynamic properties of a laser plasma produced by focusing a powerful laser beam onto a carbon target were studied experimentally. The recording technique used the slit scanning of the carbon flare interferograms.

The experimental setup is shown in Fig. 1. The energy of the neodymium laser used was 8 j for a mean pulse width of 80 nsec at the 0.1 amplitude point; maximum beam divergence = 2×10^{-3} rad. The radius of the focused spot was varied from 0.05 to 0.2 mm.

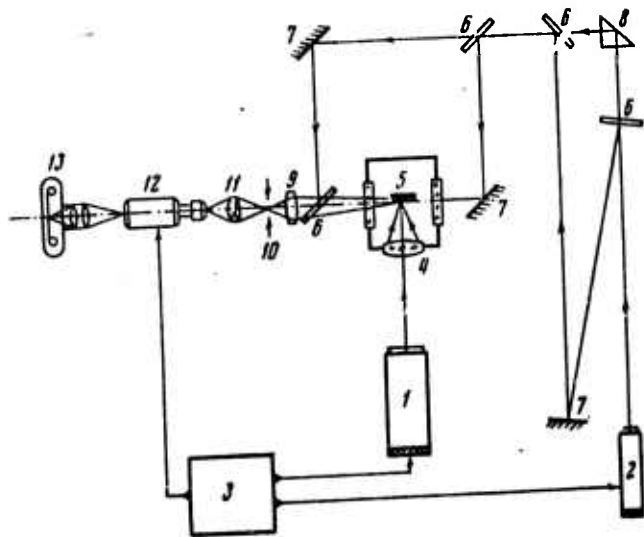


Fig. 1. Experimental setup.

1- neodymium laser; 2- ruby laser for illumination of interferometer; 3- control unit; 4- focusing lens; 5- target in a 10^{-5} torr vacuum; 6- beam splitters; 7- mirrors; 8- deflector; 9- lens focusing interference image on slit 10; 11- lens projecting slit image on the photocathode of image converter; 12- photoelectronic recorder; 13- camera.

A typical scan of the carbon flare interferogram is shown in Fig. 2. As seen in Fig. 2 the opacity zone (between $r = 0$ and interference

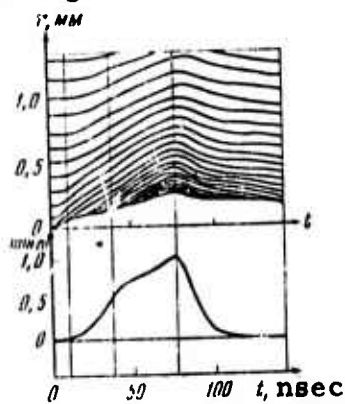


Fig. 2. Time scan of the carbon flare interferogram and laser pulse.

fringes) reaches a maximum width of ~ 0.25 mm at $t = 76$ nsec. The electron density at the boundary of the opacity zone is $\sim 0.5 \times 10^{19} \text{ cm}^{-3}$. The plasma parameters inferred from interferograms are given in Figs. 3-5.

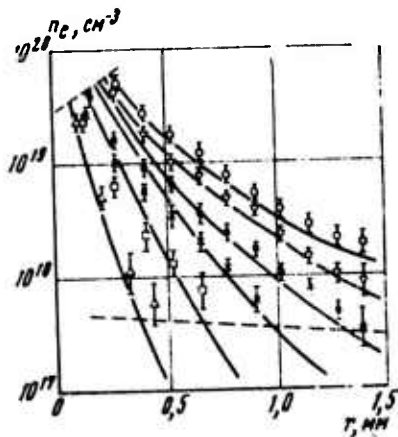


Fig. 3. Distribution of electron density along the laser beam axis (t in nanoseconds):

Δ - $t = 10$; \square - $t = 16$; \times - $t = 23$; \bullet - $t = 36$;
 ∇ - $t = 56$; \circ - $t = 76$.

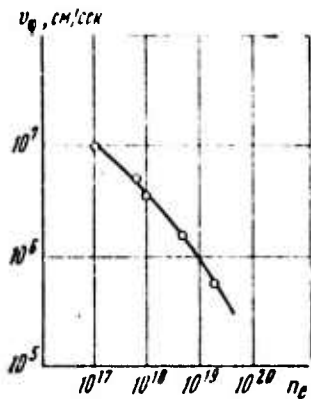


Fig. 4. Phase velocity of plasma front.

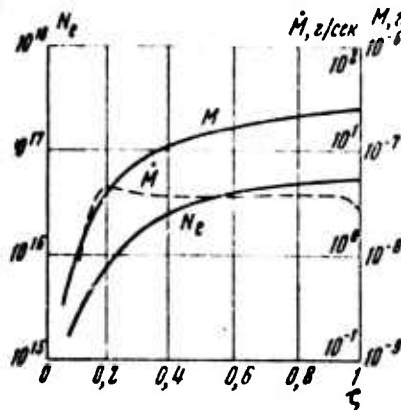


Fig. 5. Dependence of $\xi = t/\tau$ of the plasma mass M , total number of electrons N_e and mass discharge \dot{M} (τ - rise time of laser pulse)

It was noted that the velocity of the plasma with certain density remains constant over the leading edge of the laser pulse, and is as a rule smaller than the mass velocity.

The refraction of the incident beam due to a sharp density gradient, as well as crowding of the interference fringes, were suggested as causes of the opacity zone observed in the plasma. The plasma pressure on the target within the hot region (opacity zone) was determined from experimental data on plasma density and velocity, assuming spherical symmetry of the plasma diffusion, as

$$p(\zeta) = (\pi r_0^2 \tau)^{-1} dF/d\zeta, \quad (1)$$

where $F(t) = \int \rho(r, t) v_n(r, t) dV$; r_0 - radius of the focusing spot, τ - heating time, and $\zeta = t/\tau$. The velocity distribution used in the calculations and results of $p(\zeta)$ are given graphically.

The results show that the maximum plasma pressure (10^6 atm) is attained at the start of the laser pulse. This is explained as due to the small laser beam divergence at low laser pulse intensity.

Basov, N. G., V. A. Boyko, S. M. Zakharov,
O. N. Krokhin, and G. V. Sklizkov. Generating
neutrons in a laser CD₂ plasma heated by nano-
second pulses. ZhETF P, v. 13, no. 12, 1971,
691-694.

An experiment is described on neutron generation from a deuterated polyethylene (CD₂)_n target. The experimental setup is shown in Fig. 1.

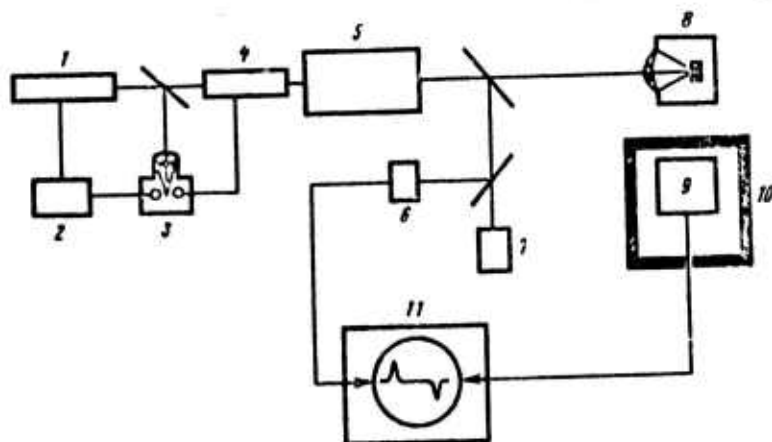


Fig. 1. Experimental diagram.

1 - Q-switched neodymium laser; 2 - pulse generator; 3, 4 - discharger with laser ignition; 5 - amplifier; 6 - coaxial photocell; 7 - calorimeter; 8 - chamber with target; 9 - scintillation detector; 10 - lead shield; 11 - oscillograph.

The laser pulse with maximum = 80 j was focused into a powdered polyethylene target by a lens with $f = 100$ mm. The heated target surface was 10^{-4} cm².

The neutron and x-radiation were recorded by photomultiplier with a 8 x 8 cm-plastic scintillator protected from hard x-rays by a 1.5 cm lead shield. The neutron velocity was determined to be 2×10^9 cm/sec; the total neutron yield was not less than 10^3 ; neutrons were recorded at energies down to 14 j. Sample laser pulse waveforms as well as neutron pulses at 10 cm and 60 cm from the target are given.

The results show that use of solid targets with nonequilibrium heating is a promising method of obtaining high neutron flux.

Alekseyev, V. A., S. D. Zakharov, P. G. Kryukov, and Yu. V. Senatskiy. Feasibility of using a dense plasma jet as a target in studies of laser heating. KSpF, no. 7, 1972, 57-61.

Experimental determination of the electron density distribution $n(x)$ in the surface plasma layer of a laser-heated solid target has not yet been achieved, because of extremely high n values and short lifetime ($10^{-9} - 10^{-10}$ sec) of a dense laser plasma. Since $n(x)$ determination is essential for research on laser fusion, the authors propose instead to substitute a low-temperature dense plasma jet for the solid targets commonly used in experimental plasma heating by laser. Measurement of n in a plasma jet would be inherently easier because jet discharge velocity is much lower than plasma dispersion. Since the $n(x)$ level could be held constant during heating by short (10^{-11} sec) laser pulses, a study of heating at different $n(x)$ would become possible.

The use of a generator introduced by Alekseyev is proposed to generate a low-temperature plasma jet in which the material is in a supercritical state. The resulting plasma jet offers the possibility of studying absorption and reflection of high-power laser radiation by a hot plasma, optimizing the initial target parameters for laser-induced nuclear fusion, and laser diagnostics of the supercritical state. In a generator described (Fig. 1), discharge of a capacitor bank through the target material (dielectric) generates sufficient energy to force a dense jet of material through a Laval nozzle during time intervals up to 1 msec. Average jet temperature and jet discharge velocity have been measured at about $7,000^{\circ}$ and 10^6 cm/sec, respectively. The high density of discharge material was confirmed by the experimentally established temporary (for ~ 0.5 msec) opacity of the jet to the red beam of a He-Ne laser. The generator described

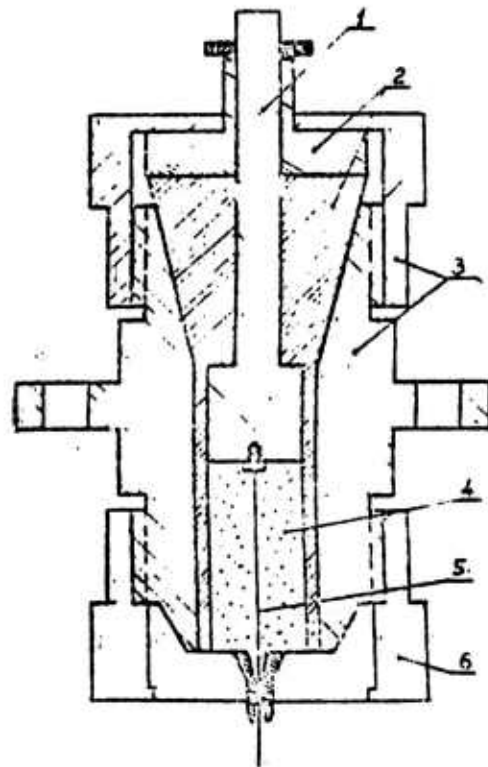


Fig. 1. Low-temperature plasma jet generator.
1- upper electrode, 2- insulation, 3- generator casing, 4- dielectric, 5- copper wire, 6- lower electrode.

could, with a simple modification, produce a quasicontinuous jet with annular cross-section for studies of laser plasma cumulation.

Aglitskiy, E. V., N. G. Basov, V. A. Boyko,
V. A. Gribkov, S. A. Zakharov, O. N. Krokhin,
and G. V. Sklizkov. Determination of electron
density, velocity and gas-dynamic pressure in
laser plasma. 10th Int. Conf. Phenomena Ioniz.
Gases, Oxford, 1971. Contrib. pap. Oxford, 1971,
229. (RZhMekh, 8/72, no. 8B198) (Translation)

An experimental determination is made of the electron concentration N_e , the expansion velocity, and the gas dynamic pressure in the dense hot region of plasma formed by the laser irradiation of a carbon target. The profile of N_e is determined on the basis of measurement of the Stark spectral line broadening of hydrogen-like ions, and the time evolution of this profile is determined by means of a high-speed interferometric procedure. The expansion velocity V of the plasma was evaluated on the basis of time scanning of the spectral lines (in the visible spectrum region), and on the basis of the Doppler shift of the resonance-absorption lines which takes place in the expanding (colder) plasma shell. The measured values of N_e and V make it possible to determine the time evolution of the gas dynamic pressure p of plasma in the hot region. An interesting feature is the nonmonotonic time change of p . The presence of the peak of p is linked to the shielding of laser radiation by peripheral regions of the plasma, and makes it possible to explain the presence, noted by other authors, of a temperature peak at the initial stage of laser heating.

Arifov, T. U., and I. M. Rayevskiy.
Injecting magnetic traps with a laser-generated
plasma. ZhTF, no. 8, 1972, 1764-1766.

Data are presented on plasma behaviour in magnetic traps of two different configurations, referred to as "plug-type" and "antiplug-

type". Experiments have shown that magnetic traps with "anti-plug" geometry are far more effective in capturing and retaining bunches of dense laser-produced plasma than the plug-type traps (probkotrons). A ruby laser, 150 x 12 mm at an energy of 0.15 joule and 50 nsec pulse duration, was focused on a flat titanium target surface in a vacuum chamber at 3×10^{-6} torr. A plasma bunch front of $n > 10^{13} \text{ cm}^{-3}$ density moved along the trap axis at a velocity $v = (4-5) \cdot 10^6 \text{ cm/sec}$. The total number of particles in the plasma bunch was determined from the mean energy of the bunch, target mass measurements, and chamber pulse pressure variations. In all three cases the total was determined to be $N = 3 \times 10^{16}$ particles. An SHF generator ($\lambda = 0.8 \text{ cm}$) was used to measure laser plasma physical characteristics. SHF cutoff period by the freely expanding plasma bunch 5 cm from the target was $\tau = 1.2-1.4 \text{ } \mu\text{sec}$. This value increased sharply with an increase in magnetic field intensity in the trap. Results are: in antiplug traps $\tau = 160 \text{ } \mu\text{sec}$ at an intensity of $H = 6 \text{ koe}$; in plug-type traps τ was 25 μsec at 7-8 koe.

The injected plasma in the trap was photographed during the trapping process and two different patterns were again observed as a function of trap geometry. In the antiplug traps, the plasma bunch moving along the magnetic field filled the trap; as revealed by the photographs, part of the bunch was disk-shaped and remained stable longer. Increases of τ were accompanied by increased flow energy q moving through the trap equatorial slot. It was observed that for the plug-type traps, although an increase of field resulted in a specific increase in time during which the plasma remained in the trap, this dependence is rather weak; with increased intensity, the plasma was also compressed into a narrow filament. The authors suggest that the brevity of plasma entrapment may be due to the nonuniformity of trap filling.

Zaritskiy, A. R., S. D. Zakharov, P. G. Kryukov, and A. I. Fedosimov. Measuring the polarization of back-scattered radiation from a laser-heated plasma. IN: Sb. Kvantovaya elektronika, no. 8, 1972, 89-90.

A brief discussion of backscatter from a laser plasma is given. The emission source in the experiment was a mode-locked Nd glass laser generating a pulse train with pulse duration and spacing of one nanosecond. The i-r emission was converted by a KDP crystal into the second harmonic with a beam divergence of 2×10^{-4} rad, energy = 10 j, and beam diameter ~ 4 cm. Both LiD and polyethylene targets in a 10^{-2} torr vacuum were exposed to the laser beam, focused by a lens with $f = 4.5$ cm. The source emission was $\geq 99.8\%$ linearly polarized.

It was found that the light back-scattered by the plasma is polarized in the same plane as incident light, with a degree of polarization = 90-95%. Assuming that observed change in polarization is induced by Faraday rotation, the authors found that, at $n_e = 5 \times 10^{20} \text{ cm}^{-3}$ and plasma layer thickness of 10^{-2} cm, the upper limit of the intrinsic axial magnetic field in the plasma is $B_{\text{max}} = 30$ kgs. This value is in agreement with that reported by Stamper et al. (Phys. Rev. Lett., 26, 17, 1971, 1012).

Andrukhina, E. D., G. S. Voronov, A. D. Smirnova, Yu. V. Kholnov, O. I. Fedyanin, and I. S. Shpigel'. Laser plasma containment in the Tor-1 stellarator. IN: Proc. 3rd Int'l Symp. Toroidal Plasma Confinement, Garching, 1973. (RZhF, 11/73, no. 11G255)

A study was made on confinement of a lithium plasma, generated by a laser, in the Tor-1 stellarator. Parameters given for the

latter are: $n_e = 5 \times 10^{10} - 10^{12} / \text{cm}^3$; $T_e = 0.3 - 3 \text{ eV}$; $T_i = 5 - 60 \text{ eV}$; magnetic field $H = 4 - 12 \text{ kgs}$; and rotary conversion angle $i = 0.03 - 0.3$. It was shown that duration τ did not depend on plasma parameters, but that the relation $\tau = \text{const} \times H^{1.4} \times i^{0.7}$ holds true. Also, plasma confinement is not governed by laws of a collision type diffusion.

Voronov, G. S., and A. P. Prokhorov.
Studying the effectiveness of laser plasma
confinement by a magnetic field. ZhTF,
 no. 8, 1973, 1641-1645.

The process of arresting and confining a laser plasma by a magnetic field was experimentally investigated. The experiment was conducted in a cylindrical vacuum chamber of 10 cm diameter and 100 cm in length (Fig. 1). A uniform magnetic field of 2 kgs intensity was applied

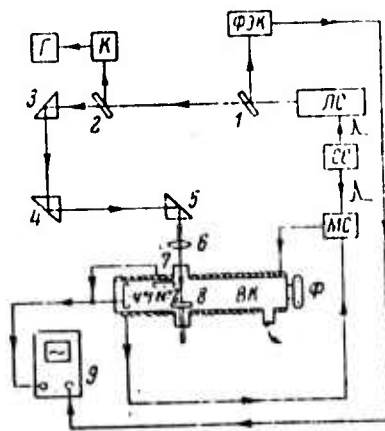


Fig. 1. Plasma chamber experiment.

by a solenoid wound on the chamber; the geometry of the injecting cross-section was similar to that used in experiments on the TOR-1 stellarator.

A 100 mw neodymium laser was focused on a lithium target, consisting of a solid disc 25 cm in diameter and 5 mm thick placed similarly as in the TOR-1. The focal point on the target surface was variable from 0.5 to 5 mm by a lens. The quantity of plasma trapped by the magnetic field was measured by an 8 cm diameter collector, placed perpendicularly to the magnetic field at about 40 cm from the injecting cross-section. The collector was composed of two stainless 0.3 mm steel plates with the front plate grounded. The ion component of the plasma was then recorded by the rear plate. An ion collector of similar construction recorded the plasma drift to the chamber walls.

Movement of plasma across the magnetic field was studied by photographing the plasma in the green line of singly ionized lithium, $\lambda = 5485 \text{ \AA}$. Curves were drawn for the quantity of generated and confined plasma (Figs. 2 and 3). The amount of confined plasma was found proportional

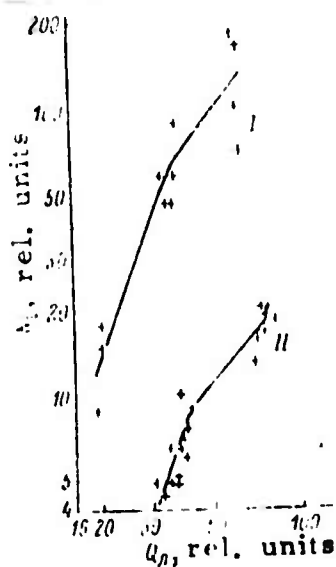


Fig. 2. Quantity of generated (I) and confined (II) plasma as a function of laser pulse energy.

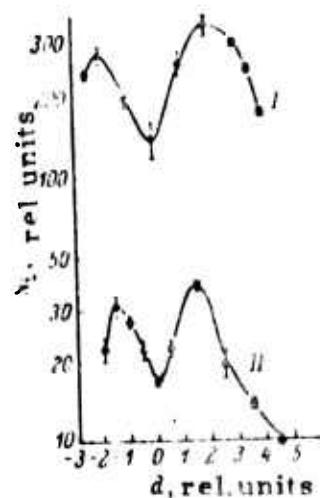


Fig. 3. Quantity of generated (I) and confined (II) laser plasma as a function of the position of lens focus relative to target surface.

to the quantity generated; in the present configuration the effectiveness of plasma confinement was measured at 10%. A method is suggested for increasing the effectiveness of plasma confinement by increasing the angle ϕ between target plane and magnetic field direction, as seen in Fig. 4.

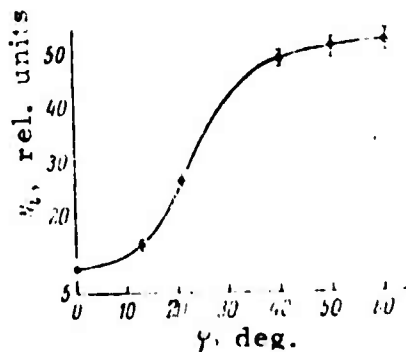


Fig. 4. Relationship of the confined plasma as a function of angle ϕ and magnetic field. (laser beam \perp mag. field).

Gribkov, V. A., O. N. Krokhin, G. V. Sklizkov, N. V. Filippov, and T. I. Filippova. Beam heating in a "plasma focus". ZhETF P, v. 18, no. 1, 1973, 11-15.

The authors consider the reasons for the unaccountably high yield of neutrons typical of a "plasma focus" source. Spectral studies show that up to 80% of the total neutron output may be of thermal origin; however the plasma temperature (~ 20 kev) raises some doubt on this in view of a density in the plasma focus on the order of $10^{19}/\text{cm}^3$. Various types of "second compression" of the plasma have been suggested to account for this yield, including beam instability, macroscopic turbulence, ionosonic instability etc., but there is no experimental evidence yet to support any of these mechanisms.

In an earlier work (ZhETF P, v. 15, 1972, 329) Gribkov et al showed that within 100 ns after initial compression the plasma reaches a density on the order of $10^{18}/\text{cm}^3$. Further interferometry tests showed that at the time of peak neutron pulse the plasma focus has a hanging constriction form, with a conical center region whose apex is toward the chamber anode; here the axial density is not over $10^{16}/\text{cm}^3$ compared to $\sim 10^{18}/\text{cm}^3$ for the walls. It is thus evident that a typical plasma waveguide appears, formed by a beam of electrons pulled from the constriction region ("plasma cathode"). The authors analyze the parameters of the electron beam and discuss its contribution to plasma heating. A numerical example using some typical plasma and beam values gives a focused beam length of about 3 mm at time of equilibrium between magnetic field and beam pressures. Test data are given comparing the effects of nitrogen and xenon doping of the deuterium, and illustrations of beam focus and hose instabilities are included. The authors conclude that the cited beam effect is a major factor in heating in the final stages of the plasma focus.

Essentially the same paper was contributed by the authors to the Sixth European Conference on Controlled Fusion and Plasma Physics, Moscow, 1973 (cf. RZhF, 12/73, no. 12G348).

Denus, S., Z. Jankiewicz, S. Kaliski, et al.
Generation of fusion neutrons in plasma produced
by a strong laser pulse. Bull. Acad. Pol. Sci.,
Ser. Sci. techn., v. 21, no. 11, 1973, 121[937]-
130[946].

The present paper contains a description and a discussion of results of an experiment, the aim of which was to produce high-temperature plasma of lithium deuteride and deuterium impregnated polyethylene and to generate neutrons of thermonuclear microfusion by a nanosecond laser pulse

with an energy of 20 to 40 j. The results of the work reported mean the attainment of the world level in the research of the laser heating of plasma and the nuclear microfusion. They will be a starting point for works using the laser-focus or laser-cumulation compression systems etc., for which the critical energy of the laser pulse necessary for positive recovery of the fusion energy is reduced to the order of tens of kJ or less. Sec. 2 concerns the experiments and the measurement systems used (the laser system and the system for measuring the X-radiation, the reflected radiation, ion expansion, emission of neutrons, etc.). In Sec. 3 the authors present the results obtained; Sec. 4 comprises some conclusions.

Basov, N. G., V. A. Boyko, S. M. Zakharov,
O. N. Krokhin, Yu. A. Mikhaylov, G. V.
Sklyzov, and S. I. Fedotov. Mechanisms for
generating neutrons in a laser plasma. ZhETF P,
v. 18, no. 5, 1973, 314-317.

Contrasting experiments are described which demonstrate both predominantly nonthermal and thermal mechanisms of neutron generation in a laser plasma. In the first case a single sharply-focused laser beam was used on a large CD₂ target; power was 10 Gw at a 2 ns pulse length, for a neutron yield of 10⁴/pulse. Results obtained with a scintillation counter 10 cm from the target showed a delayed secondary neutron pulse some 40 ns after the laser pulse. When a CD₂ screen was inserted in the test chamber, this lag time dropped and signal amplitude increased (Fig. 1, b). This indicates that neutrons were generated from the interaction of plasma deuterons with deuterium on the screen or adsorbed on the walls.

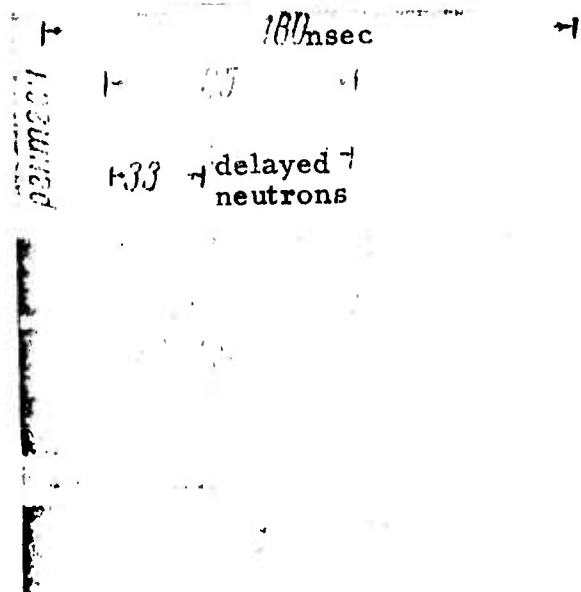


Fig. 1. Neutron yield from single focused laser.
 a - no screen; b - with screen.

It was also possible with a single-source cumulation configuration to obtain thermal neutrons directly with the laser pulse, in which case no delayed neutron pulse was observed. These results thus cast doubt on the conclusions of McCall, Young et al (Phys. Rev. Lett., v. 30, 1973, 1116), in which the appearance of fast ions was correlated with acceleration in a region of critical density.

In the second experiment a multibeam laser of 200 Gw, 1.5 ns was used on a 110 μ diameter CD_2 target, generating 10^7 neutrons/pulse. Yield was monitored by three counters at varying distances from the target; Fig. 2 shows the response. Neutron energy was calculated to be ~ 2.45 Mev, corresponding to the reaction $d(d, n)He^3$. The absence of "delayed" neutrons

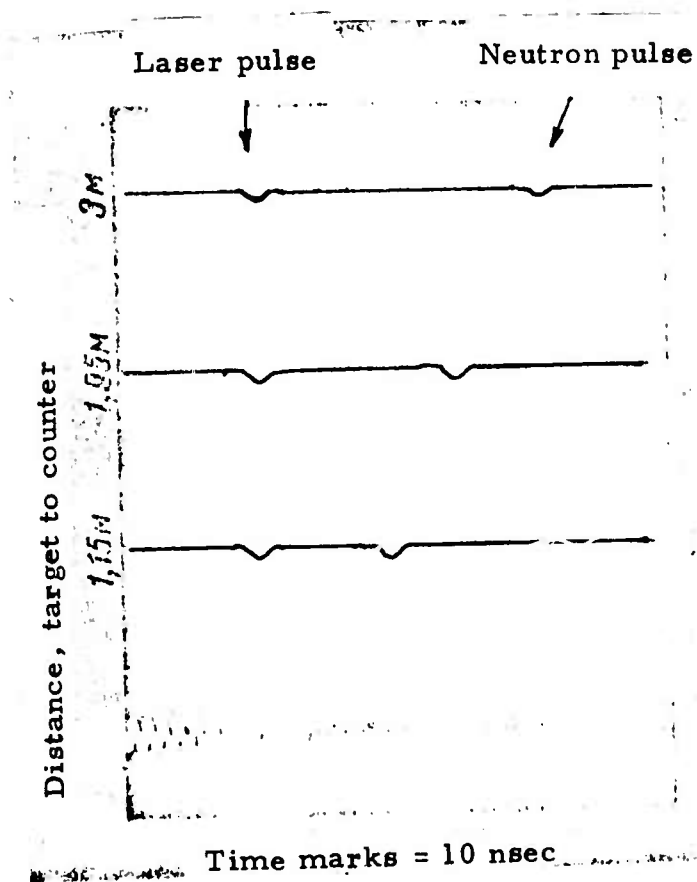


Fig. 2. Neutron yield, multibeam experiment.

resulted presumably from the high residual gas pressure of about 7 torr. With allowance for time resolution of the measuring equipment, the authors determined that plasma ion temperature did not exceed 5 kev, which strongly suggests the thermal nature of neutron generation in the spherically heated plasma.

Dyatlov, V. D., R. N. Medvedev, V. N. Sizov,
and A. D. Starikov. Measuring the reflection of
subnanosecond pulses of a powerful laser from a
solid LiD target. ZhETF P, v. 19, no. 2, 1974,
124-126.

The authors describe a study on reflectivity of a laser plasma,
as one of the factors critical to fusion. This was done with an LiD target
in 10^{-5} torr vacuum, exposed to 90 ps pulses from an Nd glass laser.
Reflectivity was measured over an incident density range of $10^{13} - 10^{15}$ w/cm²;
pulse energies to 300 j were attainable, but the most stable results were
obtained at not over 100 j. The beam was focused at $f = 235$ mm onto a target
area of 10^{-3} cm². Incident and reflected pulse energies were measured by
calorimeter; a high speed photo record was made of plasma development at
a 60 nsec resolution. Additional values measured included neutron yield,
electron temperature, and second harmonic in the reflected signal.

The results show a monotonic drop in reflectivity as incident
power density is raised (Fig. 1).

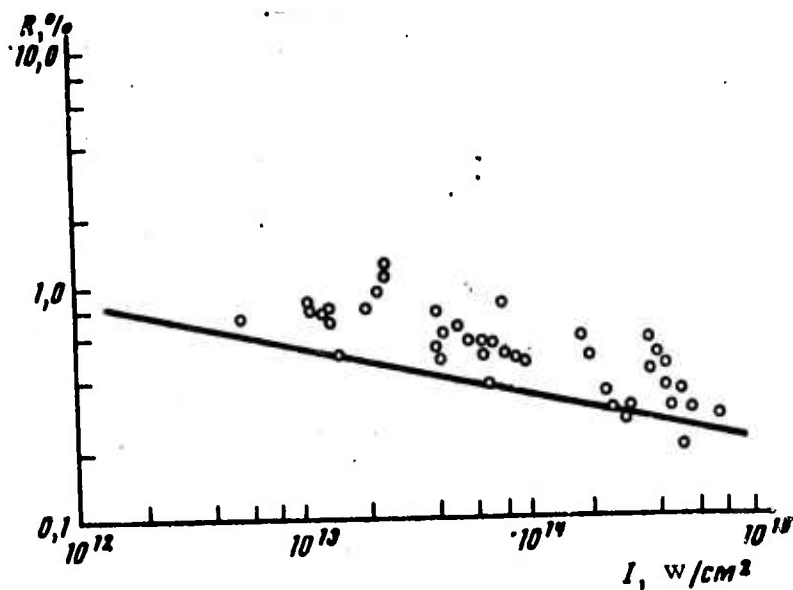


Fig. 1. Plasma reflectivity vs. power density.

Here R is the ratio of reflected to incident energy, E_R/E_{in} , and intensity $I = E_{in}/S_0\tau$, with S_0 being the interaction area. An appreciable level of second harmonic was also detected, peaking with maximum neutron yield of about 10^6 . These two effects indicate the nonlinear character of plasma absorption. The fact that R dropped with increased pulse power rather than rose as reported by other authors, is apparently due to a particular feature of this experiment, namely that the target was briefly exposed to luminescent and noise radiation of up to 10^{12} w/cm² prior to the main laser pulse. This formed a vapor cloud causing relatively high reflection, which decreased as contrast was thereafter raised.

2. Plasma Spectroscopy

Andreyeva, L. T., N. G. Basov, V. A. Boyko, M. T. Vanina, S. M. Zakharov, O. T. Krokhin, G. V. Sklizkov, B. M. Stepanov, V. N. Filinov, and V. P. Churakov. High-speed multichannel recording of the radiation spectra of a laser plasma flare. IN: PTE, no. 6, 1969, 217.

A technique for studying the spatial-time structure of a laser plasma flare is briefly reported. The flare was studied by means of a high-speed multichannel recording system which provided for time correlation of different processes with an accuracy of $2-3 \times 10^{-10}$ sec. Type 7ELV-F7 and ELU-FT high-speed multichannel multipliers (2 and 8 channels, respectively) were used, having a linear output current of 2.5 a, gains of 10^7 and 5×10^8 , and time resolution 2 msec and 5 nsec, respectively. The high-speed six-trace oscillograph used (6LOP-02M) has a sweep speed that can be regulated from 3 to 5.0 msec/cm.

It was found that plasma radiation begins simultaneously with the impact of the laser pulse, and reaches a maximum intensity at the peak of the laser pulse. The CVI and CV ions (laser energy 10 j; $\lambda = 5292 \text{ \AA}$ and 4925 \AA , respectively) are the fastest ones; they diffuse at a velocity of $2 \times 7 \times 10^3$ cm/sec, carry away a mass of $0.35 - 1.7 \times 10^{-7}$ g, and have a kinetic energy of 1-7 j.

The maximum intensity of thermal x-rays also coincided with the laser emission peak. However, their lifetime is slightly shorter than laser pulse duration. The ion temperature was determined to be 200 eV, with no significant change during the laser pulse.

Basov, N. C., V. A. Boyko, V. A. Gribkov,
 S. M. Zakharov, O. N. Krokhin, and G. V.
 Sklizkov. Time variation in temperature of a
 laser-induced plasma flare, from x-radiation.
 ZhETF P, v. 9, no. 9, 1969, 520-523.

Tests are described for determination of T_e of a laser plasma by an absorption method using soft x-rays. The method enables determination of the time dependence of plasma x-rays passing through two beryllium filters with densities of 15.5 and 31 mg/cm² with a resolution of ± 2.5 nsec. The plasma was produced by a laser pulse with energy up to 30 j and duration of 15 nsec. The laser was focused by a lens with $f = 5$ cm onto a carbon target in a 10^{-6} torr vacuum.

The time dependence of electron temperature T_e determined from the ratio of signals from photomultipliers, using numerical data according to Iahoda et al. (1960) and Elton et al. (1967) is shown in Fig. 1.

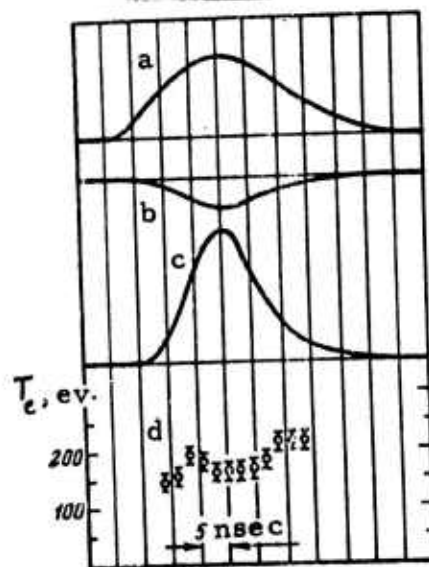


Fig. 1. Time dependence of T_e (d).

a- laser pulse, b-₂ signal from photomultiplier,
 filter = 31 mg/cm², c- same, filter = 15.5 mg/cm².
 Time resolution of photomultiplier = 5 nanosec;
 accuracy of signal correlation at least 1 nsec; laser
 energy = 27 j.

As seen in Fig. 1 the electron temperature changes negligibly in spite of significant variation in emission intensity $F(t)$. The following explanation is given: the temperature of the hot plasma generated under these conditions (flux density = 10^{12} w/cm²; laser spot diameter, 10^{-2} cm, pulse duration = 15 nsec) depends on the instantaneous flux density. Time variation of the average flux density $q = F/\pi d^2$ ($d = 2f\theta(t)$ is stipulated by $\theta(t)$ (θ = laser dispersion). According to Basov et al (DAN, v. 173, 1967, 538), $\theta(t)$ initially increases from 2.5×10^{-4} to 3×10^{-3} rad, then subsequently decreases so that d varies from 0.025 to 0.3 mm. Thus at appropriate values of $F(t)$ and $\theta(t)$, the electron temperature T_e may hold a constant value over a large part of the laser pulse.

Boyko, V. A., Yu. P. Voynov, V. A. Gribkov,
and G. V. Sklizkov. Identification of K XIII, K XIV,
K XV, and Fe XVII lines emitted by a laser plasma.
Ois, v. 29, no. 5, 1970, 1023-1024.

Spectral identification of highly ionized K and Fe lines is briefly reviewed. The excitation source is identified only as a 2 Gw laser. Resolution with a DFS-6 spectrograph was $\pm 0.04 \text{ \AA}$; line intensities were evaluated visually. Results are given in Table I. Discrepancies with data of other authors is discussed.

(Table on next page)

Table I

Ion	Transition	$\lambda, \text{\AA}$	Intensity
KXIII	$2s^2 2p^3 \ ^2D_{3/2}^0 \rightarrow 2s 2p^4 \ ^2P_{3/2}$	138.50 *	5
	$^2D_{3/2}^0 \rightarrow \ ^2P_{3/2}$	142.68 *	5
	$^2D_{5/2}^0 \rightarrow \ ^2P_{3/2}$	143.76 *	10
	$^2P_{3/2}^0 \rightarrow \ ^2P_{1/2}$	151.05	1
	$^2P_{3/2}^0 \rightarrow \ ^2P_{1/2}$	152.77	6
	$^2P_{3/2}^0 \rightarrow \ ^2P_{3/2}$	156.03	1
	$^2P_{3/2}^0 \rightarrow \ ^2P_{1/2}$	157.86	4
	$^2P_{3/2}^0 \rightarrow \ ^2S_{1/2}$	164.13	5
	$^2P_{3/2}^0 \rightarrow \ ^2S_{1/2}$	166.19	2
	$^2D_{3/2}^0 \rightarrow \ ^2D_{3/2}$	178.15	6
	$^2D_{3/2}^0 \rightarrow \ ^2D_{3/2}$	179.46	8
	$^4S_{3/2}^0 \rightarrow \ ^4P_{1/2}$	198.49 *	3
	$^2P_{3/2}^0 \rightarrow \ ^2D_{3/2}$	199.54	1
	$^4S_{3/2}^0 \rightarrow \ ^4P_{1/2}$	201.48 *	4
	$^2P_{3/2}^0 \rightarrow \ ^2D_{3/2}$	202.11	1
$^4S_{3/2}^0 \rightarrow \ ^4P_{3/2}$	208.12 *	3	
KXIV	$2s^2 2p^2 \ ^3P_0 \rightarrow 2s 2p^3 \ ^3S_1^0$	147.57	1
	$^3P_1 \rightarrow \ ^3S_1^0$	150.38	2
	$^1D_2 \rightarrow \ ^1P_1^0$	151.68	2
	$^3P_0 \rightarrow \ ^3S_1^0$	153.91	3
	$^1D_2 \rightarrow \ ^1D_2^0$	172.26	2
KXV	$^3S_0 \rightarrow \ ^1P_1^0$	173.09	1
CXVIII $\frac{1}{2}$	$2s^2 2p \ ^2P_{1/2} \rightarrow 2s 2p^2 \ ^2P_{3/2}$	175.68	1
	$2s^2 2p^2 \ ^2P_{3/2} \rightarrow 2s 2p^2 \ ^2S_{1/2}$	193.95	3
	$^2P_{3/2}^0 \rightarrow \ ^2S_{1/2}$	193.96	4

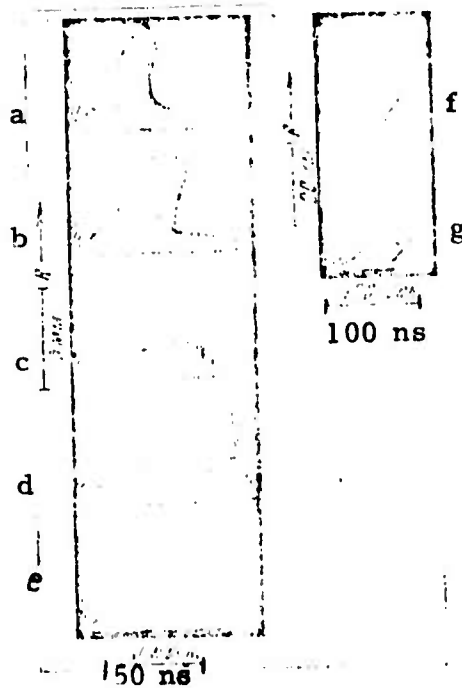
* Fawcett et al., Proc. Phys. Soc., 91, 1967, 970.

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Basov, N. G., V. A. Boyko, Yu. A. Drozhbin, S. M. Zakharov, O. N. Krokhin, G. V. Sklizkov, and V. A. Yakovlev. Study of the initial stage of gas-dynamic divergence of a laser plasma flare. DAN SSSR, v. 192, no. 6, 1970, 1248-1250.

Data on laser interaction with a carbon target are discussed. Nd glass laser radiation with pulse energy of 10 j and duration of 15 nsec was focused at $f = 5$ cm onto a carbon target in a 10^{-6} torr vacuum. A slit image of the plasma flare was obtained with a spatial resolution of 20 lines/mm and time resolution of 0.5 nsec.

Typical records of a carbon flare are shown in Fig. 1. Spatial-time diagrams of ion diffusion are shown in Fig. 2.



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Fig. 1. Slit image of a carbon flare in the form of spectral lines of different ions.

a- CVI, $\lambda = 5292 \text{ \AA}$; b- CV, $\lambda = 4946 \text{ \AA}$; c- CIV, $\lambda = 5801.51 \text{ \AA}$; d- CIII, $\lambda = 4662.7 \text{ \AA}$; e- continuous noise; f- CVI, $\lambda = 5292 \text{ \AA}$; g- CV, $\lambda = 4946 \text{ \AA}$.

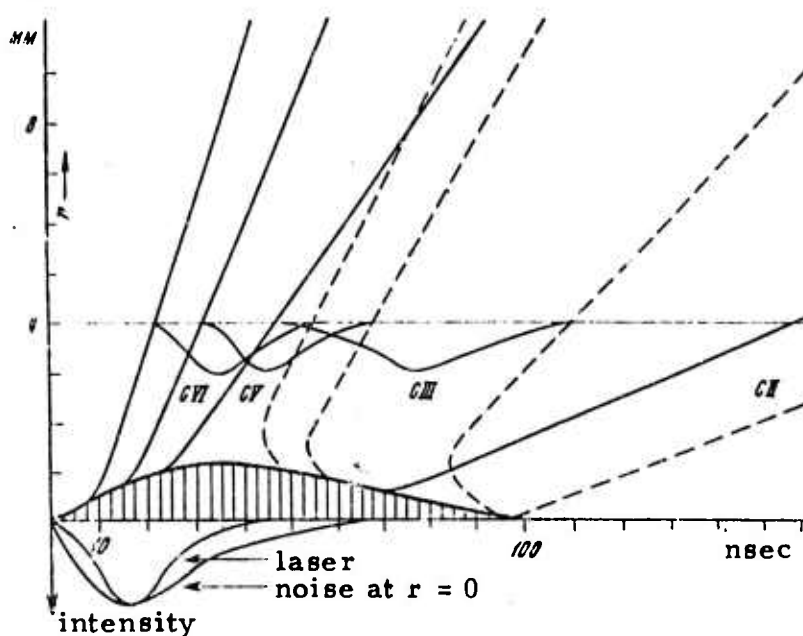


Fig. 2. r-t diagrams of diffusion of different carbon ions.

Hatched region - intensity of continuum exceeds the intensity of lines.

As seen in Fig. 1, at $r \leq 1$ mm the plasma radiates a continuous spectrum in the visible range, and at $r \geq 1$ mm, a discrete one. At $r = 10$ mm the CVI and CV ions separate from the target (Fig. 1, f, g).

Based on the experimental data the following model for the gas-dynamic motion of the heated matter is developed: from the heated region ($r < d$) where $T_e \sim 120$ eV, plasma diffuses into the vacuum normal to the surface with a velocity of $\sim 6 \cdot 10^6$ cm/sec. In this region the velocity of the plasma diffusion is close to sound velocity, and the corresponding ion temperature is $T_i \sim 125$ eV. A significant plasma acceleration then occurs at $r \leq 1$ mm, where the velocity increases by several times. Thus, for the outer region of the $C_{z=6}$ ions, an asymptotic velocity, determined from the

radiation of the CVI ions 10 nsec after their escape from the heated region, is about 3×10^7 cm/sec, which corresponds to a directional kinetic energy of 5 keV.

The total mass of the carbon nuclei and CVI ions was determined to be 10^{-7} g and kinetic energy $\sim 3-4$ j. The energy lost by the plasma in the $r < d$ region for the radiation in the 20-100 Å range was estimated to be about 0.5 j during an interval of 40 nsec.

Dymovich, V. I., S. D. Zakharov, P. G.
Kryukov, Yu. A. Matveyets, and S. M. Sil'nov.
Determining the composition of a plasma generated
by a powerful laser pulse. KSpF, no. 4, 1970, 53-60.

The authors note that LiD exposed to air will become contaminated so as to inhibit generation of deuterium ions. The reactions



occur, in addition to surface absorption of free nitrogen and other trace contaminants. Tests showing this were run on LiD targets previously exposed to air for intervals up to several days, using a Q-switched ruby and a time-of-flight mass spectrometer, as shown in Fig. 1. Tests run at 10^{-4} torr. showed a clear variation in ion content with repeated pulse "cleaning" of a given target area. Evidence of both H^+ and D^+ indicated that reactions (1) and (2) did occur; a sample oscillogram shows growth in Li^+ and D^+ with successive pulsing, when crater depth was not enough to cause defocusing.

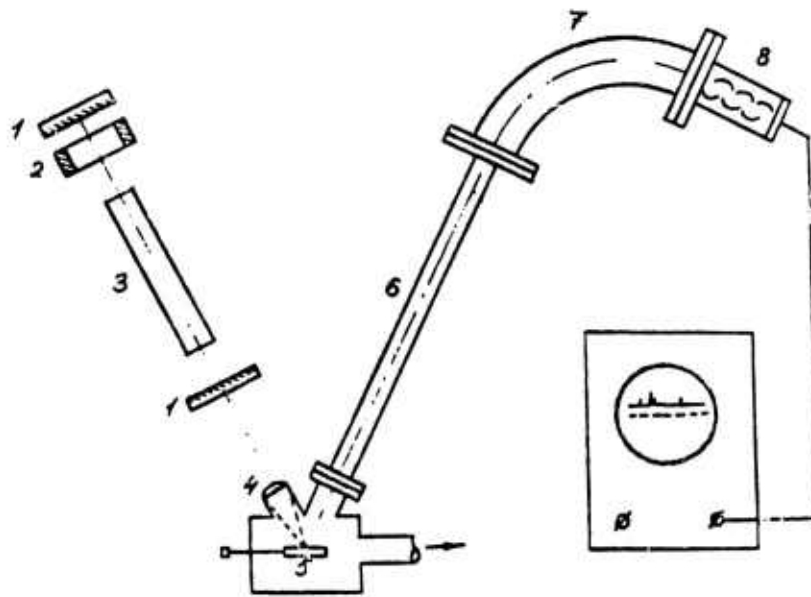


Fig. 1. Spectrometer schematic.

1, 2, 3- Mirror, filter, ruby; 4- lens; 5- target;
6- drift space; 7- analyzer; 8- photomultiplier.

Based on these studies the improved neutron generator of Fig 2 was developed. The neodymium laser generated 10 nsec pulses at 0.3 j, focused at $f = 100$ mm on an angled LiD target in a grounded container. A second target of deuterated polyethylene $(CD_2)_n$ was placed 10 cm from the first and set at a negative potential variable from 0 to (-) 50 kv. With sufficient acceleration, deuterium ions from LiD striking the ion target yielded neutrons, from



Threshold for detectible neutron generation was around (-)30 kv; a suppressor grid (Fig. 2) had to be added to prevent arc-over between targets.

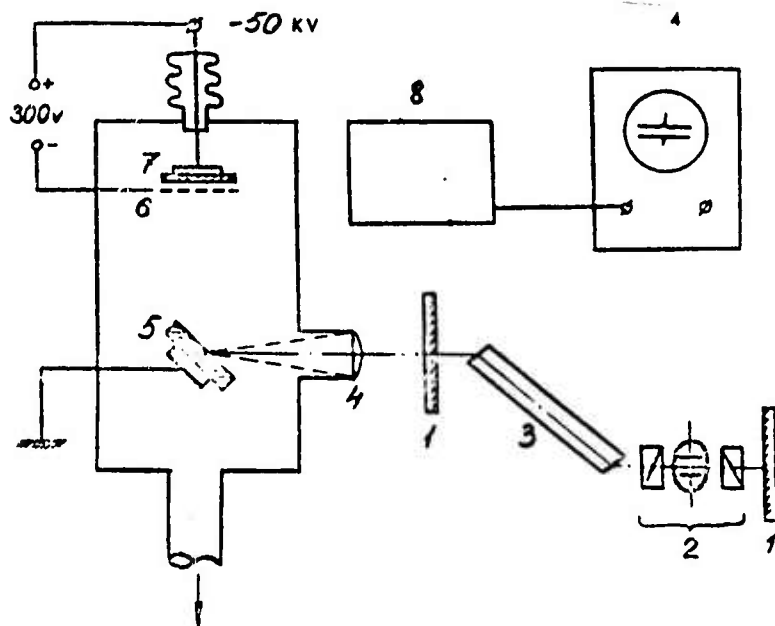


Fig. 2. Laser neutron generator
 1, 2, 3 - Nd glass laser, mirrors, Kerr cell;
 4 - lens; 5 - LiD target; 6 - suppressor grid;
 7 - auxiliary (CD₂)_n target; 8 - scintillator
 counter.

Comparison of counter results with a Cs^{137} reference showed a yield of some 10^4 neutrons/pulse by this technique, although the yield varied from pulse to pulse. The authors note that a target previously exposed to air for 10 days failed to generate neutrons, which emphasizes the importance of avoiding LiD contamination.

Aglitskiy, Ye. V., V. A. Boyko, S. M.
Zakharov, G. V. Sklizkov, and A. N.
Fedorov. Observing x-ray lines of highly-
ionized iron in a laser plasma. KSpF,
no. 12, 1971, 36-40.

A beam-target experiment in which laser pulse powers on the order of 10 Gw were obtained is described. At this level the resultant T_e in the plasma may reach 1000 eV, which indicates that transitions in the soft x-radiation band should be observed. A system for doing this is shown in Fig. 1.

A 2 nsec pulse of 40 to 100 j was focused onto an iron target in vacuo as shown in the figure. Radiation from the target plasma passed through a filter system to a tinned cylindrical steel surface, reflecting at an angle governed by wavelength to a film sector as shown. Calibration was done with the indicated x-ray tube; a resolution of $3 \times 10^{-3} \text{ \AA}$ or better is claimed for the method. The authors thus identified some forty multiply-ionized Fe lines in the 10 to 18 \AA range, and suggest that more lines might be detected with a resolution refinement to 0.001 \AA , which should be feasible. The cited results indicate nonequilibrium ionization, a question that should be resolved by simultaneous measurement of x-radiation and T_e .

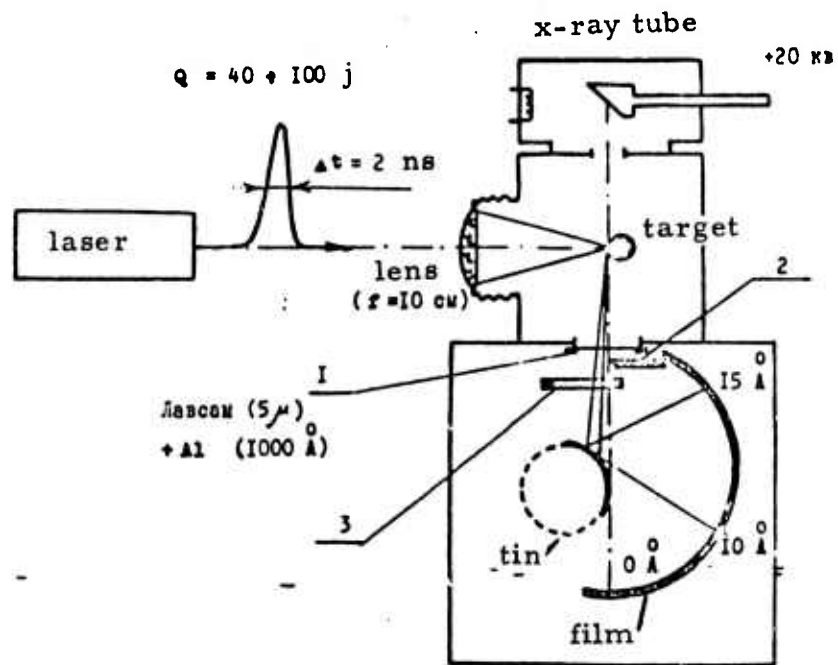


Fig. 1. X-ray spectrography of a laser plasma.
 1 - high-pass filter; 2 - null-reflection diaphragm;
 3 - control slit.

Granatkin, B. V., A. I. Isakov, and A. A. Tikhomirov. Scintillation counter for recording fast neutrons generated by a laser plasma. KSpF, no. 6, 1972, 62-68.

A scintillation counter of fast neutrons from a hot laser-generated D plasma is introduced for use in plasma diagnostics. The counter features a hydrogen-containing neutron moderator in the form of a prismatic polystyrene scintillator block incorporated into a light-proof aluminum container. As the result of collision with H atoms, the moderated and thermalized neutrons are captured by H atoms. The capture gamma rays with 2.2 MeV energy excite the scintillator molecules which emit light pulses. The latter are recorded by two photomultipliers fixed to the opposite lateral surfaces of the counter. Simultaneously, pulses from recoil protons produced in the counter by neutron radiation of the plasma are recorded by a similar photomultiplier on top of the container. The recording circuit of the counter is shown in Fig. 1.

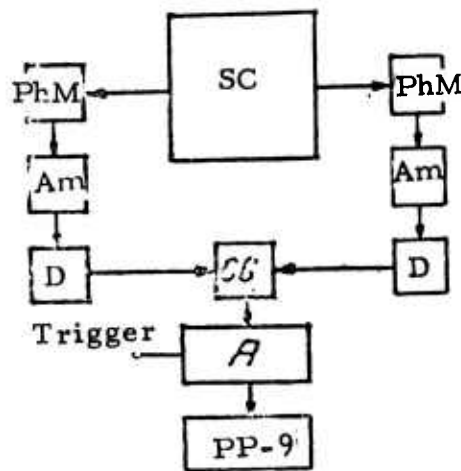


Fig. 1. Recording circuit: SC- scintillation counter; PhM - photomultipliers; Am- amplifiers; D- discriminators; CC- coincidence circuit; A- single-channel, time-delay analyzer; PP-9- high-speed scaling circuit.

The maximum efficiency ϵ_{\max} of the counter was calculated to be 0.27. The life-time T of thermal neutrons in the moderator was determined from measurements of the time dependence of neutron density decay, using the neutron detection system of Fig. 1 or the more precise AI-256 multi-channel, time-delay analyzer and a pulsed neutron generator from D-D and D-T reactions. The neutron density-time plots show that T values measured by both techniques are in good agreement (204 and 205 ± 4 μsec). The counter efficiency was also determined by monitoring with a flat-response counter the number Q of neutrons emitted in a single flash. The ϵ value thus obtained for DD neutrons was 0.2 ± 0.25 . The time lag T_M of the counter and the recording system was measured to be $(0.5 \pm 0.1) \times 10^{-6}$ sec. A minimum 100 neutrons per flash emitted into a total solid angle can be recorded. With the cited τ_M , accuracy of Q determination is little better than 20%.

In addition to the high sensitivity of the counter, its flat response and controllability of counting speed are cited as particular advantages. The recording system can be started after the plasma is dissipated (40 μsec after a fast neutron flash), thus permitting the measurement of neutron flux during x-ray emission. The counter was used to measure n of fast neutrons emitted by a laser-heated D plasma at the temperature of nuclear fusion. Using the plastic counter, the n of neutrons with 18 j energy emitted in the total solid angle was evaluated to be $(4 \pm 1.5) \cdot 10^3$; the corresponding deuteron temperature of the plasma was = 0.7 keV. The plasma was produced by heating a solid $C_n D_{2n}$ target with 2 nsec, 12 j pulses from an Nd laser.

Volobuyev, I. V., B. V. Granatkin, and A. I. Isakov. Detector with a liquid scintillator for recording neutron flux from a laser plasma. KSpF, no. 7, 1972, 69-72.

The authors observe that as neutron yield from laser fusion experiments has grown, the requirement of highly sensitive neutron detectors has been superseded by the need for fast-response detectors of improved and simplified construction. A new detector of this type is described, based on a liquid scintillator solution of white spirit ($C_n H_{2n+2}$, $n = 8-12$), type PPO organic activator, and type POPOP spectral shifter. Fig. 1 shows a functional diagram of the overall circuit. The control trigger gates the

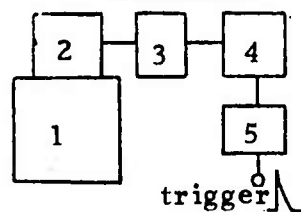


Fig. 1. Block diagram of neutron detector.

1- scintillator; 2- photomultiplier; 3- amplifier; 4- PP-9 counter; 5- trigger.

counter on 40 μ sec after the laser pulse, and holds it open for durations up to 800 μ sec. Operating characteristics of the detector are given in terms of neutron flux decay vs. scintillator element dimensions, based on excitation by pulsed generators of DD and DT-neutrons. The unit is housed in a 30 x 30 x 28 cm^3 aluminum container; it is claimed to be only 2% of the cost of a polystyrene type of scintillator.

Zaritskiy, A. R., S. D. Zakharov, P. G. Kryukov, Yu. A. Matveyets, and A. I. Fedosimov. Variation in the back-scatter radiation spectrum from laser heating of a plasma. ZhETF P, v. 13, no. 4, 1972, 184-188.

$(\text{CH}_2)_n$, $(\text{CO}_2)_n$, D_2O ice, and Al were used as targets in spectrum measurements of laser beams reflected from plasma. The emission source was a mode-locked neodymium glass laser comprising a generator and a six-stage amplifier. The spectral measurements and the plasma heating were carried out on a fundamental frequency $\lambda = 1.06 \mu$ as well as the second harmonic $\lambda = 0.53 \mu$. Harmonic conversion was effected at an efficiency of up to 50% by a KDP crystal. The initial oscillation spectrum was contracted to $\sim 0.05 \text{ \AA}$ by inserting Fabry-Perot axial mode selectors into the resonator. The laser pulse was thereby lengthened to 1 nsec.

Spectrograms for four laser bursts on a LiD target (objective $f = 4.5 \text{ cm}$, $\lambda = 0.53 \mu$) show that a large number of equidistant lines can be seen in the light spectra reflected from the plasma. The lines generally are situated both in the Stokes and the anti-Stokes portions of the spectra. The number of lines is a function of the energy and, as a rule, the greater the burst energy the greater the number of lines. The width of each line is within the resolution limits of the equipment (0.05 \AA). At an output-energy level of about 5 j, spectra were recorded with variable focusing; objective $f = 4.5 \text{ cm}$ and lens $f = 30 \text{ cm}$. In the first case line multiplication was continuous, while in the second case it was observed in about half of the bursts; this reflects the threshold character of the effect, since the focal spot diameter was one order greater for the lens.

Vinogradov, A. V., and Ye. A. Yukov.

Effect of two-photon processes on the x-ray spectrum of laser plasma. IN: Sb. Kvantovaya elektronika, no. 2(14), 1973, 105-107.

Additional discrete x-ray spectral lines (laser satellites) in a laser plasma self-radiation spectrum are analyzed as the effect of the Raman-anti-Stokes scattering of laser radiation and laser-induced two-photon emission. The additional line pairs of approximately equal intensity, with interline spacing equal to two laser quanta, appear in the laser plasma spectrum, at a sufficiently strong laser field, near the optically forbidden transitions. The satellite at the shorter wavelength corresponds to Raman-anti-Stokes scattering, that at the longer wavelength to stimulated two-photon emission. The laser satellite intensity per unit volume is expressed as

$$P = (\omega'/\omega) I_0 N_2 \sigma, \quad (1)$$

where ω and ω' are the frequencies of laser radiation and a laser satellite, respectively, I_0 is the laser radiation intensity, N_2 is the population of the excited ion level, and σ is the Raman scattering or two-photon emission cross-section. The latter is expressed in approximation of a single virtual energy level.

Using (1), the ratios of P to P_{3s-2p} or P_{3p-1s} intensities of the allowed transitions between the multiply charged ion levels are calculated for an Li-similar Fe XXIV or an He-similar Fe XXV ion, respectively. It is shown that the P/P_{3s-2p} ratio is independent of N_2 . The P/P_{3p-1s} ratio depends on I_0/N_e and can be a measure of the latter ratio. The P/P_{3s-2p} ratio can be used to determine laser flux density in the plasma, and hence to obtain information on powerful radiation absorption by the plasma and the electron temperature distribution of laser radiation field intensity.

The limit of applicability of the expression for σ is determined by

$$I_0 \ll \frac{\hbar c}{4\pi e^2} \frac{m\omega_{nn'}^3}{f_{nn'}} \quad (2)$$

where c is sound velocity, e and m are the electron charge and mass, $\omega_{nn'}$ is the frequency of the allowed transitions, and $f_{nn'}$ is the oscillator strength of the transition to a virtual level. It is calculated from (2) that, in the case of the $2s-1s$ transition in Fe XXV ions, the expression for σ is applicable for $I_0 < 10^{17}$ w/cm². At $I_0 \geq 10^{17}$ w/cm², the spontaneous ionic spectrum changes appreciably. In summary, analysis of a laser plasma x-ray spectrum indicates that additional very strong lines can arise and can be used for diagnostics of a high-temperature laser plasma ($kT_e \sim 1-10$ keV).

Voronov, G. S., and L. Ye. Chernyshev.

Change in the ion composition of a dispersing multicharged laser plasma. ZhTF, no. 7, 1973, 1484-1487.

Analytical expressions are derived for determining relative changes with time in ionization levels and temperatures of a laser-generated plasma. The model assumes an initial spherical ionized volume with diameter equal to the focused spot of a giant laser pulse, or about 0.05 cm, and expanding radially at the order of 5×10^6 cm/sec. The initial temperature is assumed high enough so that charge $k = 10$ for all plasma ions.

From solution of $T(t)$ and $N_k(t)$ for plasma temperature and charge population, respectively, curves were obtained as shown in Figs. 1 and 2. In Fig. 1 a cooling down from an initial high temperature is assumed

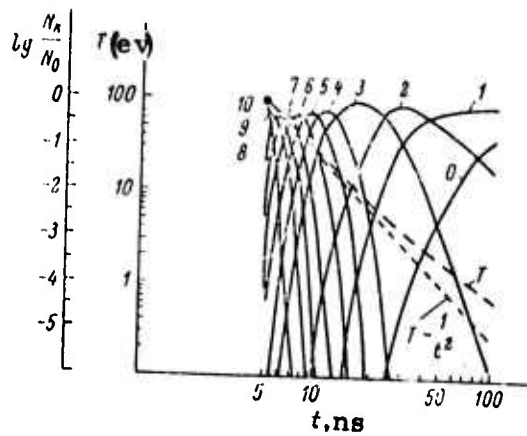


Fig. 1. Change in plasma ion composition and temperature vs. time.

$T_0 = 100 \text{ eV}$, $N_e = 10^{21} / \text{cm}^3$, initial diameter 0.025 cm. Curve figures show charge.

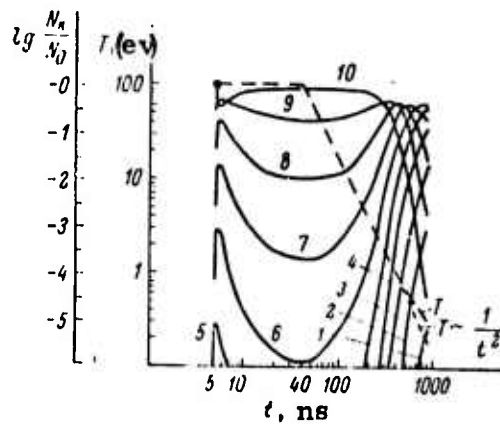


Fig. 2. Ionization change during laser pulse. Initial conditions as in Fig. 1.

to set in, while in Fig. 2 the temperature is sustained during the period of the laser pulse. Both ordinates are normalized to the total number of plasma atoms.

Results show that in the later stages of plasma development, charge state changes mostly owing to recombination from triple collisions, and that at the end of the laser pulse the charge system has evolved to a bell shaped distribution.

Aglitskiy, Ye. V., V. A. Boyko, L. A.
Vaynshteyn, S. M. Zakharov, O. N. Krokhin,
and G. V. Sklizkov. Observation of resonant
transitions in satellites of hydrogen- and
helium-like ions of Mg and Al in a laser plasma.
OIS, v. 35, no. 5, 1973, 963-966.

Using the Q-switched Nd glass laser described previously by Basov et al. in CD₂ plasma studies (ZhETF P, v. 13, 1971, 691), the authors observed x-ray spectra of magnesium and aluminum plasmas, at power densities to 10^{14} w/cm². Fig. 1 shows sample spectrograms obtained from 2--3 laser bursts. A particular feature is the presence of satellite

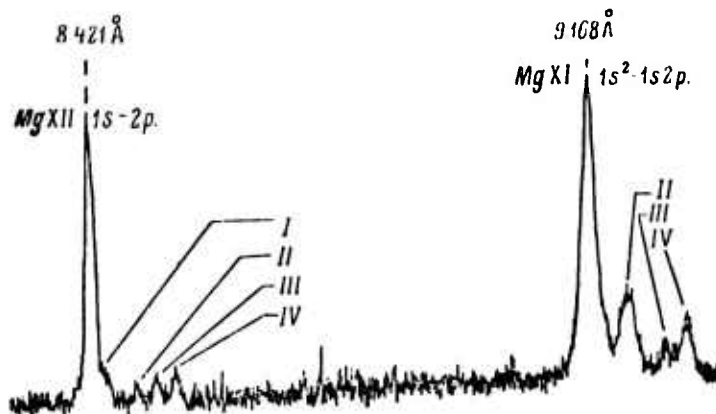


Fig. 1. Laser spectra of Mg plasma.

resonance lines of He-like Mg XI and Al XII, of the type $1s^2 nl-1s2pnl$, as well as H-like ions Mg XII and Al XIII, of type $1snl-2pnl$. A table is included listing the most intense transitions, and comparing test and theoretical data with other authors. The results are pertinent to conditions for laser plasma fusion.

Aglitskiy, Ye. V., V. A. Boyko, S. M.
Zakharov, S. A. Pikuz, and A. Ya. Fayenov.
Identifying transitions with doubly-excited
levels in lithium-like Ti and V ions in a laser
plasma. ZhETF P, v. 19, no. 1, 1974, 16-18.

X-ray spectral analyses are given of titanium and vanadium laser plasmas obtained by sharp focusing of a laser beam at 5×10^{14} w/cm² power density. The measured spectral line wavelengths of the He-like Ti XXI and V XXII ions and the Li-like Ti XX and V XXI ions are tabulated along with data of Western authors for the cited ions, as well as the wavelengths calculated earlier by three of the present authors (Preprint FIAN, no. 113, 1973). (Table 1). The tabulated 19 lines were measured accurately to 0.0005 Å. Ionization potentials of the Ti XXI and V XXII ions are 6.250 and 6.852 keV, respectively. The measured lines are related to the $1s 2pnl \rightarrow 1s^2 nl$ transitions which are tabulated.

Identification of the 2.6141 line of the Ti XX ion and the 2.3856 line of the V XXI ion was made by analogy with the corresponding Al XI line identified earlier, together with extrapolation of the author's experimental data to the Mg X - V XXI isoelectronic series. The Ti XX line was identified on the basis of theoretical data given in the cited paper. Apparently the 2.6480 Ti XX and 2.4140 V XXI lines each correspond to the total of seven theoretical lines.

Transition	Titanium			Vanadium		
	theory[2]	L. Pl.	spark [5]	corona[6]	theory[2]	L. Pl.
$1s2p^1P_1 - 1s^2^1S_0$	2,6097 ¹⁾	2,6101	2,612	2,608	-	2,3823
$1s2p^3P_1 - 1s^2^3P_0$	-	2,6141	-	-	-	2,3856
$2s2p(^1P)1s^2P_{3/2} - 1s^2s^2S_{1/2}$	2,6196	-	-	-	2,3899	-
$1s2p^2^2S_{1/2} - 1s^2p^2P_{3/2}$	2, 6195	2,6204	-	-	2,3900	2,3888
$2s2p(^1P)1s^2P_{1/2} - 1s^22p^2S_{1/2}$	2,6206	-	-	-	2,3909	2,3907
$1s2p^3P_1 - 1s^2^1S_0$	2,6221 ¹⁾	2,6229	2,623	2,621	-	2,3939
$1s2p^2^2P_{3/2} - 1s^2p^2P_{3/2}$	2,6296	2,6295	-	-	2,3986	2,3992
$2s2p(^3P)1s^2P_{1/2} - 1s^2s^2S_{1/2}$	2,6295	-	-	-	2,3989	-
$1s2p^2 \left\{ \begin{array}{l} ^2D_{3/2} \\ ^2D_{5/2} \\ ^2D_{3/2} \end{array} \right\} - 1s^22p \left\{ \begin{array}{l} ^2P_{1/2} \\ ^2P_{3/2} \\ ^2P_{3/2} \end{array} \right\}$	2,6313 2,6347 2,6356	2,6319 2,6355 -	2,631	2,634	2,4000 2,4033 2,4043	2,4013 2,4047 -
$1s2p^2^4P - 1s^22p^2P$	2,6451 [±]	-	-	-	2,4125 ⁺	-
$2s2p(^3P)1s^4P - 1s^2s^2S$	± 2,6490	2,6480 [±] ± 0,0015 2,6540 [±] ± 0,0015	-	-	+ 2,4161	2,4140 [±] ± 0,0015
?	-	-	-	-	-	2,4210 [±] ± 0,0015

Table. X-ray spectral line wavelengths of and transitions from doubly-excited Ti and V ions. [5] Lie and Elton, Phys. Rev., A3, 1971, 865. [6] Neupert, Solar Physics, 18, 1971, 474.

The data given in this paper could be useful in developing methods of thermonuclear laser plasma diagnostics, e.g., determination of plasma temperature and density from the He-like and Li-like ion lines. The quality of laser plasma emission spectra is superior to that of vacuum spark emission spectra, so that a sufficiently detailed identification of transitions in the multiply-charged ions is possible.

3. Laser Design

Basov, N. G., P. G. Kryukov, V. S. Letokhov,
Yu. A. Matveyets, and S. V. Chekalin.

Amplification of an ultrashort pulse in two-com-
ponent medium. IN: ZhETF P, v. 10, 1969,
479-482.

A description is given of a two-component stable amplifier
of ultrashort pulses, which yields a pulse train with energy exceeding 10 j
and a single ultra-short pulse with energy exceeding 1 j.

A schematic of the experiment is shown in Fig. 1. A single

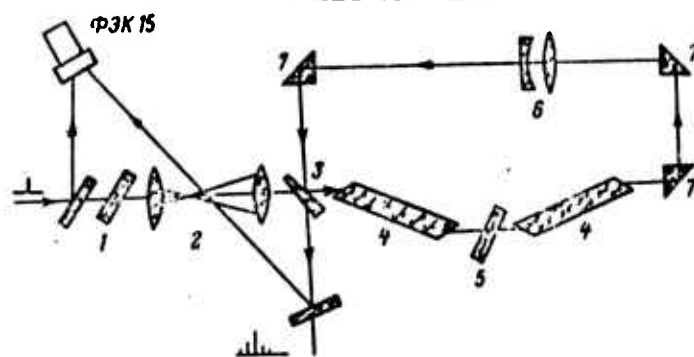


Fig. 1. Ultrashort pulse generator

ultrashort pulse with energy of $10^{-3} - 10^{-2}$ j is isolated from a laser pulse
train by a nonlinear absorber, and fed to a ring circuit through a cell with
bleachable dye having an initial transmittance of 10-15% (1), optics enlarging
the beam diameter by a factor of 3 (2) and a wedge with $T = 80\%$. The
amplifying stages consist of two 600 x 20 mm neodymium glass rods with a
design gain of $k \sim 200$ (4). Cell 5 with no. 3955 polymethine dye has an
initial transmittance of 0.5%. Lens 6 is used for distortion compensation, while
rotating reflection prisms 7 are used instead of mirrors. Additional losses in

splitter 3 as well as from Fresnel reflection exclude self-excitation of the system. The transmission time of the system is 19 nsec. Oscillograms of a typical ultrashort pulse and output are included in the article.

Batanov, V. A., B. V. Yershov, L. P. Maksimov, V. V. Savranskiy, and V. B. Fedorov. Laser system with energies up to 10 kj for studying the interaction of powerful optical beams with matter. KSpF, No 4, 1970, 8-13.

This paper is concerned entirely with the design and operating characteristics of a powerful laser array specifically developed for high-level beam-target studies. The array consists of three parallel 3-stage Nd glass lasers whose combined output is synchronized to focus on a target surface. A net energy of 10 kj at 1 millisecond is thus developed, providing a density up to 10^7 w/cm² over a 1 cm² target area; focal distances up to 2 meters are used. Pulse shape, dispersion pattern and pump characteristics are discussed. It was attempted to build high reliability into the array; however experience over two years has shown that breakdown in the output faces of the resonator elements is a limiting factor, allowing only 5 to 10 pulses at the 10 kj level, or up to 50 times at the 5 kj level, before damaged elements must be replaced. No test results with target materials are mentioned.

Vanyukov, M. P., V. A. Venchikov, V. I.
 Tsayenko, V. A. Serebryakov, and A. D.
 Starikov. High-intensity neodymium glass
laser for generating a high-temperature plasma.
 OIS, v. 28, no. 5, 1970, 1008-1012.

A high-power Nd glass laser for plasma generation is described. The laser system (see Fig. 1) consists of a low-power driver oscillator with a beam divergence near to diffraction, and a four-stage amplifier with gradually

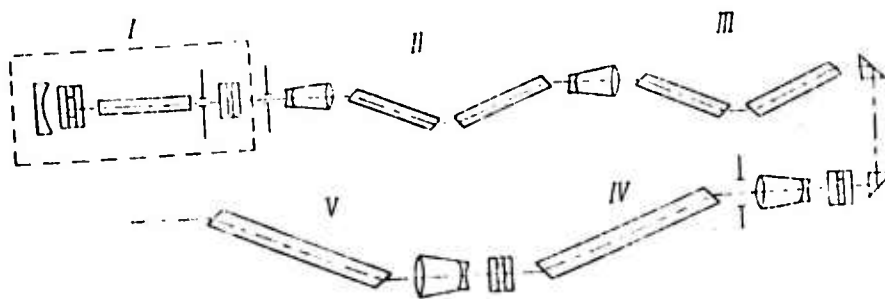


Fig. 1. Optical circuit.
 I - driver oscillator;
 II - IV - amplifier stages.

increasing rod diameters (12, 20, 30 and 45 mm, respectively); a Galilean telescope was used for the beam expansion. The laser energy was 100 j, at a power of 10 Gw; overall gain was 10^4 . The flux confined to the diffraction core (see Fig. 2) was $B = 1.3 \times 10^{17}$ w/cm² ster. Incident flux density was $10^{15} - 10^{16}$ w/cm² and laser pulse duration was 10 nsec. Beam divergence, reduced by an inclined spherical lens, was held to 50 mrad. The directivity of the output emission is shown in Fig. 3.

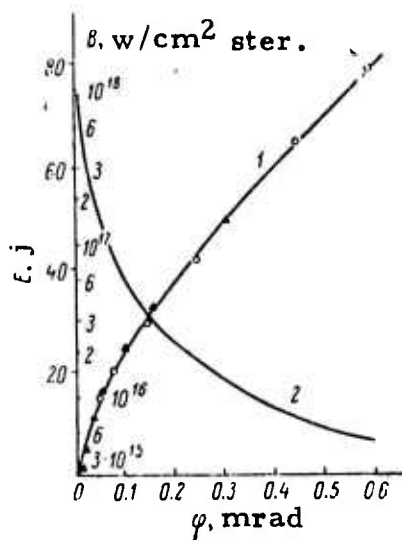


Fig. 2. Distribution of laser energy (1) and average luminosity (2).

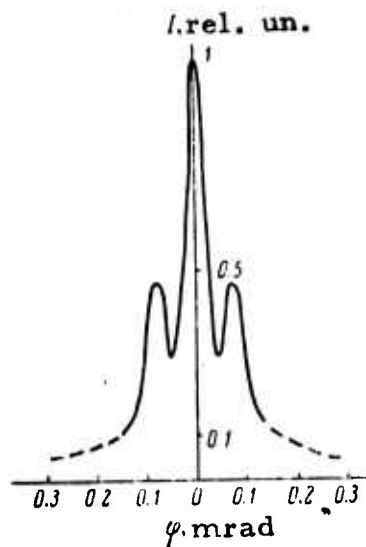


Fig. 3. Directivity of laser output.

With some refinements the authors see this design as capable of producing densities up to 10^{16} w/cm².

This same system is briefly described elsewhere by Vanyukov et al. (OMP, 11, 1969, 67).

Basov, N. G., A. R. Zaritskiy, S. D.
Zakharov, O. N. Krokhin, P. G. Kryukov,
Yu. A. Matveyets, Yu. V. Senatskiy, and
A. I. Fedosimov. Generation of powerful
light pulses at 1.06 and 0.53 μ and its
application to plasma heating. I. Experimental
studies of radiation reflection during laser
plasma heating at two wavelengths. IN: Sb.
Kvantovaya elektronika, no. 5(11), 1972, 63-71.

Calorimetric, spectroscopic, oscilloscopic, direction shift, and polarization measurement data are given for laser radiation reflected by the plasma of a solid target heated by nanosecond laser pulses at power densities above 10^{14} w/cm². The 10^{-9} sec. pulses, with a 10^{-9} sec. repetition rate, were generated at 1.06 and 0.53 μ by a mode-locked Nd glass laser and its second harmonic, respectively in the apparatus described in the next abstract by Basov et al.

The data obtained present the first known attempt at the study of plasma generated by laser heating of a solid target. It was established that energy losses due to reflection are decreased by one order of magnitude from conversion of 1.06 μ laser radiation to the second harmonic. Hence, the 0.53 μ radiation absorption by the plasma is three times as strong as absorption of the 1.06 μ radiation. It is concluded that the use of even higher harmonics of Nd laser radiation may be advantageous for plasma heating for nuclear fusion purposes.

Basov, N. G., A. R. Zaritskiy, S. D.
 Zakharov, P. G. Kryukov, Yu. A. Matveyets,
 Yu. V. Senatskiy, A. I. Fedosimov, and S. V.
 Chekalin. Obtaining high power light pulses at
 1.06 and 0.53 μ and their application in heating
 plasma. II. Nd glass laser with second harmonic
 emission. *Kvantovaya elektronika*, no. 6(12), 1972,
 50-55.

A detailed discussion is given of the critical factors which limit the output of high-power lasers, and an experimental Nd glass laser and amplifier system is described which attempted to overcome most of the limiting factors. This is an extension of the foregoing article by Basov et al. describing plasma heating with such a system.

Effective high power generation places severe demands on the laser system parameters. Principal requirements are a high spectral purity of the active signal at pulse widths ~ 1 nanosecond, minimum self-focusing, and effective decoupling of backscatter from the target back through the system. These goals were achieved to some degree by the system shown in Fig. 1, principally by using second harmonic generation in a KDP crystal.

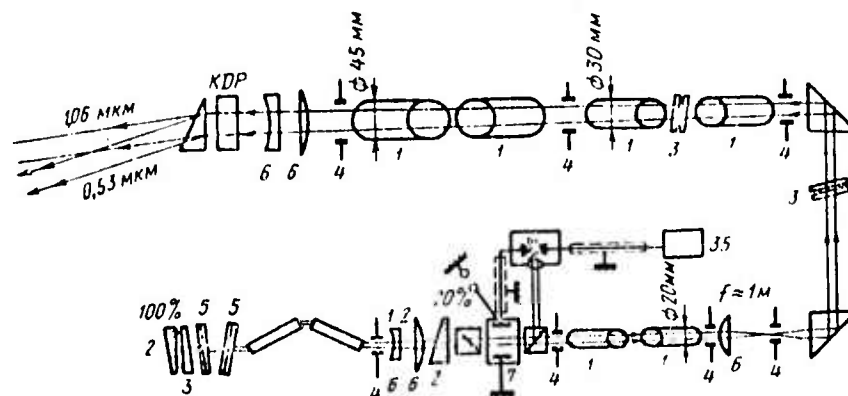


Fig. 1. Generator and amplifier.

1- Nd glass rods; 2- resonator mirrors; 3- bleachable
 absorber; 4- aperture diaphragms; 5- axial mode selector
 6- lenses; 7- laser-triggered selector switch.

The driver laser used two rods of 10 x 240 mm cut at the Brewster angle, and a nonlinear absorber (dye no. 3955 in nitrobenzol) fixed to the 100% reflecting mirror. Use of a diaphragm at the output gave a beam dispersion close to diffractive. Two Fabry-Perot interferometers were used to narrow the output spectrum to about 0.05 Å, causing pulse broadening to 1 nsec. A Kerr cell was used to segregate one pulse from the train with an energy in the 10^{-5} - 10^{-4} j range, which was then amplified in the subsequent six stages to a net gain of 10^6 .

To reduce self-focusing, the beam after the first two stages was given a slight divergence of about 0.003 rad, so that at the final stage output the beam diameter had increased to 45 mm (maximum for the available rods); the beam was then returned to parallel by afocal optics, as seen in Fig. 1. The positive effect of this was seen in a marked reduction of the filament formation typical of self-focusing. The afocal optics were also used to correct for output astigmatism; with this correction it was found that 61% of the exit energy was within a 2×10^{-4} rad angle. Intensity control was obtained by circular-hole diaphragms placed before the amplifier stages, with hole diameter slightly less than the succeeding rod diameter. The criticality of diaphragm placement to avoid power loss and rod damage is emphasized; precise setting of them was required to obtain the 50 j pulse maximum.

Reduction of backscatter was undertaken both to avoid spurious damage to the target by parasitic modes as well as reverse damage to the laser elements. This was partly achieved by placing the target up to 15 meters away from the output stage; the remaining decoupling was provided by a diaphragm at the output face, as well as the interstage diaphragms already mentioned. Thus backscatter degradation at the fundamental was substantially reduced, and at 0.53 μ was undetectable. Frequency doubling was at an efficiency of 50% with 25% absorption in the KDP cell, so maximum pulse output dropped to 10 j.

The authors conclude that their design could be extrapolated to increase performance, e.g. by increasing rod diameters to allow more beam divergence, and by using more efficient harmonic converters, such as DKDP or CDA, in place of KDP.

Basov, N. G., Yu. S. Ivanov, O. N. Krokhin,
Yu. A. Mikhaylov, G. V. Sklizkov, and S. I.
Fedotov. Generation of neutrons from spherical
irradiation of a target by powerful laser radiation.
ZhETF P, v. 15, no. 10, 1972, 589-591.

The authors note some limitations to neutron production from laser heating of a target for fusion purposes. Specifically, the effect of an increasingly powerful focused laser becomes offset by diffusion of the high temperature region owing to thermoconductive and gas dynamic energy loss. An alternative approach suggested recently by Basov et al is to heat a spherical target simultaneously with multiple beams; in the present case this was done with a deuterated polyethylene target exposed to nine equal beams, as indicated in Fig. 1, using an Nd glass laser in the giant pulse mode. This array attained a mean power density of 10^{16} w/cm² on the target surface, at 2--16 ns duration. The focusing objectives were placed to obtain a focal plane 200 μ from the target, for minimum reflection and uniform heating.

Some results are shown in Table I for various target sizes and beam energies; the measured value was obtained from three scintillation counters. The η values, calculated independently for thermoconductive and gas dynamic regimes, were 2.4×10^{12} and 2×10^{11} respectively. The effect of cumulation in the cited experiments is concluded to be a minor one.

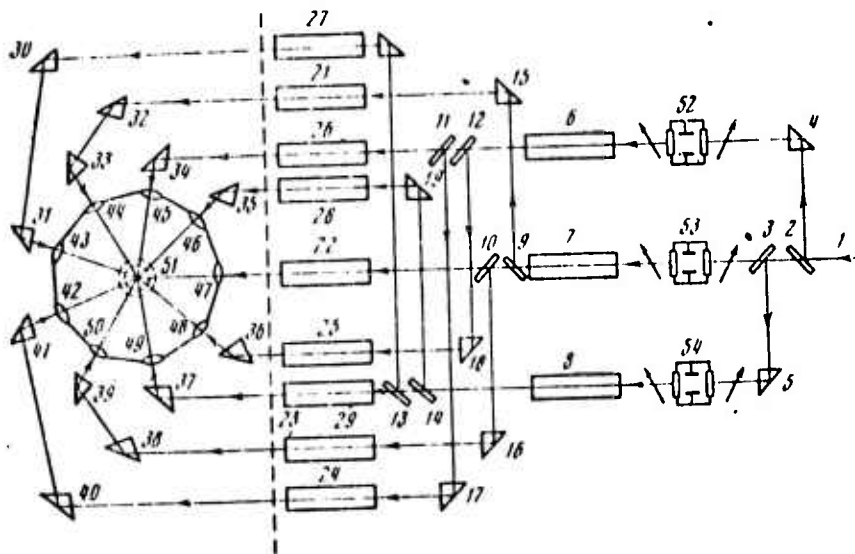


Fig. 1. Multibeam array for CTR target.

1- preamplified beam; 6-8- second amplifier;
 21-29- third amplifier; 42-50- focus lenses.
 Compensating delays for differing path lengths
 not shown.

Target radius, cm	Laser energy, j	Mean temp., ev	Neutron output per pulse	
			exp.	calc.
$2.50 \cdot 10^{-2}$	600	40	-	-
$1.25 \cdot 10^{-2}$	202	120	-	-
$5.50 \cdot 10^{-3}$	214	840	$3 \cdot 10^6$	$8 \cdot 10^7$
$3.00 \cdot 10^{-3}$	232	$4 \cdot 10^3$	-	$1 \cdot 10^{10}$

Table I. Neutron generation with multiple laser beam.

A more detailed description of this laser amplifier system and its operating characteristics is given elsewhere by Basov et al (ZhETF, v. 62, no. 1, 1972, 203).

4. Theoretical Studies

Askar'yan, G. A. Obtaining high temperatures and strong magnetic fields in a laser plasma, generated by a tubular light beam. ZhETF P, v. 10, no. 8, 1969, 392-394.

The theoretical possibility is shown for significantly increasing temperature and pressure and inducing strong magnetic fields in a luminous spark or plasma flare generated by a focused tubular laser beam. In an approximation of quasicylindrical geometry, the pressure p_1 of a convergent shock wave with initial radius r_1 would increase by compressing the medium to a radius $r_{min} = 0.1 r_1$. At the easily attainable initial electron concentration $n_{e sh} = 10^{21} - 10^{22} \text{ cm}^{-3}$ and $kT_{sh} = 100 \text{ eV}$ in a shock wave, p_1 is calculated to be $= 10^5 - 10^6 \text{ atm}$. In the case of collapse, i. e., collision between two shock waves propagating in opposite directions, the pressure behind the shock front is expressed by

$$p \approx \frac{3\gamma-1}{\gamma-1} p(r_{min}) \approx \frac{3\gamma-1}{\gamma-1} (r_1/r_{min})^b p_1 \approx K p_1 \quad (1)$$

where γ is the adiabatic exponent and the exponent b for a very hot gas ($\gamma = 7/5 = 1.4$) is 0.4-0.5. In this case, p_1 would increase by a factor $K = 5-20$. This increase in p_1 may cause a significant increase in the output of hard x-rays and neutron emission from a highly light-absorbing gaseous mixture with deuterium, liquid deuterium or a deuterated solid target.

An initial magnetic field $H_1 = 10^4 - 10^5 \text{ oe}$ can also be compressed within a convergent shock wave in a tubular spark or flare to a value $H(r) = H_1 (r_1/r)^2$. A maximum field strength $H \geq 10^7 \text{ oe}$ is calculated from the equality of the magnetic pressure to the pressure in the shock wave reflected by the compressed magnetic field. The cited method of producing magnetic fields is simple, compact and easily controllable. It follows that a magnetic

mirror with a forward propagation rate $\approx 10^9$ cm/sec can be used to accelerate conducting or charged particles and plasma portions.

Afanas'yev, Yu. V., E. M. Belenov, O. N. Krokhin, and I. A. Poluektov. Ionization processes in a laser plasma. ZhETF P, v. 10, no. 11, 1969, 553-557.

A brief theoretical treatment is given describing the ionization processes which occur in a laser-generated plasma. Two general cases are considered, namely for incident radiation density q limited to values for which the plasma can be considered as in quasiequilibrium, and for higher values of q where thermodynamic equilibrium breaks down owing to rapid electron diffusion. The principal treatment is given to the latter case, and a model is postulated for it which yields approximate expressions for plasma parameters including electron temperature, ionization level, radiative output, and others. The cited case is characterized by an increasing divergence between electron and ion temperatures in the plasma; for example, for $q = 10^{12}$ w/cm², the difference may be on the order of 10^3 ev. The treatment given is directly relevant to interpreting laser plasma diagnostics in terms of bremsstrahlung output or ion radiation lines.

Bunkin, F. V., and A. Ye. Kazakov. Electron heating and noncoherent hard radiation generated by interaction of ultrashort powerful laser pulses with matter. ZhETF, v. 59, no. 6, 1970, 2233-2243.

A theoretical study is described on electron heating mechanisms in laser-generated plasmas. The analysis is principally concerned with the

case of pulse widths on the order of a picosecond, at a wide range of intensities. For intensities I substantially above critical I_{cr} , it is assumed that beam interaction is entirely with the plasma electrons and nuclei, with ionization occurring "instantaneously", i. e. within the first one or two periods of the exciting radiation. Continued irradiation at this level can result in hard, noncoherent bremsstrahlung generation from the plasma, conditions for which are discussed. It is pointed out, however, that bremsstrahlung can also occur at appreciably lower electron temperatures ϵ_e , owing to electron vibratory energy ϵ_{vib} . For the sake of analysis, therefore, the conditions governing bremsstrahlung are defined in terms of two general conditions, namely $\epsilon_e > \epsilon_{vib}$ ("heated" electrons) and $\epsilon_e < \epsilon_{vib}$ ("unheated" electrons). Practical limits for obtaining the critical temperature and plasma density are also discussed.

Bunkin, F. V. and A. Ye. Kazakov. Compton mechanism in laser heating of an electron gas.
DAN, v. 192, no. 1, 1970, 71-73.

A theoretical treatment is given to the problem of high-power laser absorption in a plasma, for the particular case in which a multiphoton Compton effect takes place. This has been shown to occur in energy exchanges in which a plasma is heated to thermonuclear temperatures within the focus of a sufficiently powerful laser beam. The authors derive expressions for energy absorption coefficient and rate for the assumed multiphoton mechanism. The rigorous equations for these are simplified for practical solution by assuming an initially relatively cool electron gas ($T \ll 10^8$ deg), such that electrons are nonrelativistic. With this assumption the approximate solutions for the energy equations were obtained by computer, over a wide range of test parameters; a neodymium glass laser was assumed as a source. The theoretical data show that for powerful e-m fields the electron gas can be

strongly heated by multiphoton Compton effect; for example, for an incident laser intensity on the order of 10^{20} w/cm² and within a picosecond pulse width, the electron gas temperature can rise 10^7 degrees, or to thermonuclear temperatures.

Bunkin, F. V., and A. Ye. Kazakov.

Generation of electron-positron pairs from
focused laser radiation in a dense plasma.

DAN, v. 193, no. 6, 1970, 1274-1275.

The authors continue their analysis of the general case postulated in their foregoing paper herein, namely the production of relativistic energy levels in a nonrelativistic plasma by irradiation with a high-power focused laser. The conditions for generation of electron-positron pairs are analyzed quantitatively in terms of the parameter γ where

$$\gamma = \frac{e}{mc^3} \frac{H_0}{H_{Cr}} = \frac{e}{mc^3} \frac{E_0}{E_{Cr}}$$

in which E_0 , H_0 = electric and magnetic field amplitude; E_{Cr} , $H_{Cr} = m^2 c^3 eh$, and ϵ = electron energy. For laser energies conceivably attainable in the near future, i. e., on the order 10^{19} w/cm², $\gamma \simeq 10^{-5}$. Hence the authors take $\gamma \ll 1$ and assume scattering effects by nuclei as well as interaction with free electrons, in formation of electron-positron pairs. From these assumptions an expression is obtained for the number of pairs formed in a given plasma volume at a given initial electron density and incident laser radiation energy. An assumed limiting case, determined by maximum tolerable electron density, is shown for $\lambda = 1.06 \mu$ (Nd laser), radiation density = 5×10^{19} w/cm², a one-picosecond pulse and a focus volume of 10^{-7} cm³. From this the maximum attainable number of pairs $N_p \simeq 8 \times 10^4 Z$ where Z

is atomic charge. An expression for absorption coefficient is also derived. The authors note that the model does not require a prior ionization of the target volume since it can be shown that total ionization of the irradiated atoms can conceivably take place within the first period of the incident optical wave owing to tunneling action.

Anisimov, S. I. Effect of ultrashort laser pulses on absorptive substances. ZhETF, v. 58, no. 1, 1970, 337-340.

An analysis is given of the dynamics of material evaporation by laser pulses on the order of a picosecond, and significant differences are pointed out between these results and those obtained with the usual longer duration pulses. The specific differences occur in the mechanisms of condensed matter evaporation and in the kinetics of expansion of the resulting plasma. The author assumes a laser pulse duration well below the characteristic time for hydrodynamic motion, τ_0 , thus mass motion during the pulse interval may be neglected and the hydrodynamic and optical portions of the problem can be treated separately. The analysis shows that determination of specific vaporization energy and of vaporized mass can be obtained from knowledge of shock wave parameters in the target material. It is found that for sufficiently short pulses, the evaporated mass M is related to absorbed energy Q by $M \sim Q^{1-\alpha}$ where $\alpha < 1/6$. This is contrasted with the normally longer applied pulse, in which case the specific energy of evaporation rises rapidly with increased Q .

Boyko, V. A., and A. V. Vinogradov. On the role of reflection in high-temperature heating of condensed matter by laser radiation.
 KSpF, no. 5, 1970, 14-19.

Since the absorption of incident radiation in the generated plasma is critical to the laser fusion process, the authors analyze the factors governing absorption coefficient. The model assumes normal incidence of the e-m wave on a fully-ionized deuterium plasma, in which N_e is an exponential function of distance x from the target. Expressions are derived for complex dielectric constant in terms of laser wavelength and other parameters; these formulas relate coefficient of reflection to electron temperature, density, and nonuniformity level of the plasma in a useful way.

Fig. 1 shows the resultant graph which allows determination of reflection coefficient for a wide range of the other parameters; here $L =$

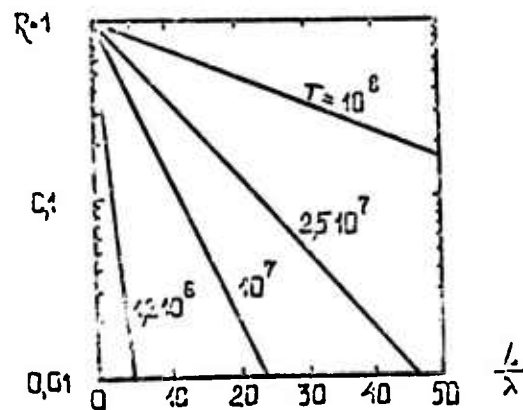


Fig. 1. Correlation of transition layer temperature T , °K, reflection coefficient R and nonuniformity factor L/λ for a deuterium plasma.

distance over which N_e drops from 10^{21} to 10^{20} . The graph shows, for example, that at $T_e = 2.5 \times 10^7$ deg K, in order to have effective absorption of incident radiation the nonuniformity factor, L , must be on the order of 50 times incident wavelength λ .

The authors note that their analysis accounts for nonlinear behavior of dielectric constant with x ; this makes it a refinement of a similar study by Dawson et al. (AIEE Fluid and Plasma Dyn. Conf., 68-676, Los Angeles, 1968) who assumed that $\epsilon(x)$ was linear.

Afnas'yev, Yu. V., E. M. Belenov, O. N. Krokhin, and I. A. Poluektov. Hydrodynamics and kinetics of a multiply-ionized, confined weakly-absorbing laser plasma. KSpF, no. 5, 1970, 43-47.

This is an extension of an earlier paper by the authors on the kinetics of a multiply-ionized laser plasma (ZhETF P, v. 10, 353-357), which did not consider hydrodynamic motion of the plasma. The treatment is generalized here to include hydrodynamic motion effects, one result of which is to remove constraint on pulse duration. The problem then is solution in Lagrange coordinates of the energy balance equation

$$d \epsilon / dt + P dv / dt = Q \quad (1)$$

where ϵ = unit thermal energy of the plasma, P = pressure, and Q includes incident energy plus ionization losses. The variables are further defined in terms of the absorptive coefficient of laser radiation, ionization level z_t and electron temperature T_e .

It is shown that the solution of (1) is independent of the nature of hydrodynamic motion, and that the hydrodynamics only affect $z(t)$ and $T_e(t)$. Hence for a full solution it is sufficient to know the density vs. time relationship of a fixed mass of plasma. The treatment accordingly examines $z(t)$ and $T_e(t)$ using a simplified model of a uniform plane plasma layer of fixed mass. From

the derived expressions an optimum incident flux density q^* is apparent, for which z attains maximum. In the cited model it can be shown that q^* is on the order of 10^{12} w/cm². Also, the lower limit for the validity of this model is given as $q = 10^{10}$ w/cm², below which ionization equilibrium evidently will occur.

Zakharov, S. D. and V. N. Fayzulayev.

Bremsstrahlung absorption of powerful
e-m radiation pulses in a fully ionized
plasma. KSpF, no. 5, 1970, 8-13.

The authors note that under high temperature heating of a plasma by laser radiation, absorption of light may be caused principally by bremsstrahlung emission, in which case the absorption coefficient K is independent of e-m field intensity. However, for powerful laser pulses in the picosecond range the field amplitude may have an appreciable effect on absorption; also, in this case the pulse width is comparable to the periodicity of electron-ion collisions, which would tend to reduce the absorbed energy. Assuming the latter case, the authors calculate K as functions of field strength E and pulse width τ , basing their work on an earlier paper by Bunkin et al (ZhETF v. 49, no. 10, 1965). A graphical solution for $K(E)$ is seen in Figure 1 for two heating levels.

(Figure on next page)

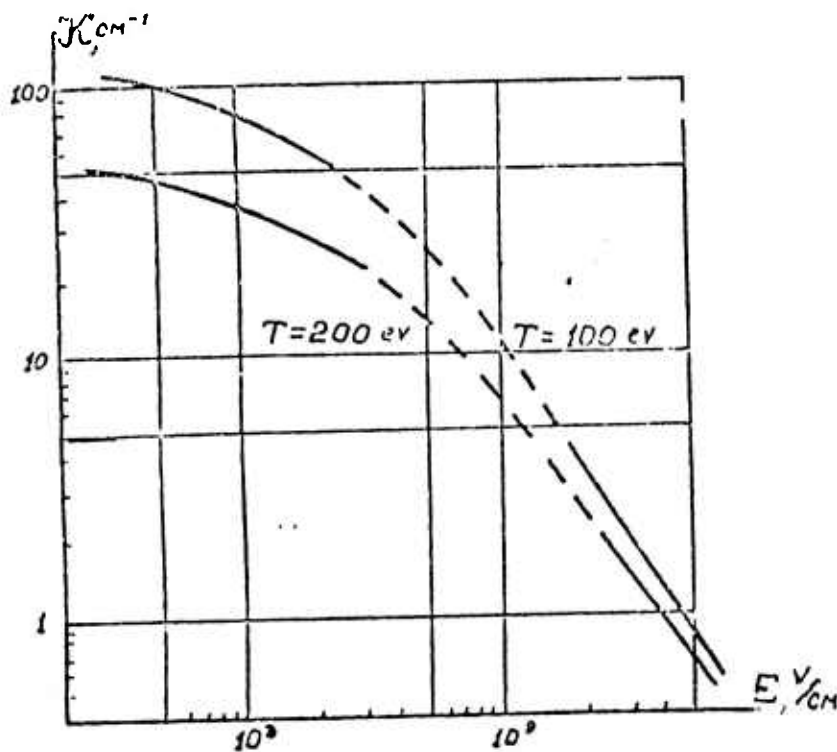


Fig. 1. Bremsstrahlung absorption vs. field intensity.

$$\lambda = 1 \mu, N_e = 5 \times 10^{20} / \text{cm}^3, Z = 1.$$

Zakharov, S. D., O. N. Krokhin, P. G. Kryukov, and Ye. L. Tyurin. Electron-ion relaxation in a plasma produced by ultrashort laser pulses. ZhETF P, v. 12, no. 2, 1970, 115-118.

This is a theoretical description of electron-ion relaxation in a high-temperature dense plasma obtained by focusing powerful ultra-short ($\tau = 10^{-11} - 10^{-12}$ sec) laser pulses onto a solid target, e.g., LiD. Electron thermal conductivity is assumed to be negligible at an initial temperature $T_0 < 500 \text{ eV}$ in the plasma with $n_0 X_0 = 10^{19} \text{ cm}^{-2}$, where n_0 is the electron density and X_0 is the plasma initial dimension. Also gasdynamic expansion of such

a plasma during time τ can be neglected; it is noted that τ is much shorter than the time τ_{ei} of electron-ionic relaxation.

The assumption that electrons are heated instantly to T_0 is justified, because the time τ_{e1} of electron-electron relaxation is shorter, e. g., $\sim 10^{-13}$ sec., than τ . A completely ionized plasma with bremsstrahlung is considered at $T_0 > 100$ ev. Heating of a small particle and a thin foil is described by a set of equations of plasma motion, energy conservation with allowance for radiation, and electron-ion relaxation. The initial conditions are: $T_e(0) = T_0$, $T_i(0) = 0$, $X(0) = X_0$, and $n_e(0) = n_0$.

An approximate solution to the cited equations is presented in the form of the maximum ion temperature T_{im} versus T_0 , since the T_{im} value is the most important for determination of neutron yield. The $T_{im}(T_0)$ plot (Fig. 1) shows that, as T_0 increases, relaxation in the process of

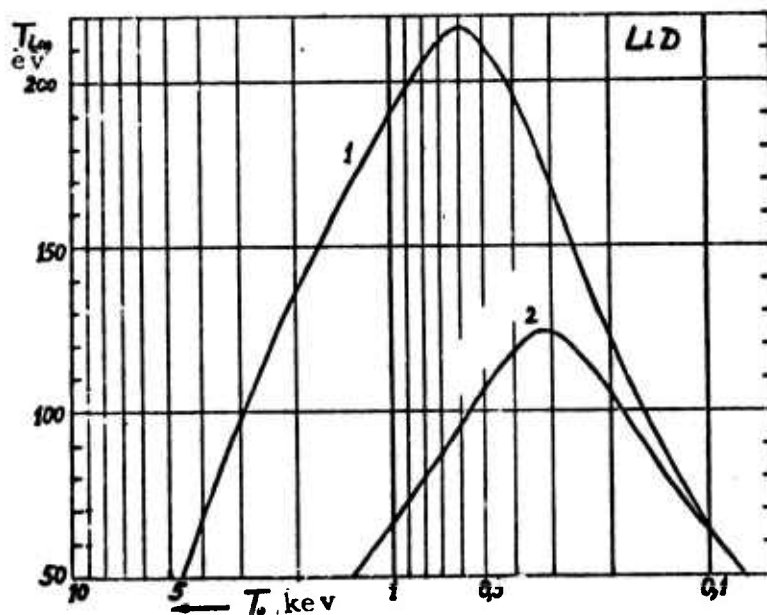


Fig. 1. Maximum ion temperature T_{im} vs. initial electron temperature T_0 in LiD plasma at $n_0 X_0 = n_0 \tau_0 = 10^{19} \text{ cm}^{-2}$.

Curve 1- two-dimensional dissipation, curve 2- spherical dissipation.

dissipation causes a slowdown in T_{im} rise. The decrease of T_{im} with further increase in T_o is explained by a plasma dissipation faster than heat transfer from electrons to ions. At a given T_o , T_{im} depends on $n_o X_o$. At $n_o X_o = \text{const}$, the temperature T_o^* of the peak T_{im} is $\sim (n_o X_o)^{1/2}$. At $n_e = \text{const}$, $T_o^* \sim Z^{3/4}$, where Z is the average ion charge.

It is concluded that it is impossible to attain $T_i > T_{im}^*$ in a shielded plasma ($n_o X_o = \text{const}$). Higher T_i can be obtained by simultaneous increase in T_o and $n_o X_o$, which is attainable by interaction of a very powerful pulse with a massive target. In this case, a high ion temperature is obtained with concurrence of the thermal conductivity mechanism.

Zakharov, S. D., Q N. Krokhin, P. G. Kryukov, and Ye. L. Tyurin. Plasma heating by ultrashort laser pulses in the process of electron heat conduction. ZhETF P, v. 18, no. 1, 1970, 47-50.

Results are presented of the numerical estimate of the ion temperature increase in a laser plasma due to thermal conductivity. The model considered assumed instantaneous heat release from electrons in an infinitely thin skin layer of the target. $T_e(x, t)$ as well as $T_i(x, t)$ were given in the form $T_e(t) (1 - x^2/x_f^2)^{2/5}$ where x_f is the electron thermal wave front coordinate (Zel'dovich and Rayzer, 1966). In the determination of the maximum ion temperature T_{im} the effect of the diffusion of the heated layer could be neglected, while the time τ_m during which T_{im} maintains relative stability depends on the diffusion of the heated layer with a thickness of x_m . Expressions for T_{im} , x_m and τ_m were developed for solving equations of thermoconductivity, energy conservation and electron-ion relaxation for the average temperature T .

The results of calculations are shown in Fig. 1. They are seen to be in good agreement with the values reported by Shearer and Barnes (Phys. Rev. Lett., 24, 1970, 92).

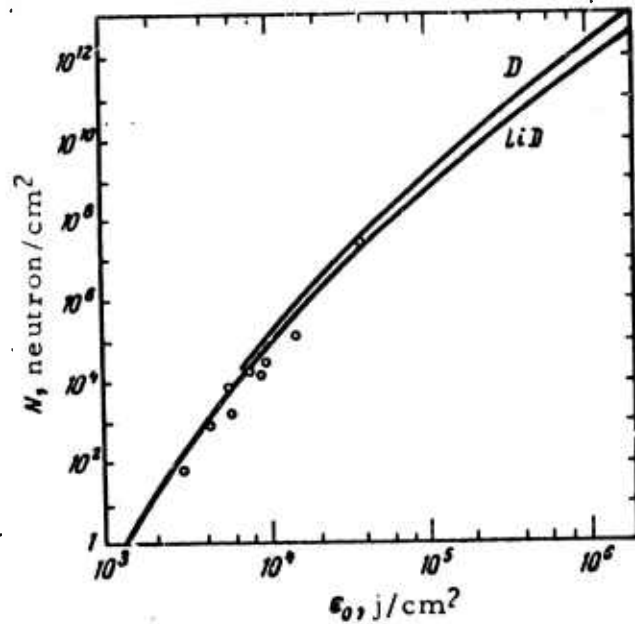


Fig. 1. The dependence of plasma neutron yield on the absorbed laser energy, calculated for solid D and LiD.

Circles- calculations of Shearer and Barnes (1970).

Zakharov, S. D., O. N. Krokhin, P. G. Kryukov, and Ye. L. Tyurin. Role of focusing in thermal conductivity heating of a plasma by strong laser radiation. IN: Sb. Kvantovaya elektronika (Moskva), no. 2, 1971, 104-107.

Laser heating of a plasma is studied for the high beam energy case in which penetration of the thermal wave into the target surface exceeds the focused spot size, $2r_0$. It is shown that a spherical model of heat propagation under these conditions is reasonably well supported by observed data.

The model assumes a substance with low z , so that a fully ionized plasma is generated, or $n_e = zn_i$. From energy balance and conservation expressions, further expressions are obtained for maximum electron and ion temperatures, as well as neutron flux decay with time. A comparison with other experimental data is given in Fig. 1. Using results from their related earlier work (see foregoing abstract, Zakharov et al.) The authors arrive at the relation of neutron yield, beam energy and focused area shown in Fig. 2. The results apparently confirm the validity of the spherical model used.

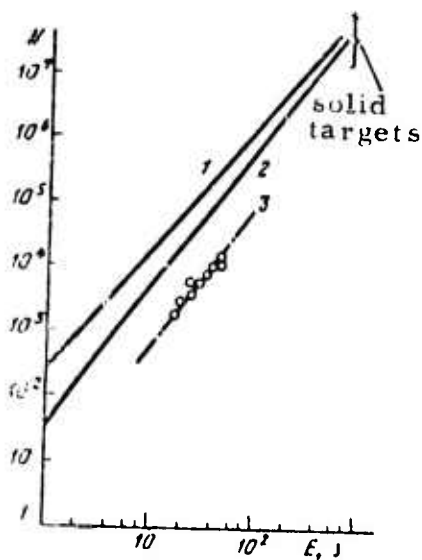
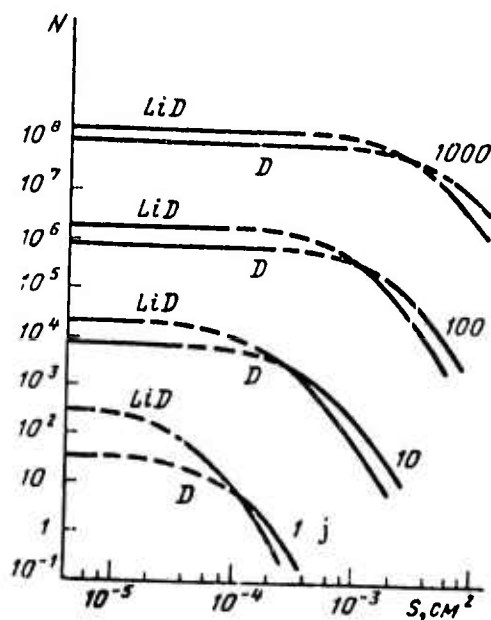


Fig. 1. $N(E)$ for the hemispherical thermal model. 1- LiD; 2- D with $n_d = 5 \times 10^{22}/\text{cm}^3$; 3- D with $n_d = 2.1 \times 10^{22}/\text{cm}^3$. Experimental points are those of Floux (Mezhd. konf. kvant. elektr, Kyoto, 1970)

Fig. 2. N yield vs. laser pulse energy and focused beam area, for LiD and D targets.



Zakharov, S. D., Ye. I. Tyurin, and V. A. Shcheglov. On the propagation of monochromatic radiation through a plasma. ZhETF, v. 61, no. 4, 1971, 1447-1451.

A rigorous analytical solution is obtained to the problem of propagation of pulsed monochromatic radiation in an absorptive plasma. The laser pulse is assumed to have an arbitrary waveform, and a radiation frequency well above plasma frequency; the volumetric change in electron density is also assumed to occur smoothly. With these assumptions, reflected radiation may be neglected. It is further assumed that electron collision frequency ν_e meets the condition $\nu_e \tau \gg 1$, where τ is the characteristic time to alter the mean electron energy in the plasma; this permits use of the concept of electron temperature. Expressions are then derived for pulse intensity as a function of penetration into the plasma and for absorption coefficient, assuming a bremsstrahlung mechanism. Fig. 1 shows theoretical

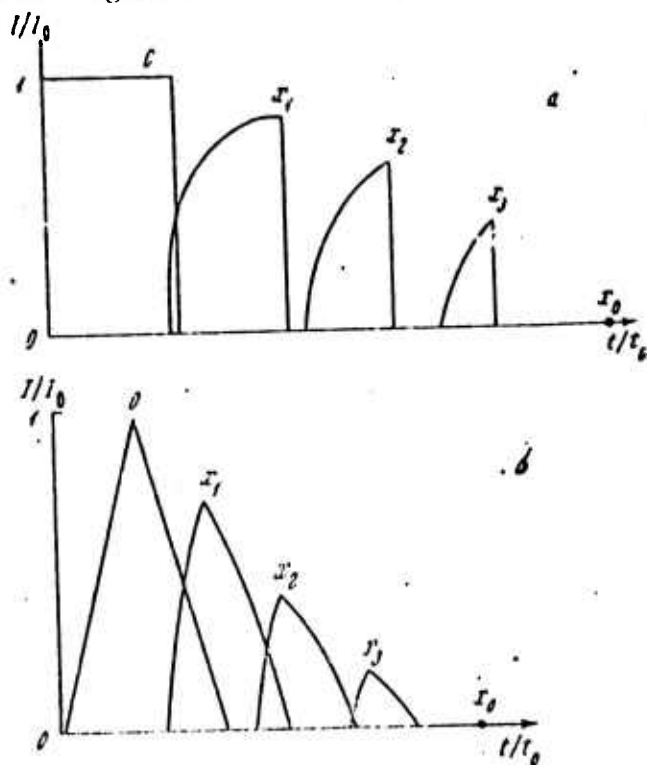


Fig. 1. Variation in pulse waveform vs. penetration into plasma.

degradation of an initially rectangular and triangular laser pulse vs. penetration depth. Other idealized solutions are presented, based on typical parameters of an Nd glass laser and a hydrogen plasma.

Zakharov, S. D., O. N. Krokhin, P. G. Kryukov, and Ye. L. Tyurin. Increasing the effectiveness of laser heating of a plasma by adding heavy trace elements to the target. IN: Sb. Kvantovaya elektronika, no. 2, 1971, 102-103.

Early tests on laser plasma generation from deuterium or various deuterides stressed the need for purity in the target material. The authors note however that in the inertial confinement case, when a divergence of ion and electron temperatures can occur, an enhanced ion temperature can be obtained by adding certain heavy trace elements such as CD_2 , CD_4 , ND_3 or D_2O . The resultant radiation and ionization losses would be negligible at least up to a ten-level ionization. Expressions are accordingly obtained for temperature behavior of a two-ion plasma, for the two general cases of reaching equilibrium temperatures during electron thermal conductivity and during plasma diffusion. Some hypothetical results based on added LiD , CD_4 or D_2O are given.

Zakharov, S. D., Ye. L. Tyurin, and V. A. Shcheglov. Dynamics of heating a fully ionized plasma by focused laser radiation. IN: Kvantovaya elektronika, (Moskva), no. 3, 1971, 106-108.

The authors derived expressions which define laser heating of a fully ionized plasma, for the symmetrical spherical optics case illustrated in Figure 1. The analysis assumes that gasdynamic expansion, electron-ion

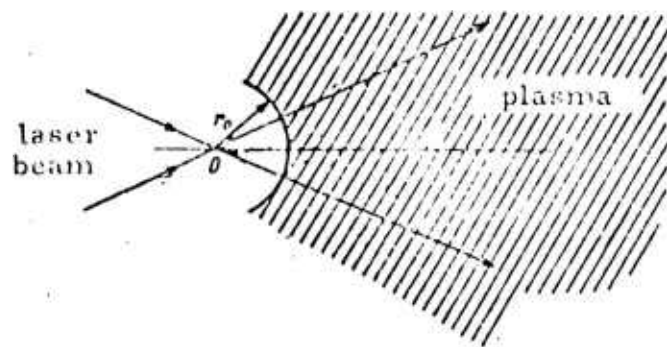


Fig. 1. Plasma heating model.

relaxation, and conduction and radiation losses may all be neglected. This is the accepted case for a nominally dense plasma ($n \approx 10^{20}/\text{cm}^3$) and for pulse widths in the ultrashort range ($< 10^{-10}$ sec). Following development of heat equations for the general case in terms of beam intensity I and plasma temperature T , the authors determine $T(r, t)$ and $I(r, t)$ for the specific case of interest of a sharply-focused beam such that the depth of the heated region $\gg r_0$ and plasma temperature in this region rises well above its initial value. It follows that an absorption wave of laser radiation will exist; an expression for the radius coordinate of this wave is given, from which a maximum effective penetration depth may be determined. The described model is applicable only on the condition that the length of the caustic of the focusing objective is substantially less than maximum penetration depth; otherwise a planar one-dimensional model must be used.

Pashinin, P. P., and A. M. Prokhorov.

Obtaining a dense high-temperature plasma
by laser heating of a special gas target. ZhETF,
 v. 60, no. 5, 1971, 1630-1636. (Translation)

The possibility is analyzed of using optical breakdown of gas (laser spark) to obtain a dense plasma at thermonuclear temperatures. It is

shown that to achieve ion temperatures on the order of $T_i = 10^8$ deg. K requires a laser pulse energy of 10^9 j. If a field on the order of 10^6 oe is applied for magnetic thermoisolation of the plasma, the laser threshold energy is considerably reduced, such that a pulse energy of 3×10^5 j at 10^{-7} sec. duration is sufficient for an energetically productive thermonuclear synthesis. This would require a special cylindrical gas target in a heavy shell, filled with a mixture of H-D and H-T isotopes at a pressure of 20 atm.

Afanas'yev, Yu. V., E. M. Belenov, O. N. Krokhin, and I. A. Poluektov. Possibility of obtaining a powerful neutron source from interaction of a pulsed laser beam with a complex target. ZhETF P, v. 13, no. 5, 1971, 257-260.

A theoretical evaluation is presented of the possibility of obtaining higher fusion neutron yields N_n from interaction of short laser pulses of equal energy with a complex rather than a pure condensed D-T target (Basov, et al. VAN, no. 6, 1970, 55). The complex condensed target presumably consists of a D-T mixture with $\sim 10\%$ admixture of a heavy element of mass number $A \cong 250$. A comparative theoretical description of heating the complex and pure targets under conditions of electron thermal conductivity shows that a complex plasma temperature $T^z = 20-30$ keV can be attained with a laser pulse energy $W^z = 10^3 - 10^4$ j and a plasma ion charge number $z = 50$. Under identical conditions, the pure D-T plasma temperature T^{DT} is calculated to be 10 keV. The corresponding N_n^z would be $= 10^{15}$ versus a several orders lower N_n^{DT} in a pure plasma. It is noted, however, that higher energy is required with the complex than with the pure D-T plasma to obtain gain in a thermonuclear reaction.

Numerical calculations of the complex DT plasma parameters T , N_n^z , heating depth x_{fr} , and energy gain W_{out}/W_z are made using the formulas for T , z , x_{fr} , W_o^z , W_{out}/W^z , and pulse duration τ_o^z . These formulas were obtained by solving the differential equations which describe the one-dimensional case of heating a target occupying the half-space $x \leq 0$, in terms of electron thermal conductivity $k = k_o \eta^{5/2} z^4$ and probability of ionization. At $x = 0$ and $K \partial T / \partial x = q(t)$, the radiation flux density, an exact analytical solution of the cited equations becomes possible. The solution represents heating and ionization waves with $T(x)$ and $z(x)$ variation rate dependent only on laser pulse parameters and target material characteristics. Examples are given of the numerical calculations for the fixed values of the parameter $\eta = T(z)$, where η is the Coulomb logarithm. Thus for $\eta = 0.7$, $W^z = 10^3$ joules, and $\tau^z = 10^{-10}$ sec., $T = 26$ keV, $N_n^z = 2 \times 10^{14}$, $X_{fr} = 2.3 \times 10^{-3}$ cm, and $W_{out}/W^z = 3.5 \times 10^{-1}$.

Afanas'yev, Yu. V., E. M. Belenov, O. N. Krokhin, and I. A. Poluektov. Self-consistent heating of matter by a laser pulse under conditions of nonequilibrium ionization. ZhETF, v. 60, no. 1, 1971, 73-82.

This theoretical paper deals with the one-dimensional plane problem of forming a multiply ionized plasma by a high-power laser pulse ($q > 10^{12}$ w/cm²) striking the surface of a solid target consisting of heavy elements, and occupying a half-space $x \leq 0$ under conditions of nonequilibrium ionization. Analytic expressions are derived for the hydrodynamic parameters, electron temperature, and ionization level of the plasma as functions of time, beam flux density, and target properties. Under conditions

of thermodynamic equilibrium, the ionization energy is the basic component of the intrinsic energy in the partially ionized plasma. This being the case, at large flux densities the presence of nonequilibrium conditions causes plasma behavior to resemble more closely that of an ideal gas, the pressure and internal energy of which are determined by electrons, and the inert properties, by its ions. This nonequilibrium implies also that the plasma produced by heating has a comparatively high temperature, a fact that can be used in those cases where it is desirable to raise plasma temperature. However, this implication holds only in those cases in which energy losses arising from radiation or thermal conductivity do not play an essential part.

Kaliski, S. Generalized equations for laser heating of a dual-temperature plasma with allowance for heat of thermonuclear synthesis.

Biul. WAT J. Dabrowskiego, v. 20, no. 12, 1971, 25-30. (RZhF, 5/72, no. 5G299)
(Translation)

Generalized equations are derived for laser heating of a plasma to obtain fusion, for the case of different ion (T_i) and electron (T_e) temperatures. The equations are based on the following simplifying assumptions: bremsstrahlung depends only on T_e , heat yield only on T_i ; radiation losses are negligible; thermal conductivity of ions is small relative to that of electrons; electron and ion densities are roughly equal; and the mechanical parameters of the system are not distinguishable by ion and electron component. Equations for laser heating of the plasma are obtained for $T_i = T_e$.

Askar'yan, G. A., and N. M. Tarasova. Initial stage of the optical explosion of a particle of matter in a powerful light beam. ZhETF, v. 60, no. 2, 1971, 617-620.

This theoretical paper is concerned with the very early stages of plasma generation from powerful laser impact on a solid, i. e. the period during which the size of the exploded volume of matter has not yet exceeded the dimensions of the incident laser beam. For their analysis the authors assume a simplified physical model in which total energy absorption occurs in the initially dense plasma, which is justified on the basis of known strongly nonlinear absorptive behavior to very powerful ultrashort laser pulses. In view of the resultant high electron thermal conductivity and small initial plasma dimensions, one may also safely assume an even temperature distribution throughout the plasma at this stage; furthermore, the short time interval involved permits the assumption of no radiant heat loss from the plasma. With these qualifications the authors use energy balance methods to arrive at a characteristic initial expansion velocity v_0 which depends only on incident flux density and initial material density.

Askar'yan, G. A., and V. A. Pogosyan.
Thermal track and self-focusing of a powerful beam in a medium. ZhETF, v. 60, no. 4, 1971, 1295-1299.

A theoretical study is given in which temperature distribution in time and space and nonlinear refraction are analyzed, during absorption of a powerful c-w laser beam or long laser pulses in a liquid or gaseous medium, with index of refraction derivative $n_T' < 0$. In such a medium the possibility exists of thermal self-focusing of a beam with a particular radial intensity distribution profile $I(r)$ which exhibits an intensity dip near the axis. At a

given $I(r)$ and moderate light absorption, heat propagation in time τ and space along the beam radius a is described by a nonstationary equation in a one-dimensional cylindrical approximation. The equation is solved for dimensionless temperature field Φ .

The solution shows a continuous temperature rise with time according to a logarithmic law, i. e., the temperature regime is nonstationary. The temperature gradient expressed as the derivative Φ'_ξ of dimensionless temperature Φ with respect to $\xi = r/a$ is analyzed in the near-axis region of the beam ($\xi \leq 1$) at any $\tau = \chi t/a^2$, where χ is the thermal diffusivity. As long as $\Phi'_\xi > 0$, T on the axis is always lower than T near the axis, i. e., conditions for self-focusing exist in a medium with $n_T^l < 0$. This condition is formulated as

$$\xi^2 < \frac{1+4\tau}{1+2\tau+8\tau^2}, \quad \xi \leq 1. \quad (1)$$

In the near-axial region (1) becomes

$$\tau < a^2/2r^2 \quad (2)$$

This unexpected result shows that even at very long durations, nonstationarity of the process is essential to self-focusing in the near-axial beam region with an intensity dip. Analysis of the Φ'_ξ expression at short $\tau \leq 1$ (initial heating stage) shows that $\Phi'_\xi > 0$ at $\xi < 1$, and hence there is self-focusing in the near-axial region, and $\Phi'_\xi < 0$ at $\xi > 1$, hence there is defocusing on the beam boundary, leading to banana-type self-focusing.

Solution of the transcendental equation $\Phi'_\xi = 0$ at any given ξ value shows that self-focusing is still possible within a fairly wide region at $\tau \sim 1$. At $4\tau \geq 1$, the near-axial self-focusing condition is the same as in (2). The increase in the focal distance during development of banana self-focusing from $\tau = 1/4$ to $\tau > 1/4$ is evaluated to be $L_f/L_{f1} \approx 4\tau$.

Gribkov, V. A., V. Ya. Nikulin, and
G. V. Sklizkov. Methodology of a dual-
wave interferometric study of axisymmetric
configurations of a dense plasma. IN: Sb.
Kvantovaya elektronika, no. 6, 1971, 60-68.

Limitations are discussed of conventional ultra-high speed dual-wave interferometry as applied to dense hot plasma diagnostics, e.g., in the study of laser plasma, θ pinch, plasma focus and other types of thermonuclear devices. Generally, determination of the plasma electron density N_e by dual-wave interferometry is feasible only when plasma wavelength λ_{ik} is much shorter than the incident radiation wavelength λ . This is not always the case, hence as a rule spectroscopic measurements take precedence over interferometric measurements. It is also shown that a plane monochromatic source and the absence of plasma waves with λ_{ik} equal to the selected λ are necessary conditions.

Laser interferometry of axisymmetric plasma inhomogeneities with a large N_e gradient is outlined in the framework of geometrical optics, under an assumption of negligible beam refraction. The interferometric band shift $\delta(y)$ which is measured with a given accuracy is used to calculate the index of refraction $\nu(r) = n(r) - n(0)$ of the plasma inhomogeneity by solving the Abel integral equation (Fig. 1). N_e is expressed as a difference of plasma

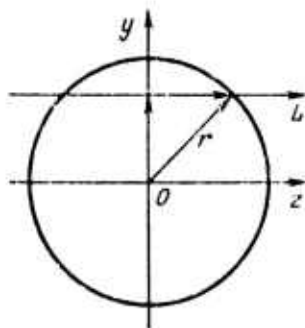


Fig. 1. Beam trajectory through an inhomogeneous region.
O- center of region symmetry normal to the figure plane;
L- incident beam.

polarizations (n-1) at λ_1 and λ_2 of the first and second harmonics of a ruby laser used a light source. Numerical calculation of the phase index of refraction $n(r)$ by conventional linear approximation, e.g., using the trapezoidal rule, is shown to be significantly erroneous in the case of a sharp N_e gradient. To reduce the computation error, approximation of the $\nu(r)$ function is proposed by a Lagrangian parabolic interpolation polynomial, which is equivalent to the Taylor expansion. This approximation is preferable to the linear one only within a certain N_e gradient range.

The proposed approximation, as applied to calculation of the Abel integral, is reduced to computation of the factors A_{ji} , B_{ji} , and G_j in the formula for $\delta(y)$ for a number N of segments of the inhomogeneity cross-section. In the case of $\nu(r) = \exp(-r/r_0)$, calculations show that the parabolic approximation error $\Delta\nu(r_i)/\nu(r_i)$ decreases as the reciprocal of $N^{-5/2}$, while the error in the trapezoidal rule method decreases as the reciprocal of $N^{-1/2}$, hence it is necessary to increase N to minimize the approximation error. However, with increase of N , the $\delta(y)$ measurement error is increased. Consequently, the summary error is minimum for an optimum N_{opt} , which is calculated, for $r_N/r_0 = 5$ and $\Delta\delta/\delta = .01$, to be 15 and 125, respectively, in the parabolic and trapezoidal rule approximations. The respective summary errors of ν_0 determination are 7 and 50%.

It is concluded that the parabolic method of interferogram treatment is preferable to any other known method of interferometry of plasma configurations with large but not discontinuous N_e gradients.

Galeyev, A. A., V. N. Orayevskiy, and R. Z. Sagdeyev. Anomalous absorption of electromagnetic radiation at double plasma frequency. ZhETF P, v. 16, no. 3, 1972, 194-197.

The probability is discussed of an anomalous absorption of e-m radiation by a hot plasma with density $n_0 = 1/4 n_{crit}$. The mechanism of the

cited absorption is an effective increase in electron collisions with the ω_1, k_1 and ω_2, k_2 plasma waves which develop following conversion of the pumping wave ω_0, k_0 . At $k_{1,2} > k_0$, the plasma instability increment is expressed through the interaction matrix

$$V_{k_1, k_0, -k_2} = \frac{\omega_p}{\sqrt{4n_0 m |\omega_0|}} k_0 \sin 2\theta \cos \phi, \quad (1)$$

where θ and ϕ are the spherical coordinates. Eq. (1) correlates probability measures of the three waves. On the theory that effective collisions of particles with turbulent plasma pulsations raise the instability threshold, the effective collision frequency ν_{eff} is described by

$$10,5 \omega_p (\epsilon E_0^2 / 8\pi n_0 m c^2)^{1/2} - \nu_{\text{eff}}^{\text{el}} |W_k^{\text{el}}| = 0 \quad (2)$$

where W_k^{el} is the power spectral density of plasma oscillations. It is assumed that $\nu_{\text{eff}}^{\text{el}}$ defines electromagnetic mode dissipation.

A theoretical model is presented for the nonlinear process of stimulated plasmon scattering on ions in a inhomogeneous rarified plasma interacting with an incident e-m wave at a 45 degree angle. The existence is presumed of a non-Maxwellian electron tail which absorbs plasmons from the plasmon condensates formed in the rarified plasma. In this case a one-dimensional turbulence model can be described by two equations which are solved for W_k^{el} and the electron distribution function $F_e(v)$. The solution for W_k^{el} includes the factor W which is the average power spectral density. The W value can be determined either from the linear amplification law or with allowance for nonlinear instability saturation due to stimulated scattering of plasmons by ions.

The amplification factor

$$K = (2\pi\omega_p L / 4\pi c) E_0^2 / 8\pi n_0 T_e \quad (3)$$

is maximum for a perturbation pair, one of which is at a constant frequency.

Instability threshold is determined by the condition $K > \log \Lambda$, the Coulomb logarithm, for attaining nonlinearity level. From the solution for W_k^2 and the second quasilinear equation, the solution for $F_e(v)$ is obtained in terms of a probability integral. At a small density-gradient scale length L , the solution becomes

$$F_e(v) = K / \pi \omega_p L, \quad v / v_{Te} < \sqrt{3\omega_p / (\omega_0 - 2\omega_p)}. \quad (4)$$

At a very high L value, a condensate of plasmons is formed, which may cause an increase in plasma inhomogeneity.

Krokhin, O. N., and V. B. Rozanov. Emission of alpha particles from the region of a thermonuclear reaction induced by a laser pulse. IN: Sb. Kvantovaya elektronika (Moskva), no. 4, 1972, 118-120.

The fraction of α -particle energy which remains within the region of a D + T thermonuclear reaction is evaluated, as a function of target dimensions, density and temperature $T = 3-50$ keV of the plasma. This fraction $(1-\eta)$ helps sustain a high T in the plasma. Only the α -particle energy fraction transferred to the plasma electronic component is considered, since an α -particle with energy $E \geq 35T$ is decelerated, mostly by electrons, in any completely ionized material. The cited limitation applies to the energy fraction $1-35T/E_0$ where E_0 is the initial energy of an α -particle.

The energy of an α -particle in a point of the plasma volume at a distance r from the point of the particle generation is expressed as

$$E = E_0 (1-r/\lambda)^2 \quad (1),$$

where $\lambda = 2.6 \times 10^{21} T^{3/2} / n_e$ is the mean free path of α -particles in the plasma. The energy fraction η carried by the α -particles outside a spherical volume of radius R is given as

$$\eta = \frac{1}{4\pi} \left[\frac{1}{160\tau^2} + \frac{1}{2} + \frac{R}{l} + 1 - \frac{3\pi}{2} + \frac{4}{5} \tau + \frac{1}{2} \right] \quad (2)$$

where $z = t\mu + [1-t^2(1-\mu^2)]^{1/2}$ and $t = \rho/R$ are the variables, $\mu = \cos \theta$ defines the angular particle distribution, and $\tau = R/\lambda$. Eq. (2) makes it possible to evaluate the fraction $(1-\eta)$. The formula is applicable within the cited T range which is of interest to nuclear fusion, under the assumption that the α -particle E and its transverse impulse p_1 satisfy the conditions

$$\frac{E}{T} > \frac{M_\alpha}{m} \left(\frac{3V_0^2 - m v_1^2}{4M_\alpha e} \right)^{2/3} \quad (3)$$

and

$$p_1^2/p_0^2 = 6T/E_0 \ln(v_0/v_1) \ll 1, \quad \text{since } T \ll E_0 \quad (4)$$

respectively. In the formulas (3) and (4) M_α , M_i , and m are the masses of an α -particle, ion, and electron, respectively, e_i and e are the charges of an ion and an electron, p_0 is the α -particle initial impulse, V_0 and V_1 are the initial velocity and that resulting from the α -particles deceleration. It is calculated that $\sim 40\%$ of the thermonuclear energy from α -particles would remain in a plasma sphere of $R = 0.5$ cm at $n_e = 5 \times 10^{22}$ cm⁻³ and $T = 10$ keV.

Equations are also derived for the total charge Q accumulated in the region of thermonuclear reaction and the energy $\Delta E = Z_\alpha e Q/R$ which an α -particle must expend to overcome the Coulomb barrier, assuming that the plasma electric conductivity is due entirely to Coulomb forces. It is hence calculated that $\Delta E \leq E_0$ for $R = 0.1-1$ cm, $n_e = 5 \times 10^{22}$ cm⁻³, and $T = 1-10$ keV.

Kaliski, S. Explosion cumulation of a plane electromagnetic field at relativistic initial velocities of a conductive shell. Bull. Acad. pol. sci., ser. sci. techn., v. 20, no. 2, 1972, 119-125. (RZhF, 8/72, no. 8A242)

In connection with plasma heating by lasers, a solution is presented to the problem of contraction of a plane magnetic field from implosion of a heavy conductive shell, moving through the field at a given initial velocity v . Assuming v is quasirelativistic, the problem is formulated by equations of electric and magnetic field components and shell motion with boundary and initial conditions. The E and H fields obey Maxwell equations and the boundary conditions are in the form of ordinary differential equations. A solution for the equations is obtained by the method of characteristics (Fig. 1). Assuming v is constant in the T_{i+1}, t_i sections, H on the plate surface is given by

$$H_i^* = H(t_i) = F(ct_i + x_{0i}) + F(ct_i - x_{0i}) \quad (1)$$

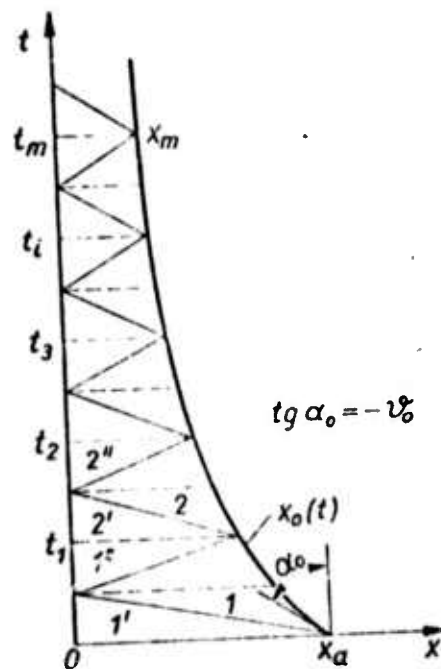


Fig. 1. Solution plots in the plane of characteristics.

The relation between H^* and the function F for successive sections of the solution is

$$F(\kappa) + F(\kappa) \frac{1+v_{j+1}}{1-v_{j+1}} - F(\kappa) \frac{2}{1-v_j} = H^*(\kappa) \quad (2)$$

where

$$c\tau + x_0(\tau) = \kappa, \quad (3)$$

and $F_{j+1} = F$.

Solution of the equation of shell motion in a non-relativistic approximation is given as

$$v = \sqrt{v_0^2 - \frac{H_0^2 x_a^2}{4\pi m} \frac{1}{x_0}} = \dot{x}_0 \quad (4),$$

where

$$H = H_0 \frac{\chi_a}{\chi_0}$$

and m is the mass of the wall unit surface. Practical values would be $v \approx 10^9$ cm/sec, $H_0 = 10^5$ gs, and $m \approx 1$ g/cm². A closed solution to the problem of magnetic field contraction was obtained based on the quasi-relativistic approximation. When $v/c \leq 1$, the field discontinuity of the characteristics can be disregarded and solution (4) is applicable, in agreement with the known non-relativistic (quasi-static) solution of field constriction by implosion. The quasi-relativistic solution may be applicable for very high implosion velocities, particularly in cumulative laser heating of plasma.

Kaliski, S. Conductive laser heating of nonhomogeneous plasma. Bulletin de l'Academie Polonaise des Sciences, serie des sciences techniques, v. 20, no. 12, 1972, 211 (963)-215 (967).

A simplified method of momenta, which was introduced by the author in the same periodical [v. 20, 1972, 1(35) and 7(41)] for spherical and cylindrical waves in single-temperature plasma, is extended to solution of the plane wave problem in a nonhomogeneous plasma heated by a laser. The method of solving averaged equations is based on assumption of the electron mechanism of heat conduction and disregards, in a first approximation, the fusion energy recovered. It is shown that the general solution obtained by the simplified method describes weak inhomogeneities more realistically than the solution obtained by the classical method of momenta. In addition, a closed form solution was derived for linear inhomogeneities (two-temperature plasma). It is noted that a general simplified solution, but not in closed form, can be obtained for the spherical or cylindrical wave with allowance for the recovered energy of nuclear fusion. The author concludes that the cited solutions extend to some degree the range of averaged description to inhomogeneous, specifically weakly inhomogeneous, media.

Kaliski, S. Numerical analysis of averaged equations of laser concentrated plasma cumulation, taking into account nuclear fusion energy. IN: *ibid.*, 3-9. (RZhF, 5/73, no. 5G233). (Translation)

Numerical solutions obtained by analog computer are given which define the intense compression of a plasma, obtained by laser explosion of a solid shell target. A simplified solution is presented in which the inter-

action with the shell is treated in terms of the initial velocity of a given mass of D-T plasma. A complete solution of the problem may be given based on more generalized equations of integral probability for the assumed model.

Kaliski, S. Average equations of deuterium-tritium plasma compression due to laser explosion with a heavy cloud ablation, taking nuclear fusion energy into account. Biul. WAT J. Dabrowskiego, v. 21, no. 12, 1972, 11-12. (RZhF, 5/73, no. 5G234).

Solutions are given of averaged equations for the integral self-similar problem defining concentrated laser compression of a D-T plasma, generated by laser explosion of a heavy shell. A Fermi liquid model is taken to apply to the D-T pellet; the shell is modelled as an ideal two-temperature gas. The method of laser compression of a plasma is presented as a new step toward realization of microsynthesis reactions; it permits a reduction in critical level of laser energy, in comparison with other techniques. The derived equations, accounting for laser pulse energy and nuclear fusion yield, are solvable by computer.

Kaliski, S. Conductivity-type laser heating of a nonhomogeneous plasma. Bull. Acad. pol. sci. Ser. sci. techn., v. 20, no. 12, 1972, 963-967. (RZhF, 5/73, no. 5G235)
(Translation)

A generalized pulse method is applied here to thermally conductive heating of a nonuniform plasma, obtained from laser-target interaction. A general solution is obtained for a nonuniform case, and a

closed analytical solution is given. This method can also be applied to solve the problem of a spherical or cylindrical thermal wave, accounting for energy released in the plasma in the course of a thermonuclear reaction; it applies also for the case in which ion and electron temperature differ (two-temperature plasma). In the latter case, however, a closed solution cannot be obtained.

Pashinin, P. P., and A. M. Prokhorov.
Obtaining a high temperature deuterium
plasma by laser heating of a special gas
target. ZhETF, v. 62, no. 1, 1972, 189-194.

An estimate is made of the electron temperature during laser heating of a deuterium plasma; a special gas target is assumed which is a cylindrical tube closed at the ends by a thin film and filled with gaseous deuterium. The dependence of the plasma temperature and the neutron yield on laser energy were numerically estimated for such a target. The radius of the heated plasma volume and the time of inertial confinement were estimated as well. Calculations are made for different initial gas pressures within the target and various values of external magnetic fields applied.

1. Zero magnetic field. In this case the calculations reduce to the case of inertial plasma confinement on a semi-infinite solid target (Basov and Krokhin, 1970; Shearer and Barnes, 1970). The time of inertial confinement equals the thermalization time τ_{ei} ; the diameter of the plasma volume heated by electron thermoconductivity η_e is determined from $r^2 = \tau_{ei} \eta_e / C_v$ where C_v is specific heat. The results of the calculations are shown in Figs. 1 and 2.

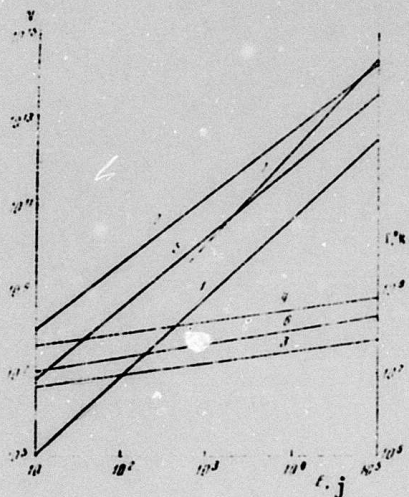


Fig. 1. Dependence on laser energy of the total neutron yield (curves 1, 2, 5, 7) and maximum temperature (curves 3, 4, 6)

1- $n = 10^{21} \text{ cm}^{-3}$, $H = O$; 2- $n = 5 \times 10^{22} \text{ cm}^{-3}$; $H = O$;
 5- $n = 10^{21} \text{ cm}^{-3}$, $H \neq O$; 7- $n = 10^{21} \text{ cm}^{-3}$, $H = 10^6 \text{ oe}$.

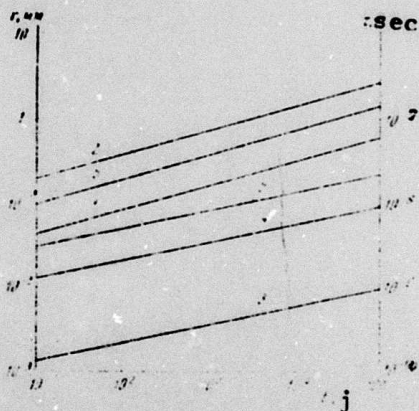


Fig. 2. Dependence on laser energy of the radius of heated plasma volume (curves 1, 2, 6) and the time of inertial confinement (curves 3, 4, 5).

1- $n = 5 \times 10^{22} \text{ cm}^{-3}$, $H = O$; 2- $n = 10^{21} \text{ cm}^{-3}$, $H = O$;
 6- $n = 10^{21} \text{ cm}^{-3}$, $H \neq O$.

2. Moderate magnetic field. An external magnetic field applied parallel to the target axis can considerably reduce the electron thermoconductivity in the radial direction, i. e. $\eta_{e\perp} < \eta_i$. The magnetic field which meets this condition is given by $H \geq 2.5 \times 10^{-5} n_e / T_e^{3/2}$. In this case the energy balance of the heated plasma is determined as in the previous case, while the radius of the plasma volume heated is determined from $r_1^2 = \tau_{ei} \eta_i / C_v$. The results of calculations are given in Fig. 1 (curve 5, 6) and Fig. 2 (curves 5, 6).

3. Strong magnetic field. A sufficiently strong magnetic field can reduce the ion thermoconductivity as well. This occurs when $\omega_i \tau_i \geq 1$. The field which meets this condition is given by $H \geq 1.3 \times 10^{-4} n_i / T_i^{3/2}$. In this case the calculations are made using a classical expression for ion thermoconductivity. The radius of the heated plasma volume is then determined from $r_1^2 = \tau_{ei} \eta_u / C_v$. The results of these calculations are shown in Fig. 1 (curve 7).

It is concluded that the use of a pulsed magnetic field for plasma thermoisolation in conjunction with inertial confinement by a heavy shell is promising over a wide range of laser energies, even at a moderate magnetic field of $H \approx 5 \times 10^5$ oe. In addition the focusing sharpness at all levels of the laser energy is within an attainable range.

It was pointed out that both in the case of $H = 0$ and a moderate magnetic field, $N \sim E^{3/2}$, which is in agreement with the results of Floux et al. (cf. Phys. Rev., A1(3), 1970, 821).

Fanchenko, S. D., and G. V. Sholin. Possible mechanisms of turbulent heating of a plasma by ultrashort laser pulses. DAN SSSR, v. 204, no. 5, 1972, 1090-1093.

The authors consider the initial ionization phenomena arising from interaction of a picosecond laser pulse with a very dense plasma. A feature of this case is that the optical field strength E is comparable to intra-atomic field E_a ; this results in an ionization time τ_{ion} on the order of or less than electron-atom or electron-ion collision time, and possibly less than the laser wave period. The model used assumes a picosecond pulse with optical frequency Ω falling on a condensed neutral target. During the first portion of the optical wave rise time, light penetrates the target virtually without ionization taking place; as the optical field approaches its peak of E , ionization begins but with an electron plasma frequency ω_{pl} still below Ω . As $E \rightarrow E_a$ the affected electrons proceed from bounded to unbounded motions in a time interval $\sim 10^{-15}$ sec. The authors then treat the two general intervals of collisionless plasma heating which ensue, namely when $\omega_{pl} < \Omega$ and $\omega_{pl} > \Omega$. Ionization parameters are obtained taking into account the magnetic piston effect exerted by the optical field when ω_{pl} overtakes Ω . Results show that at this point a beam of electrons forms in the focal region which may attain directional energies of 10^4 ev. Calculations based on a typical set of plasma parameters show that this current may exist for up to 10^{-12} sec. and reach densities above 10^{12} a/cm². It is emphasized that these deductions apply only to the initial one or two periods of laser pulse oscillation, applied to a neutral medium. Analogous effects from shock-wave and electron beam heating of a plasma are also noted.

Rayzer, Yu. P. Discharge propagation and confinement of a dense plasma by electromagnetic fields. UFN, v. 108, no. 3, 1972, 429-463.

This is a systematic review and analysis of known experimental and theoretical research data on continuous discharge plasma generation, and its confinement in an electromagnetic field. Soviet sources comprise 75% of the 55 references. The data reviewed are divided into three main groups according to the type of discharge propagation regime: supersonic shock wave, subsonic equilibrium heat conduction, and nonequilibrium ionization wave regimes. An analogy is drawn between the different discharge propagation regimes and detonation or slow burning mechanism of combustion. Thus the supersonic propagation of the laser plasma front in air is related to optical detonation, which may be treated as a hydrodynamic discontinuity by analogy with a detonation wave in combustion.

Flow propagation, e. g. at ≈ 40 m/sec, of the plasma front initiated by a spark discharge in air, and maintained by a focused laser beam with subthreshold intensity, is interpreted as a slow burning of the laser beam. In this case, the optical discharge propagates by a heat conduction mechanism. The same mechanism explains generation of a dense low-temperature plasma by h-f discharge in a static gas at atmospheric pressure, or in a gas flow through an induction plasma torch, "flame" propagation in atmospheric air in s. h. f. waveguides, s. h. f. discharge in a gas flow in plasmatrons of different geometry, or in a Kapitza resonator, as well as arc discharge in a plasmatron in the absence of gas flow.

Temperature determination and h. f. or s. h. f. discharge stabilization are discussed for the cited configurations. One chapter is devoted to stabilization of an optical discharge in an optical plasmatron by laser beam focusing, a subject frequently reported on by Rayzer. A nonequilibrium ionization wave regime is established in a pulsed discharge

in stationary inert gases with a cesium vapor admixture, owing to electron thermal conductivity. The well-known static discharge contraction in a d.c. field is variously explained by radiation or heat transfer to the wall. The ionization wave in a shock wave or spark-induced, localized inert gas plasma in a s.h.f. waveguide propagates by the mechanism of resonance radiation transfer. In contrast, the ionization wave initiated by s.h.f. discharge in a molecular gas (N_2 , air) propagates by a thermal conduction mechanism. Another possible mechanism of optical-discharge-induced wave propagation is the superdetonation heat conduction regime which prevails at a beam intensity higher than that which initiates supersonic detonation. Plasma temperature in this case attains several million degrees and the discharge wave propagates with a velocity higher than the shock wave velocity. This regime is analogous to the heat wave generated at an early stage of very strong explosions.

Finally, the radiation mechanism is discussed in relation to propagation of a laser spark from giant pulses. The breakdown wave initiated by a focused laser beam with intensity above the breakdown threshold propagates at "phase" velocities by a mechanism basically different from all cited mechanisms.

Bunkin, F. V., P. P. Pashinin, and A. M. Prokhorov. Possible use of i-r lasers for high temperature heating of a superdense plasma.
ZhETF P, v. 15, no. 9, 1972, 556-559.

The authors investigate the energy delivery, target density and associated parameters required for optimum laser heating of a superdense plasma at i-r wavelengths, specifically for a CO_2 laser, $\lambda = 10.6 \mu$. An axial magnetic field is assumed, and the problem solution predicates a high enough energy transfer rate so that inertial confinement applies.

The main criterion for quasilongitudinal wave propagation in a plasma generated by laser frequency ω is given by

$$(\omega_H/\omega) \cos \phi > 1, \quad (1)$$

where ω_H is electron gyrofrequency and ϕ is the angle between wave propagation direction and the applied magnetic field. The question then becomes how effectively this wave can be propagated in a superdense plasma. It is shown that besides a small dispersion angle ϕ , a sufficiently high gradient of electron density, i. e. $\Delta z = (N_e/N_e') \omega_p = \omega'$ is required at $\omega_p \approx \omega$ for high energy transfer. In an example given for a CO_2 laser pulse of one nanosecond and $N_0 = 5 \times 10^{22}/\text{cm}^3$, it is shown that ϕ should be less than 2×10^{-2} rad, which is within experimental capability.

If the magnetic thermal insulation effect which is present is also taken into account, i. e. the "hard shell" postulated by Pashinin et al. (ZhETF, v. 82, 1972, 189), the energy requirement for the laser pulse is substantially lowered. Using the same conditions as above, the authors arrive at a figure of $E_{\text{min}} = 3 \times 10^3$ j, which is over two orders lower than the most optimistic estimates at the time of writing.

Tyurin, Ye. L., and V. A. Shcheglov.

Radiant heat wave in a moving plasma.

ZhTF, no. 8, 1972, 1586-1590.

The article presents an analytical solution to a problem of heated plasma flow with a preset density and random time dependence of flow velocity $v(t)$. At the boundary $x = 0$, a laser energy flow occurs with a random time form $I_0(t)$. This corresponds to the physical condition when plasma is heated by powerful laser radiation in the energy range of 10--100 joules per pulse, and pulse duration τ which agrees with the gas-dynamical plasma dispersion τ_{gd} , and equals 10^{-9} sec. Plasma heating

by two or more pulses is examined which improves the heating quality when the process is essentially unstable and absorption is determined by the number of discharge particles.

Radiation transfer and energy conservation equations are solved for a medium where $n = \text{const}$ and $v \ll c$ at the preset boundary conditions. The solutions describe the process of heat wave propagation in a moving radiation absorbing medium. The solutions are applicable to any form of absorption coefficient K temperature dependence and cover a broad range of initial conditions. Heating of sufficient intensity generates a sharp front wave $x = x_0$, where $\partial t / \partial x$ is maximal and the temperature $T_{\text{fr}} = \text{const}$. As a function of current time t and setting time t_s when $dx_{\text{fr}} / dt = 0$, two heat wave propagation modes were noted: at $t < t_s$ the heat wave motion is unstable and it propagates into the plasma; at $t = t_s$ the front comes to a stop, and its motion and other wave parameter variations are subsequently dependent on changes in the plasma flow velocity $v(t)$ and radiation energy velocity $I_0(t)$. In other words, when $t \geq t_s$ the heating process becomes stabilized and at the boundary $x = 0$ this leads to equality between plasma radiation energy flow $I_0(t)$ and heat energy flow. Heat wave parameters were computed under two conditions: 1) $v = \text{const}$ is the plasma flow average velocity under the pulse effect; and 2) $v \sim T_0$ accounts for an increase in plasma velocity during the heating process. It was proven that variations in velocity in relation to heating had only a slight effect on the time t_s but doubled the heating time. Numerical estimates are given for t_s and the maximum depth of heat wave penetration into plasma x_{max} under typical laser heating conditions. At $I_0 = 10^{13} \text{ w/cm}^2$, $n = 10^{21} \text{ cm}^{-3}$, and $v = 2 \times 10^7 \text{ cm/sec}$, the values $t_s = 5 \times 10^{-9} \text{ sec}$ and $x_{\text{max}} = 5 \times 10^{-2} \text{ cm}$ were obtained. At a relatively high pulse energy ϵ expressed in joules per square centimeter, the heat wave possibly approaches the non-transparent plasma layer when $n \geq n_{\text{crit}}$, which leads to the reflection of laser energy from the target.

The solutions obtained by the authors permit estimates of the optimal duration τ_{opt} of single or pulse packets from specific ϵ , n , v and plasma absorption layer thickness values with non-reflecting characteristics and under maximum temperature conditions. It was also demonstrated that only about one half of radiation energy was used for plasma heating, the remainder being dissipated in the plasma.

Plis, A. I., Ye. L. Tyurin, and V. A. Shcheglov. Heating of materials by short laser pulses. ZhTF, v. 17, no. 12, 1972, 2568-2576.

In connection with the use of laser energy for heating solid materials to fusion temperatures, a theoretical analysis is given of two-dimensional solid target heating by ultrashort ($\tau_p \lesssim 10^{-11}$ sec) powerful laser pulses. The heat conduction and gas dynamic unloading of the heated material are taken into account. A density profile $n(x)$ and the optimum heating conditions of a plasma layer formed by single-pulse interaction with the target are defined for ice, lithium deuteride, or polyethylene materials used for neutron generation.

An analytic method was developed for calculating plasma layer temperature T_{lim} and energy Q absorbed in the plasma at the pulse cut-off time t_c . Pulse reflection from the cut-off boundary x_c , where the electron density is $n_c \approx 10^{21}/\text{cm}^3$, is taken into account in calculations. With allowance for additional plasma heating by the reflected pulse, the approximate formulas of Q and T_{lim} for an arbitrary $n(x)$ are, respectively,

$$Q = \left(\frac{2}{3}\right) n_c (mc^2)^2 \int_{-\infty}^{x_c} \left(\frac{u}{u_c}\right)^2 dx \text{ (erg/sq. cm)} \quad (1)$$

and

$$T_{\text{lim}} = \left(\frac{10u_c \delta c}{3u_c}\right)^2 \text{ (erg)}. \quad (2)$$

where ϵ_0 is the pulse energy density (erg/cm²) and a is a constant. It was found that by allowing for reflection, absorption increases by 32%. The maximum Q , for a given initial thickness x_0 and electron density n of the plasma layer, is given by

$$Q \approx 1.35 n_0 x_0 \left(\frac{\epsilon_0 \delta_0}{n_e} \right)^{1/2} \quad (3)$$

The lifetime of the absorbing layer with optimum parameters is

$$t_{opt} = \frac{n_0 r_0}{2 n_e c_0} \quad (4)$$

where c_0 is the initial sound velocity at $T_e = T_i$. At pulse cut-off the electronic heat-conduction wave and the unloading wave start to propagate into the target material. These processes are distinguished by the equality $T_e = T_i$ at the time τ_{ei} at which a noticeable fusion reaction sets in.

Plasma heating, with allowance for the cited processes, is described by a single universal integrodifferential equation. At the dimensionless time $t = t/\tau \rightarrow 0$ the self-similar solution of this equation, with exclusion of gas dynamic terms is

$$T = (t/\tau)^{-1/2} \bar{T} \quad (5)$$

where $\bar{T} = T/\theta$ is the dimensionless temperature, and $\bar{x}_T = x_T/\delta$ is the dimensionless coordinate of the heat wave front. Comparative T/θ and x_T/δ versus t/τ show that the unloading wave overtakes the heat wave in a finite time, and adiabatic expansion of plasma occurs. At a time $t = \tau$, separation of x_T from x_s is at a maximum ($x_s/x_T = 0.4$) and $T_e \approx T_i$. The fusion neutron yield is calculated from this time onward using the given solutions and data from the literature. The neutron yield N and the total fusion energy $Q_{f.e.}$ were accordingly calculated for solid deuterium D and a D-T mixture, respectively, and were plotted against the absorbed Q (Fig. 1

and 2). The lifetime of a hot plasma was calculated to be $10^7 n_0^3 Q'$.

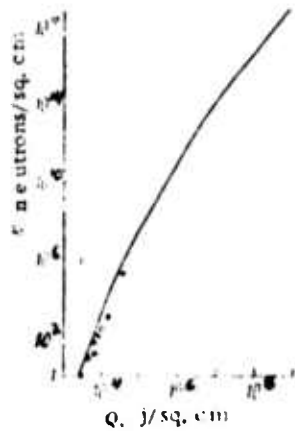


Fig. 1. N versus Q plot for a solid D target, $n_D = 5 \times 10^{22} \text{ cm}^{-3}$. Dots are for literature data.

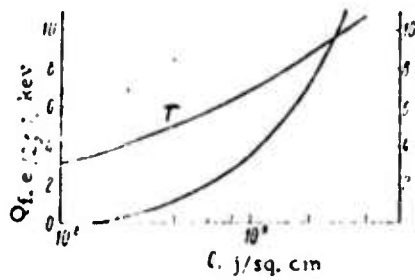


Fig. 2. Relative fusion energy yield $Q_{f, e.v.} / Q$ and plasma average temperature T versus Q plots for D ($n_D = 2.4 \times 10^{22} \text{ cm}^{-3}$)-T ($n_T = 3.6 \times 10^{22} \text{ cm}^{-3}$) target.

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Lugovoy, V. N., and A. M. Prokhorov.
Heating and confinement of plasma in
crossed light beams. ZhETF P, v. 17,
 no. 1, 1973, 52-55.

A new method of plasma heating by a pulsed laser radiation is proposed to produce a nuclear fusion reaction. The method consists of heating a material by two beams, e.g., emitted by the same laser, intersecting at some angle α . In contrast to previously discussed techniques, this method enables heating the plasma much longer than the time of hydrodynamic dissipation, and obtains a skin layer area much larger than the surface area of the heated plasma volume.

Interference of the two-focused beams intersecting near their focal regions of diam. $d\Phi_1$ and $d\Phi_2$ produces three-dimensional "microregions" or potential wells which prevents plasma dissipation if the electromagnetic field pressure p_{lim} on the boundary surface of a microregion is greater than plasma pressure p_{pl} . Assuming the condition $p_{lim} > p_{pl}$ holds within the time interval $(t_1 - t_0)$, where t_0 is the time of total ionization, the time dependence of power $p_1(t)$ is shown to be exponential for a typical laser pulse. The above assumption is then valid, if the pulse duration

$$\tau_H < \tau(1) = \frac{3V}{c d\Phi \mu} \quad (1)$$

where V is the total plasma volume confined to the microregions, $d\Phi = \max(d\Phi_1, d\Phi_2)$, and μ is the efficiency of optical energy conversion into thermal energy. Plasma temperature T_1 at maximum p_1 is given by

$$T_1 = \frac{\mu}{6nkV} E_L \quad (2)$$

where n is the ion density and E_L is the total energy in the laser pulse. Application of (1) and (2) to a D-T plasma ($n = 5 \times 10^{22} \text{ cm}^{-3}$) heated by laser pulses with $E_1 = 3 \times 10^4 \text{ j}$ and $\mu = 10^{-1}$ gave $\tau_p < 10^{-9} \text{ sec.}$ and $T_1 = 3 \times 10^7 \text{ deg.}$ Free dissipation time of the plasma with $d\Phi = 5 \times 10^{-3} \text{ cm}$ would be $4 \times 10^{-11} \text{ sec.}$, i. e. an order of magnitude shorter than τ_p . Plasma confinement is feasible even for the case when material layer thickness l is significantly smaller than the length of microregions, provided $l \gg \nu_s \tau_p$, where ν_s is the sound velocity in the plasma. Shorter laser pulses, e. g., $\tau_p = 3 \times 10^{-11} \text{ sec.}$ would promote a greater plasma contraction and increase n in the microregions.

Krasyuk, I. K., P. P. Pashinin, and A. M. Prokhorov. Effect of stimulated Compton scattering in the interaction of laser radiation with a superdense plasma. ZhETF P, v. 17, no. 2, 1973, 130-132.

The amplification of laser radiation reflection from a superdense plasma is evaluated theoretically on the assumption that stimulated Compton scattering of photons by plasma electrons is the amplification mechanism. A strong reflection of laser radiation must be accounted for in any theoretical description and practical realization of rapid plasma heating by laser radiation to initiate a controlled fusion reaction.

The total reflection R of laser radiation from a plasma layer of thickness l is evaluated from earlier established equations which describe amplification of a weaker laser pulse (I_2) by the stronger (I_1) during their propagation through a plasma in opposite directions (Kazakov, et al. ZhETF P, v. 14, no. 7, 1971, 416). Solution of the cited equations gives

$$R = R_0 \exp \beta I_{10} l (1 - R), \quad (1),$$

where $R_0 = I_2(0)/I_1(0)$ is the initial reflection, I_{10} is the intensity of a laser pulse entering the plasma layer l , and β is the factor defined earlier as a function of ν^{-3} (ν is the laser radiation frequency). The solution (1) is plotted in Fig. 1 and 2. Fig. 1 shows a significant amplification of laser

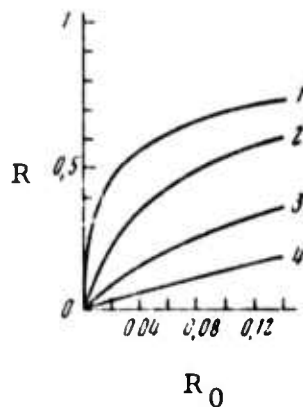


Fig. 1. $R = I_2(l)/I_{10}$ versus R_0 for $l = 0.2$ (curve 1), 0.1 (2), $.05$ (3), and $.01$ cm (4) at $I_{10} = 10^{16}$ w/cm².

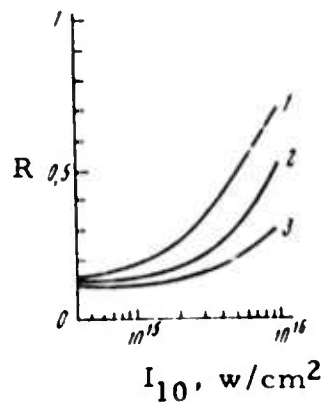


Fig. 2. $R = I_2(l)/I_{10}$ versus I_{10} at $R_0 = 0.1$ and $l = 0.2$ (curve 1), 0.1 (2) and $.05$ cm (3).

radiation reflection by the plasma owing to the Compton effect. In spite of the strong β dependence on ν , it may be assumed that the real ν dependence of R would be weaker than ν^{-3} because of ν dependence of l and I_{10} .

Fig. 2 shows that amplification of reflection on account of the Compton effect becomes noticeable at $I_{10} \cong 10^{15}$ w/cm². The importance of the effective electric field to the Compton effect is stressed for the plasma density range where plasma frequency equals that of laser radiation. In this range, the Compton effect may be greatly increased because of the corresponding increase in electric field, and may decrease radiation flux to the level at which reflection amplification becomes significant.

Samokhin, A. A. Effect of superheating in a developed vaporization regime. KSpF, no. 4, 1973, 7-10.

The author considers the case of intense e-m heating of a target surface such that a superheated condition occurs at the melt-solid interface, and investigates the effect of the superheat regime on vaporization development. The maximum temperature for a highly absorptive medium occurs at some small distance l_0 from the interface, the temperature difference between this point and the surface is given by

$$\Delta T = \epsilon l_0 / cl \quad (1)$$

where ϵ is heat of fusion, c = thermal capacity of the liquid phase, and l defines the effective heating depth of the liquid phase. Here $l = \chi/v$ where χ is thermal conductivity and v = velocity of the vapor boundary.

The effect of superheating of the liquid phase becomes pronounced if the frequency of nucleation of the gas phase reaches a value of $v l_0^{-4}$. Evaluating the corresponding temperature T_{lim} directly for metallic targets is difficult, but may be arrived at by using the limit superheat parameters identified with known liquids. Using this method the author arrives at an expression for T_{lim} in terms of critical temperature and pressure. The analysis shows that the superheat regime actually occurs only over a limited range of incident flux densities, namely those which bring the surface to the vicinity of critical temperature.

The author recommends more controlled experimentation with this phenomenon, specifically in tests where thickness of the liquid phase and vaporization rate would be controllable. A possible subject for this would be semiconductor materials which metallize on fusing and become opaque to incident radiation.

Gribkov, V. A., O. N. Krokhin, G. V. Sklizkov, N. V. Filippov, and T. I. Filippova. Powerful neutron sources based on a Z-pinch. ZhETF v. 18, no. 9, 1973, 541-544.

The experimental pinch effect data of different authors are summarized (Table 1) and interpreted in terms of the proposed model of neutron formation in a Z-pinch. The tabulated data show that the total neutron yield N_n and the relative thermal neutron yield N_n^T/N_n^A increase as the pinch diameter a at breakdown decreases and plasma density $N_{e\text{ pl}}$ increases. In accordance with theory the main neutron pulse appears and hard x-rays disappear at 20 to 100 nsec after pinch formation, i. e., only when $T_{e,i}$ attains 10^3 - 10^4 eV. The electron beam stopping length l estimated from experimental data and calculated from a theoretical formula is roughly the reciprocal of $N_{e\text{ pl}}$.

Summarizing the cited data, the authors conclude that neutrons in a Z-pinch form mainly on account of collisions between D ions accelerated in an axial electric field $E_1(a)$ and cold (≤ 1 keV) D in the pinch, but also on account of plasma heating to $T \geq 10^4$ eV, by powerful relativistic electron beams. The effect of the latter mechanism increases with increase in $E_z(a)$, density, and temperature of the Z-pinch plasma. Initially, the electron beam energy is dissipated almost totally at the cold anode. Hence preheating the solid deuterated target at the Z-pinch anode to a temperature of several keV, as by a powerful laser beam, is suggested as a means to increase N_n . In this way the plasma can be efficiently heated at the onset of electron beams on account of a two-beam instability development. In the case of a micro-pinch, the same effect of increasing N_n can be obtained by preheating to 10^3 eV and precompression of an exploding wire near the anode by means of a powerful laser beam.

Device type Parameters	Classical Z-pinch	Plasma focus	Laser-induced Z-pinch	Micropinch (exploding wire)
Capacitor battery voltage U_0	~30 kv	~25 kv	~15 kv	~600 kv
Current I_0	~400 ka	~1 Ma	~250 ka	~1.2 Ma
Pinch diam. before break- down, $2a$	~2 cm	~0.5 cm		$\sim 10^{-2} - 10^{-3}$ cm
Peak neutron pulse density, $N_{e pl}$	$\sim 10^{17}$ cm ⁻³	$\sim 10^{18} - 10^{19}$ cm ⁻³	$\sim 10^{21}$ cm ⁻³	$\geq 10^{21}$ cm ⁻³
Temperature from soft x-rays and neutron spectra, $T_{ei max}$	$< 10^2$ eV	$\sim 10^4$ eV	$8 \cdot 10^3$ eV	$\sim 10^4$ eV
Energy of hard x-ray component, W_{ob}	350 keV	~200 500 keV	~500 keV	≥ 600 keV
Total neutron yield, N_n	$\sim 10^7 - 10^8$	$\sim 10^{10} - 10^{11}$		$\sim 10^{11}$
Thermal-to- accelerated neutrons ratio, N_n^T / N_n^A	$\ll 10^{-1}$	$\sim 10^{-1} - 10$		> 10

Table 1. Experimental pinch effect data

Makhankov, V. G., and V. N. Tsytovich.
Anomalous heating of dense plasma by laser radiation. Phys. scr., v. 7, no. 5, 1973, 234-240. (RZhF, 11/73, no. 11G137)

An evaluation is given of the range of plasma parameters over which it appears possible to obtain anomalous laser heating of the plasma, caused by collective processes. Conditions are defined for generating oscillations at frequencies both above and below that of paired collisions. The correlation is considered between the effective frequencies corresponding to anomalous heating, and incident energy together with plasma temperature and density.

Galeyev, A. A., G. Laval, T. O'Neil,
M. Rozenblyut, and R. Z. Sagdeyev.
Interaction of a powerful electromagnetic wave with plasma. ZhETF, v. 65, no. 3, 1973, 973-989.

Linear and nonlinear plasma theories are expanded to describe parametric instability processes in a nonuniform D-T plasma interacting with powerful laser radiation at ω_0 frequency. Linear theory is applied to calculation of the amplification factor ν of small perturbations and the parametric instability increment γ for the parametric absorption and parametric backscatter processes. The parametric absorption processes are described as useful instability development which results in plasma heating. The processes leading to plasma heating are decays of photon (t) \rightarrow plasmon (l) + phonon (s), $t \rightarrow l + l'$, and $t \rightarrow l + \text{ion}$ (i). The backscatter or "harmful" processes are decays of $t \rightarrow t' + s$, $t \rightarrow t' + l$, and $t \rightarrow t' + i$.

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To simplify calculations of linear γ the case of a plane-polarized monochromatic laser beam is considered. Expressions for γ are derived from a simplified expression for the nonlinear dielectric constant of the plasma. An example of γ calculation is given for the $t \rightarrow t' + s$ decay or stimulated Brillouin scattering. The factor ν is calculated in normal mode or quasimode approximations. The maximum γ and ν values are tabulated for the parametric backscatter along with γ and ν values for the parametric heating processes.

It is shown that both $t \rightarrow t' + l$ and $t \rightarrow t' + s$ stimulated scatterings occur at a ~ 40 degree angle. Threshold γ value is first attained for $t \rightarrow l + s$, then for $t \rightarrow l + l'$ instabilities. The parasitic decay instabilities $t \rightarrow t' + s$ and $t \rightarrow t' + l$ arise at even higher incident power of the $n_c T$ order. The latter instabilities cause an additional nonlinear reflection and hence can be extremely harmful to laser-induced nuclear fusion in a D-T pellet. In view of this possibility the authors attempted to analyze the nonlinear phase of parametric scattering. Nonlinearity consists of parametric backscatter of pumping radiation on increasing perturbations with saturation of instability at the end. Two approximate nonlinear models of the $t \rightarrow t' + s$ process are discussed, because this process results in maximum linear ν . At not too high incident power the model of soft inclusion of decay instability, i. e., a smooth penetration by e-m radiation of the plasma corona region, with amplification factor $\sim e^L$, describes radiation relaxation in a quasilinear approximation. The upper amplitude limit of the incident laser radiation, below which the quasilinear model is applicable, is given as

$$E_0^2 / 8\pi n T_e < \gamma_s / \omega_s \quad (1).$$

At an amplitude above the critical value given by (1), parametric scattering can be described by the nonlinear model of hard inclusion of instability. In that case, the relaxation length Δx of the incident radiation or depth of

nonlinear scattering is estimated to be of the order of

$$\Delta x \approx \frac{c}{\omega_0} \left(\frac{\omega_0}{\omega_p} \right)^4 \frac{nT}{I_0}. \quad (2).$$

For a Nd glass laser at $\omega_0 = 2 \cdot 10^{15} \text{ sec}^{-1}$, $\omega_0/\omega_p \approx 2$, and $I_0/nT \approx 0.1$, Δx is calculated to be of the order of $10^{-2} - 10^{-3} \text{ cm}$. The practical importance of the analyzed processes is emphasized for the physics of electromagnetic wave-plasma interactions. An abbreviated treatment of this same topic is also given elsewhere by Sagdeyev (Uspekhi fiz. nauk, v. 110, no. 3, 1970, 437-441).

Plis, A. I., Ye. L. Tyurin, and V. A. Shcheglov. Laser-initiated thermal wave in a substance. ZhTF, no. 11, 1973, 2267-2272.

The authors examine factors governing heat conduction in a solid target exposed to intense laser pulses, for the case where energy delivery time is appreciably faster than heat dispersion rate into the material. The analysis is based on a set of gas dynamic equations in terms of target parameters (density, velocity, specific energy etc) and incident flux density. Graphical solutions are included showing temperature and thermal wavefront variation as a function of time.

Kaliski, S., C. Rymarz, L. Sclarz, and E. Wlodarczyk. Numerical solution to boundary value problems of laser heating of a plasma with energy yield from nuclear synthesis. Biul. WAT J. Dabrowskiego, v. 22, no. 6, 1973, 61-84. (RZhF, 12/73, no. 12G227). (Translation)

A numerical analysis is presented of laser heating of a one-temperature plasma, with allowance for energy yield from nuclear fusion. The two-dimensional case is analyzed at a fixed and a free boundary with a specified pressure. Time dependence of temperature, density, and velocity is calculated.

Heat and shock wave configurations are studied in particular and their separation point is determined along with the effect of fusion energy on the process. Distinguishing the thermal wavefront effect from that of the shock wavefront becomes possible by analysis under specially selected, although somewhat artificial, boundary conditions. The distinction of the cited effects is important to development of the new averaging methods, which is the main purpose of this analysis. A two-temperature plasma can be described in similar terms.

Askar'yan, G. A., V. A. Namiot, and M. S. Rabinovich. Using supercompression of material by reactive pressure for obtaining micro-critical masses of fissionable material to generate superstrong magnetic fields and for particle acceleration. ZhETF P, v. 17, no. 10, 1973, 597-600.

The authors discuss the theoretical production of extremely small critical masses of fissionable materials from supercompression by reactive pressure, generated by high-temperature evaporation of material. It is assumed that powerful laser radiation impacts the entire surface of the target material. Expressions are obtained for pressure during evaporation, nuclear concentration and neutron multiplication. It is noted that pulsed micro-critical masses may be used for obtaining powerful pulsed neutron and neutrino fluxes ($\sim 10^{17}$ neutrons in 10^{-10} sec). The authors also show that during supercompression of material, it is possible to obtain superstrong magnetic fields ($\geq 10^9$ oe) and particle acceleration.

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6. SOURCE ABBREVIATIONS

AiT	-	Avtomatika i telemekhanika
APP	-	Acta physica polonica
DAN ArmSSR	-	Akademiya nauk Armyanskoy SSR. Doklady
DAN AzSSR	-	Akademiya nauk Azerbaydzhanskoy SSR. Doklady
DAN BSSR	-	Akademiya nauk Belorusskoy SSR. Doklady
DAN SSSR	-	Akademiya nauk SSSR. Doklady
DAN TadSSR	-	Akademiya nauk Tadzhikskoy SSR. Doklady
DAN UkrSSR	-	Akademiya nauk Ukrainskoy SSR. Dopovidi
DAN UzbSSR	-	Akademiya nauk Uzbekskoy SSR. Doklady
DBAN	-	Bulgarska akademiya na naukite. Doklady
EOM	-	Elektronnaya obrabotka materialov
FAiO	-	Akademiya nauk SSSR. Izvestiya. Fizika atmosfery i okeana
FGiV	-	Fizika goreniya i vzryva
FiKhOM	-	Fizika i khimiya obrabotka materialov
F-KhMM	-	Fiziko-khimicheskaya mekhanika materialov
FMiM	-	Fizika metallov i metallovedeniye
FTP	-	Fizika i tekhnika poluprovodnikov
FTT	-	Fizika tverdogo tela
FZh	-	Fiziologicheskiy zhurnal
GiA	-	Geomagnetizm i aeronomiya
GiK	-	Geodeziya i kartografiya
IAN Arm	-	Akademiya nauk Armyanskoy SSR. Izvestiya. Fizika
IAN Az	-	Akademiya nauk Azerbaydzhanskoy SSR. Izvestiya. Seriya fiziko-tekhnicheskikh i matematicheskikh nauk

IAN B	-	Akademiya nauk Belorusskoy SSR. Izvestiya. Seriya fiziko-matematicheskikh nauk
IAN Biol	-	Akademiya nauk SSSR. Izvestiya. Seriya biologicheskaya
IAN Energ	-	Akademiya nauk SSSR. Izvestiya. Energetika i transport
IAN Est	-	Akademiya nauk Estonskoy SSR. Izvestiya. Fizika matematika
IAN Fiz	-	Akademiya nauk SSSR. Izvestiya. Seriya fizicheskaya
IAN Fizika zemli	-	Akademiya nauk SSSR. Izvestiya. Fizika zemli
IAN Kh	-	Akademiya nauk SSSR. Izvestiya. Seriya khimicheskaya
IAN Lat	-	Akademiya nauk Latviyskoy SSR. Izvestiya
IAN Met	-	Akademiya nauk SSSR. Izvestiya. Metally
IAN Mold	-	Akademiya nauk Moldavskoy SSR. Izvestiya. Seriya fiziko-tehnicheskikh i matematicheskikh nauk
IAN SO SSSR	-	Akademiya nauk SSSR. Sibirskoye otdeleniye. Izvestiya
IAN Tadzh	-	Akademiya nauk Tadzhiksoy SSR. Izvestiya. Otdeleniye fiziko-matematicheskikh i geologo-khimicheskikh nauk
IAN TK	-	Akademiya nauk SSSR. Izvestiya. Tekhnicheskaya kibernetika
IAN Turk	-	Akademiya nauk Turk.menskoy SSR. Izvestiya. Seriya fiziko-tehnicheskikh, khimicheskikh, i geologicheskikh nauk
IAN Uzb	-	Akademiya nauk Uzbekskoy SSR. Izvestiya. Seriya fiziko-matematicheskikh nauk
IBAN	-	Bulgarska akademiya na naukite. Fizicheski institut. Izvestiya na fizicheskaya institut s ANEB
I-FZh	-	Inzhenerno-fizicheskiy zhurnal

IR	-	Izobretatel' i ratsionalizator
ILEI	-	Leningradskiy elektrotekhnicheskiy institut. Izvestiya
IT	-	Izmeritel'naya tekhnika
IVUZ Avia	-	Izvestiya vysshikh uchebnykh zavedeniy. Aviatsionnaya tekhnika
IVUZ Cher	-	Izvestiya vysshikh uchebnykh zavedeniy. Chernaya metallurgiya
IVUZ Energ	-	Izvestiya vysshikh uchebnykh zavedeniy. Energetika
IVUZ Fiz	-	Izvestiya vysshikh uchebnykh zavedeniy. Fizika
IVUZ Geod	-	Izvestiya vysshikh uchebnykh zavedeniy. Geodeziya i aerofotos'yemka
IVUZ Geol	-	Izvestiya vysshikh uchebnykh zavedeniy. Geologiya i razvedka
IVUZ Gorn	-	Izvestiya vysshikh uchebnykh zavedeniy. Gornyy zhurnal
IVUZ Mash	-	Izvestiya vysshikh uchebnykh zavedeniy. Mashinostroyeniye
IVUZ Priboro	-	Izvestiya vysshikh uchebnykh zavedeniy. Priborostroyeniye
IVUZ Radioelektr	-	Izvestiya vysshikh uchebnykh zavedeniy. Radioelektronika
IVUZ Radiofiz	-	Izvestiya vysshikh uchebnykh zavedeniy. Radiofizika
IVUZ Stroi	-	Izvestiya vysshikh uchebnykh zavedeniy. Stroitel'stvo i arkhitektura
KhVE	-	Khimiya vysokikh energiy
KiK	-	Kinetika i kataliz
KL	-	Knizhnaya letopis'
Kristall	-	Kristallografiya
KSpF	-	Kratkiye soobshcheniya po fizike

LZhS	-	Letopis' zhurnal'nykh statey
MiTOM	-	Metallovedeniye i termicheskaya obrabotka materialov
MP	-	Mekhanika polimerov
MTT	-	Akademiya nauk SSSR. Izvestiya. Mekhanika tverdogo tela
MZhiG	-	Akademiya nauk SSSR. Izvestiya. Mekhanika zhidkosti i gaza
NK	-	Novyye knigi
NM	-	Akademiya nauk SSSR. Izvestiya. Neorganicheskiye materialy
NTO SSSR	-	Nauchno-tekhnicheskiye obshchestva SSSR
OiS	-	Optika i spektroskopiya
OMP	-	Optiko-mekhanicheskaya promyshlennost'
Otkr izobr	-	Otkrytiya, izobreteniya, promyshlennyye obraztsy, tovarnyye znaki
PF	-	Postepy fizyki
Phys abs	-	Physics abstracts
PM	-	Prikladnaya mekhanika
PMM	-	Prikladnaya matematika i mekhanika
PSS	-	Physica status solidi
PSU	-	Pribory i sistemy upravleniya
PTE	-	Pribory i tekhnika eksperimenta
Radiotekh	-	Radiotekhnika
RiE	-	Radiotekhnika i elektronika
RZhAvtom	-	Referativnyy zhurnal. Avtomatika, telemekhanika i vychislitel'naya tekhnika
RZhElektr	-	Referativnyy zhurnal. Elektronika i yeye primeneniye

RZhF	-	Referativnyy zhurnal. Fizika
RZhFoto	-	Referativnyy zhurnal. Fotokinotekhnika
RZhGeod	-	Referativnyy zhurnal. Geodeziya i aeros"- yemka
RZhGecfiz	-	Referativnyy zhurnal. Geofizika
RZhInf	-	Referativnyy zhurnal. Informatics
RZhKh	-	Referativnyy zhurnal. Khimiya
RZhMekh	-	Referativnyy zhurnal. Mekhanika
RZhMetrolog	-	Referativnyy zhurnal. Metrologiya i izmer- itel'naya tekhnika
RZhRadiot	-	Referativnyy zhurnal. Radiotekhnika
SovSciRev	-	Soviet science review
TiEKh	-	Teoreticheskaya i eksperimental'naya khimiya
TKiT	-	Tekhnika kino i televideniya
TMF	-	Teoreticheskaya i matematicheskaya fizika
TVT	-	Teplofizika vysokikh temperatur
UFN	-	Uspekhi fizicheskikh nauk
UFZh	-	Ukrainskiy fizicheskii zhurnal
UMS	-	Ustalost' metallov i splavov
UNF	-	Uspekhi nauchnoy fotografii
VAN	-	Akademiya nauk SSSR. Vestnik
VAN BSSR	-	Akademiya nauk Belorusskoy SSR. Vestnik
VAN KazSSR	-	Akademiya nauk Kazakhskoy SSR. Vestnik
VBU	-	Belorusskiy universitet. Vestnik
VNDKh SSSR	-	VNDKh SSSR. Informatsionnyy byulleten'
VLU	-	Leningradskiy universitet. Vestnik. Fizika, khimiya
VMU	-	Moskovskiy universitet. Vestnik. Seriya fizika, astronomiya

ZhETF	-	Zhurnal eksperimental'noy i teoreticheskoy fiziki
ZhETF P	-	Pis'ma v Zhurnal eksperimental'noy i teoreticheskoy fiziki
ZhFKh	-	Zhurnal fizicheskoy khimii
ZhNiPFiK	-	Zhurnal nauchnoy i prikladnoy fotografii i kinematografii
ZhNKh	-	Zhurnal neorganicheskoy khimii
ZhPK	-	Zhurnal prikladnoy khimii
ZhPMTF	-	Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki
ZhPS	-	Zhurnal prikladnoy spektroskopii
ZhTF	-	Zhurnal tekhnicheskoy fiziki
ZhVMMF	-	Zhurnal vychislitel'noy matematiki i matematicheskoy fiziki
ZL	-	Zavodskaya laboratoriya

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