PACS numbers: **42.55.–f**, **42.62.–b**, **52.57.–z**
DOI: 10.3367/UFNe.0181.201104m.0434

High-power lasers and their applications in high-energy-density physics studies

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1. Introduction

Work on the development of high-power lasers was initiated at the All-Russian Research Institute of Experimental Physics (ARIEP or VNIIEF in *Russ. abbr.*) in 1963 by the scientific supervisor Yu B Khariton. These studies were headed by S B Kormer and G A Kirillov. Active experimental investigations in this field were started in the mid-1960s. In 1965, N G Basov proposed to Yu B Khariton that collaborative studies be carried out on the possibility of the development of lasers emitting the maximum achievable output energy.

This proposal was based on the idea of using extremely high-power optical radiation accompanying the explosion of a nuclear charge for pumping lasers. However, the emission temperature of a shock wave in air produced by a nuclear explosion does not differ substantially from the emission temperature of a shock wave in noble gases excited by a standard explosive. This simpler and real pumping method was proposed for joint investigations by researchers at the Lebedev Physical Institute, Russian Academy of Sciences (LPI or FIAN in *Russ. abbr.*) and ARIEP.

In December 1965, the first explosion experiment on lasing in ozone was performed, and in December 1966, lasing was obtained in CF_3I. In 1970, an important stage in the study of explosion photodissociation lasers (EPDLs) was completed, when a megajoule laser emitting ~ 100 μs pulses was built in cooperation with LPI and the State Optical Institute (GOI in *Russ. abbr.*).

The successful development of work in this area gave an impetus to the construction of laser facilities at the Russian Federal Nuclear Center in Sarov (RFNC–ARIEP) for studying high energy density physics, including investigations in the field of laser fusion. The natural question arises: Why did this area begin to develop so rapidly at the nuclear center, where the main field of research was nuclear weapons development?

Physical processes proceeding during the explosion of a thermonuclear charge occur at high energy densities. And although such high energy densities cannot yet be achieved under laboratory conditions, it is possible to improve the understanding of the physics of these processes by refining theoretical models for simulations and testing them in laboratory experiments. An advantage of laser studies is the possibility of performing repeated experiments by using the developing precision diagnostics. This allows one to study individual phenomena proceeding in plasmas at thermonuclear temperatures.

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Uspekhi Fizicheskikh Nauk **181** (4) 434–441 (2011)
DOI: 10.3367/UFNr.0181.201104m.0434
Translated by M Sapozhnikov; edited by A Radzig

The use of a laser to ignite a thermonuclear fuel was first proposed by Basov and Krokhin [1]. More recently, paper [2] by American scientists was published. The first successful experiments with spherical targets were performed at the Kal'mar facility at LPI [3]. These investigations initiated the development of laser facilities for studying the physics of inertial thermonuclear fusion.

At present, two basic schemes for compressing thermonuclear targets are considered, which take advantage of either direct or indirect irradiation. In both, the external surface of a spherical shell filled with a thermonuclear fuel [for example, a deuterium–tritium (DT) mixture] is exposed to laser radiation producing the evaporation of the shell, thereby building up the ablation pressure. Under the action of this pressure, an unevaporated spherical piston compresses the fuel up to the required density ρ and heats it up to the needed temperature T.

In the direct irradiation scheme, the shell is evaporated directly upon laser irradiation of the target. In the indirect method, the thermonuclear fuel is compressed by X-rays produced by the laser radiation heating of a special spherical or cylindrical capsule surrounding the thermonuclear target.

In fact, the principle of inertial plasma confinement is realized in such targets, including the existence of a compressed fuel for the time τ required for compressed plasma unloading. During this time, it is necessary to create conditions for igniting the target, i.e., conditions under which the thermonuclear energy release exceeds the energy deposited on the target. Taking into account that $\tau \approx R/c_s$, where R is the radius of a compressed core, and c_s is the speed of sound, we can arrive at the ignition condition in the form $\rho R \geqslant 0.3$ g cm^{-2} for $T \geqslant 10$ keV.

Work on developing single-pulse lasers for studying various aspects of laser fusion was started in 1972 on the initiative of Yu B Khariton, S B Kormer, and G A Kirillov at the RFNC–ARIEP, where high-power Iskra-4 [4], Iskra-5 [5], Luch [6], and Femto [7] laser facilities were built.

2. High-power photodissociation iodine lasers for laser fusion studies

Interest in a photodissociation iodine laser as a driver for laser fusion appeared after the publication of paper [8] in 1971. The possibilities of applications of iodine lasers for these purposes were also studied by Russian [9–11] and foreign [12–14] scientists.

In 1979, a high-power Iskra-4 single-channel iodine laser facility was built at ARIEP, which emitted 2000-J, 0.1–0.3-ns pulses. The facility was equipped with a system dividing the laser beam into four beams for irradiating thermonuclear targets in the tetrahedral symmetry. In the mid-1980s, this facility was the world's highest-power (10 TW) single-channel laser.

The successful solution to the problem of developing and starting the Iskra-4 facility made it possible to begin the development of a considerably larger and higher-power Iskra-5 photodissociation iodine facility, which was started at the end of 1989 and still operates. This facility consists of 12 laser channels emitting ≈ 0.25-ns pulses with a total output energy of up to 30–40 kJ. Pump flashlamps and electric-discharge sources were powered by a specially built system of capacitive energy storage providing a total energy storage of up to ≈ 65 MJ [15].

The target camera of the Iskra-5 facility is equipped with 12 unique three-component mirror–lens focusing systems [16]. The main experiments in the 12-channel irradiation regime were performed with 0.3–0.4-ns pulses with the output energy of 9–10 kJ. At present, this facility provides the coupling of 0.5–0.6-ns, 2.4–3-kJ second-harmonic pulses into the interaction chamber [17].

3. Investigations at the Iskra-4 laser facility

Investigations performed at the Iskra-4 facility were mainly devoted to the direct drive targets in the exploding-shell mode (see also, for example, Ref. [18]). This mode is characterized by a low volume compression degree ($\delta \approx 100$) and a weak sensitivity to the shell converging asymmetry [19]. In this case, the neutron yield N is sufficient for the reliable detection of neutrons, which makes it possible to analyze a complete set of experimental data.

To reach such a compression regime, the laser pulse duration should be $\tau_L \leqslant 0.3$ ns, and the laser power density on the target surface should be $I_L \approx 10^{15}$W cm^{-2}. These irradiation parameters were attained in experiments.

For this laser power density at a wavelength of 1.315 μm, the pressure produced by laser radiation (the ponderomotive pressure) is comparable to the thermal pressure of plasma, which leads to the formation of a density jump at the point corresponding to the critical plasma density (see, for example, [20–22]). Under these conditions, the classical inverse bremsstrahlung absorption of laser radiation decreases, and the role of nonlinear mechanisms resulting in the generation of 'hot' electrons and fast ions in a laser corona becomes dominant.

In experiments [23, 24], spherical glass targets 120–240 μm in diameter, with the aspect ratio $A_s = R_0/\Delta R$ (the ratio of the initial radius to the shell thickness) ranging from 30 to 100, and the initial pressure $P_{DT} = 10-30$ atm of the DT mixture were utilized. Figure 1 shows the absorption coefficient k_a and the fraction k_f of absorbed energy transferred to fast ions as functions of the laser radiation intensity.

These experiments were analyzed by constructing the models of radiation absorption and generation of fast particles, which took into account the above-mentioned effects in the SNDP one-dimensional radiation gas dynamics code [25, 26] and gain satisfactory agreement between experimental and calculated coefficients k_a and k_f (see Fig. 1). The density ρ_f of the compressed DT gas, determined both from the size of a compressed core measured with a pinhole camera and from the line emission of neon added to the DT mixture, was also consistent with the calculated value. In this case, the maximum value of ρ_f was about 1 g cm^{-3} [23].

Although measurements of the target energy input and volume compression were consistent with calculations, the experimental neutron yield, amounting to $10^4 - 10^6$, was 10–100 times lower than the yield predicted by the development of calculations. This discrepancy is mainly explained by the development of hydrodynamic instabilities and turbulent mixing caused by the nonuniform irradiation of a target.

After modernization of the Iskra-4 facility to generate the second-harmonic radiation, a series of experiments on compressing high-aspect-ratio shells with $A_s > 200$ was performed. The stable generation of thermonuclear neutrons was obtained in a strongly converging shock wave with the record high yield of 6×10^7 neutrons per pulse.

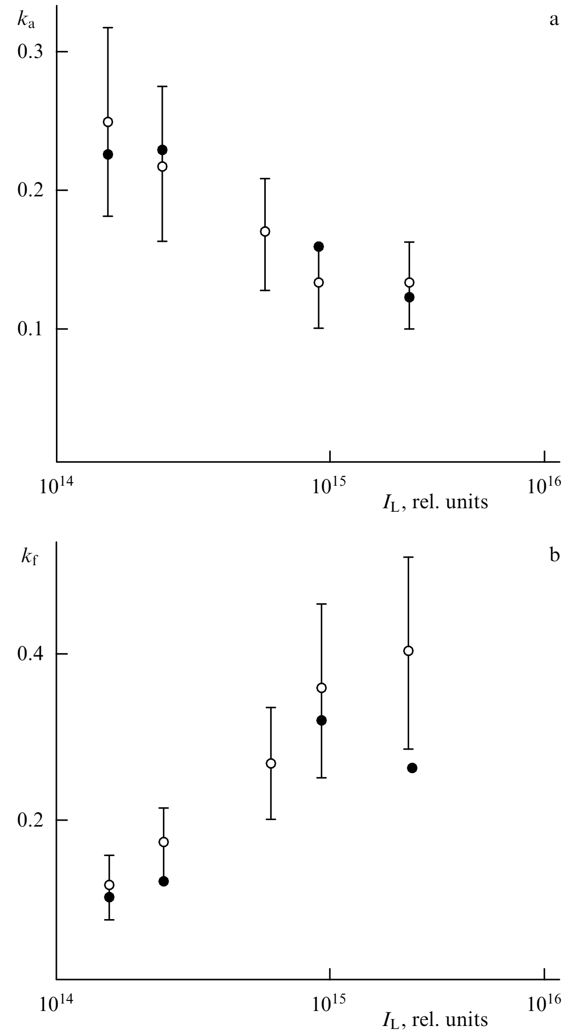
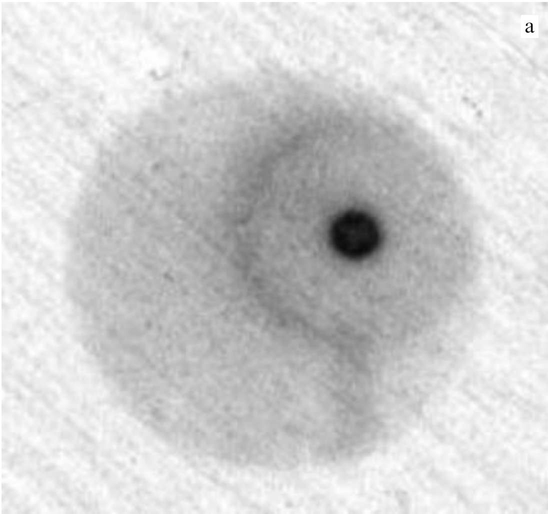


Figure 1. Dependences of the absorption coefficient k_a (a) and the fraction k_f of absorbed energy in fast ions (b) on the laser radiation intensity (○ — experiment at the Iskra-4 facility, and ● — calculations).

4. Investigations at the Iskra-5 laser facility

Experimental investigations at the Iskra-5 facility [27–41] were mainly concerned with the indirect drive targets consisting of a spherical copper box 1.3–4 mm in diameter with a glass capsule, containing the DT gas, located at the center of the box. The efficiency of coupling laser radiation into the box was verified in a series of experiments on targets with a reversed corona [29]. In these experiments, a hot plasma with a record high ion temperature of about 12 keV was obtained. The neutron yield reached $\approx 10^{10}$ DD neutrons per pulse.

An important stage of investigations covered the X-ray field characteristics inside the box, the field spectrum, the effective temperature, and the symmetry properties of irradiation of the central target. For this purpose, the parameters of the central capsule were varied: its diameter was changed from 270 μm to 0.9 mm, the thickness was changed from 1 to 40 μm, and the initial pressure of the DT gas was changed from 3 to 50 atm. Experiments and calculations revealed that the inhomogeneity of the X-ray flux on the capsule surface did not exceed 2–3% for the ratio of the box radius to the central capsule radius in the range from 5 to 10.



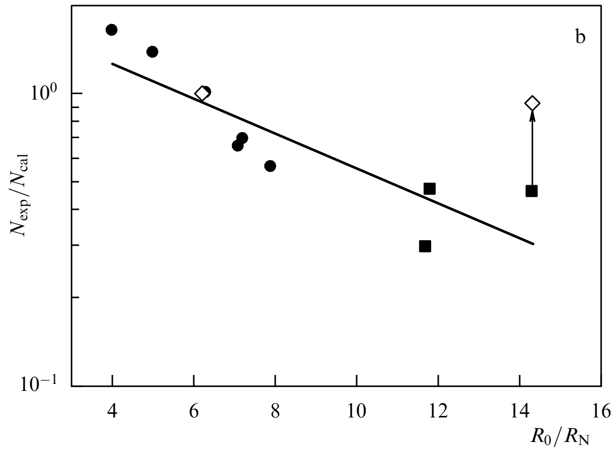


Figure 2. (a) Camera-obscura photograph of a central target obtained in a typical experiment with X-ray targets. (b) Dependences of the ratio of experimental and calculated neutron yields on the calculated degree of the radial convergence of the central capsule at the instant of neutron generation: (●) shell without a coating; (■) shell with a polyparaxylilene coating; (◇) calculations taking turbulent mixing into account.

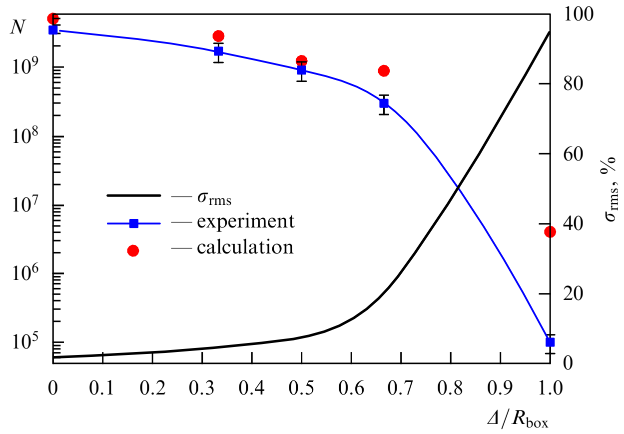


Figure 3. Dependences of the neutron yield N and the inhomogeneity degree σ_{rms} of the X-ray field on the capsule surface on the displacement Δ of the target with respect to the center of the box.

The recording of the spectrum of X-ray radiation generated by the box walls [37–39] showed that the spectrum is nonequilibrium. According to the absolute measurements of the X-ray energy, the X-ray flux irradiating the glass capsule surface corresponds to the effective temperature of 160–170 eV.

To analyze the experiments, it was necessary to develop one-dimensional and two-dimensional radiation gas dynamics codes. Methods were developed for calculating the generation and transfer of X-rays in a laser plasma by using the spectral-diffusion approximation and the kinetic equation method. The validity and accuracy of both the physical models and developed algorithms and calculation programs were verified in experiments.

Figure 2a presents a camera-obscure photograph of the X-ray emission of the central target, which demonstrates the high degree of symmetry of the compressed region, thus confirming calculated estimates. The high degree of symmetry made it possible to detect the density of the compressed DT gas in experiments at the level from 0.8 to 1.1 g cm^{-3} [31, 33]. Measurements of the shell convergence time $\tau_{\gamma\gamma}$ performed with an X-ray streak camera gave the estimate of the typical shell removal velocity, which was about 3×10^7 cm s^{-1} for a shell thickness of 5–7 μm.

The neutron yield changed from 10^7 to 10^{10}, depending on the shell parameters and experimental conditions. For a target 280 μm in diameter with a shell 5 μm in thickness, the neutron yield was at a level of about 3×10^9, which corresponds to the DT gas temperature of 2.5 keV measured by the time-of-flight method.

A comparison of experimental data with calculations based on the one-dimensional SNDP code showed that the neutron yield was well described within the framework of spherically symmetric calculations (Fig. 2b) for the degrees of a gas volume compression up to 10^3. At higher compression ratios, the neutron yield was lower than that predicted by spherically symmetric calculations, which can be explained by the influence of turbulent mixing.

The high symmetry of the X-ray field made it possible to perform the world's first experimental studies on the influence of a radiation asymmetry on the dynamics of thermonuclear targets and the generation of neutrons in them. The influence of asymmetry in the initial geometry of targets [36, 40, 41] and in the X-ray flux on the target surface was investigated.

The asymmetry of the X-ray field was varied by using an additional hole in the box and displacing the spherical capsule in its direction.

A comparison of experimental results with gas dynamic calculations of the compression of central capsules with the help of the Mimoza-ND program [42, 43], with the target and X-ray parameters corresponding to experiments (Fig. 3), demonstrates the qualitative and quantitative agreement between experiments and calculations in a wide range of varying X-ray field asymmetry [36, 44].

5. Ignition of a thermonuclear target

The key issue of laser fusion is the question about the minimum laser energy E_L required to ignite a laser thermonuclear target. It was shown in Ref. [45] that the optimistic estimate of E_L points to 500 kJ for a nanosecond laser pulse. More detailed information can be obtained with the help of gas dynamic calculations making allowance for combined physical processes determining the target compression dynamics.

Calculations were performed using the SNDP code taking into account the following physical processes [46]: gas dynamic processes, inverse bremsstrahlung absorption of laser radiation, electron and ion heat conductions, electron–ion relaxation, X-ray radiation transfer in the nonequilibrium spectral diffusion approximation, plasma ionization kinetics in the average ion approximation [47], and the kinetics of thermonuclear reactions with due regard for the transfer of α particles in the multigroup, restricted-flow diffusion approximation [48]. In calculations, the equation of state in the average ion approximation taking cold pressure into account was used [49]. The physical models constructed in this program were confirmed in experiments at the Iskra-4 and Iskra-5 facilities, as shown in Sections 3 and 4.

The calculated optimization of the target design demonstrates that a 500-kJ laser pulse can ignite a thermonuclear target representing a plastic spherical shell ~ 1.5 mm in diameter with ~ 30-μm-thick walls. A 25-μm-thick DT ice layer was frozen on the internal surface of the shell. To provide the isentropic compression, the laser pulse is profiled:

$$P(t) = \begin{cases} P_0 \left(\dfrac{t}{t_0}\right)^{2.8} & \text{for} \quad t < t_0\,, \\ P_0 & \text{for} \quad t_0 < t < t_0 + \Delta t\,, \end{cases}$$

where $P(t)$ is the laser radiation power conveyed to the target, $t_0 = 8.6$ ns, $\Delta t = 1.48$ ns, and $P_0 = 1.34 \times 10^{14}$ W (these values were selected in accordance with the shell radius and mass). Calculations show that in this case the gain coefficient of the target (the excess of the thermonuclear energy over the deposited laser energy) is about 10. The yield of thermonuclear neutrons reaches 2×10^{18} neutrons per pulse, the volume compression of the thermonuclear fuel is about 10^4, and the density of the DT mixture at the instant of maximum compression is about 100 g cm^{-3}.

The nonuniform irradiation of the target, the deviation of the shell symmetry from spherical, and the different thickness of the DT ice layer cause the violation of the one-dimensionality of compression, thereby increasing the energy required for a target ignition. These factors can be conditionally divided into two groups according to the spatial scale. Large-scale inhomogeneities include perturbations with a wavelength of $(0.1-1)R_0$, where R_0 is the initial radius of the target, while small-scale inhomogeneities correspond to perturbations with a wavelength shorter than $0.1R_0$.

The influence of large-scale inhomogeneities has been studied in many laboratories in Russia and abroad (see, for example, preprint [50]). We will analyze this influence based on two-dimensional Mimoza-ND calculations comprising the same thermonuclear target for which the results of one-dimensional calculations were presented above. The variation of the laser radiation intensity along the target surface can be written out in the form

$$I = I_0 \left[1 + a_l P_l(\cos\Theta)\right],$$

where I_0 is the laser radiation intensity averaged over the target surface, $P_l(\cos\Theta)$ is the Legendre polynomial, and a_l is the perturbation amplitude. The influence of the inhomogeneity on the target ignition is characterized best of all by the ratio of the thermonuclear energy released during laser fusion and obtained in two-dimensional calculations to the energy produced in one-dimensional calculations. The dependence of this parameter on the perturbation amplitude a_l for two harmonics with $l = 2$ and 10 testifies that the close perturbation levels for both harmonics cause an approximately equal decrease in the released energy (Fig. 4). Note that the energy

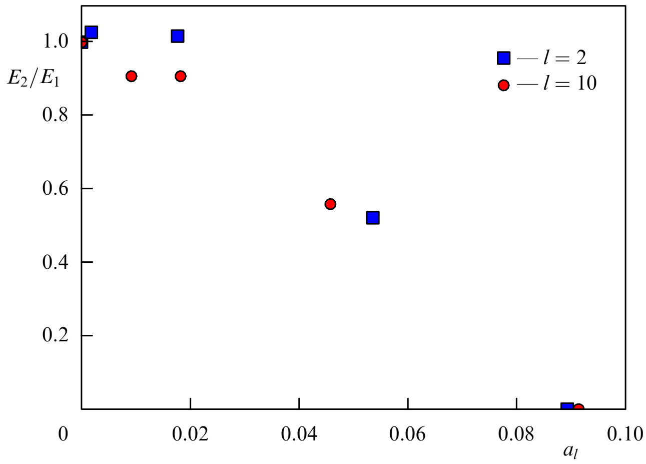


Figure 4. Ratio of thermonuclear energy releases obtained in two-dimensional (E_2) and one-dimensional (E_1) calculations as a function of the amplitude of large-scale perturbations.

release decreases by half when the irradiation inhomogeneity amplitude reaches 5%, and the neutron yield is virtually absent when the inhomogeneity amounts to 9%. These investigations suggest that, when the volume compressibility factor reaches 10^4, large-scale inhomogeneities with the amplitude on the order of 3% do not affect the compressibility and combustion dynamics of a thermonuclear fuel.

The presence of small-scale inhomogeneities leads to the efficient development of gas dynamic instabilities and turbulent mixing. Unfortunately, it is impossible at present to perform direct simulations of the influence of these effects on the compression dynamics of the target and its ignition. Although many experimental and theoretical studies are now underway, it is not clear so far how much the laser energy should be increased to compensate for energy losses caused by instabilities.

6. Megajoule laser facility

Experiments at the Iskra-5 facility revealed its restricted possibilities. In particular, the neutron yield for a laser energy of about 30 kJ is insufficient for studying all the regimes of thermonuclear target compression. In 1996, RFNC–ARIEP proposed building a megajoule laser facility [51] for experiments on the ignition of a nuclear fusion target. In addition, this facility would be used for studying the problems like the X-ray energy transfer in closed volumes, the spectroscopy of hot dense plasmas, the spectral measurements of the X-ray absorption coefficients in equilibrium plasma, the radiative gas dynamics of asymmetric flows, the determination of the equations of state of matter in the pressure region from 10 to 100 million atm, and the development of hydrodynamic instabilities and turbulent mixing on contact boundaries.

Analysis of different possible designs of such a facility showed that the technology of neodymium lasers, which was considerably developed in the 1970s–1980s, provided the best opportunities for increasing the efficiency of the facility and, therefore, for reducing its dimensions. A characteristic feature of such facilities was a multipass (four-pass) power cascade with a sectioned aperture and active rectangular phosphate glass elements (so-called slabs). This design provides a significant increase in the amplifier efficiency and reduces the number of intermediate amplification cascades.

At the first stage, a four-channel Luch neodymium facility was built at RFNC–ARIEP for testing and working out basic scientific and technical solutions [52]. The optical scheme of the Luch facility channel is mainly similar to those of the NIF (National Ignition Facility) [53] and LMJ (Laser Mégajoule) facility [54]. The laser efficiency is increased by utilizing an amplification scheme in which a laser pulse passes four times through active laser elements (neodymium slabs), thereby increasing the extraction of energy stored in them. In addition, laser channels are combined in blocks pumped by a common pumping system containing xenon flashlamps, which also increases the laser efficiency. The amplifying stage of the Luch facility includes two power amplifiers, each of them containing nine neodymium slabs. The laser beam cross section is a 20 $\times$ 20-cm square. To suppress self-excitation in the laser channel, the second and third amplification passages are separated by a Pockels cell, and the laser beam quality is improved by means of a special adaptive system.

It was shown in Ref. [55] that the radiation resistance of domestic optical elements in the facility channel, specifically, Nd-phosphate glass slabs [56], provides an operation with mean output energy densities of up to $\varepsilon \approx 10$ J cm^{-2}. Calculations of the laser pulse amplification showed that, to achieve such a level of ε, the gain should be $g \approx 0.04$–0.05 cm^{-1}; in this case, the output energy of one channel should be 3–3.5 kJ. Experiments [57] demonstrated that amplifiers of the selected design provide the required value of g. These results and the required operation regimes obtained in all systems of the facility made it possible to achieve in experiments the expected output energy of 3.3 kJ per channel (Fig. 5) [58].

A specific feature of the capacitor bank of the Luch facility with the 4.7-MJ energy storage at a voltage of 24 kV is that reversely switched semiconductor dynistors [59] with very high commutation parameters were utilized for the first time in world practice in a high-power laser.

The experimental results demonstrated the validity of the chosen scientific and technical solutions. Further studies aimed at improving the main systems of the facility, including the development of a large-aperture Pockels cell with plasma electrodes [60], the development of manufacturing technology for Nd slabs with enlarged apertures [61], and the application of new operation algorithms for an adaptive system [62], made it possible to formulate the concept for building a laser facility emitting $\sim$ 2.8 MJ, 3–5-ns pulses at a wavelength of 0.53 μm. The laser beam aperture is 40 $\times$ 40 cm, and the number of amplification channels reaches 192. At present, the technical design of this facility is being developed at RFNC–ARIEP.

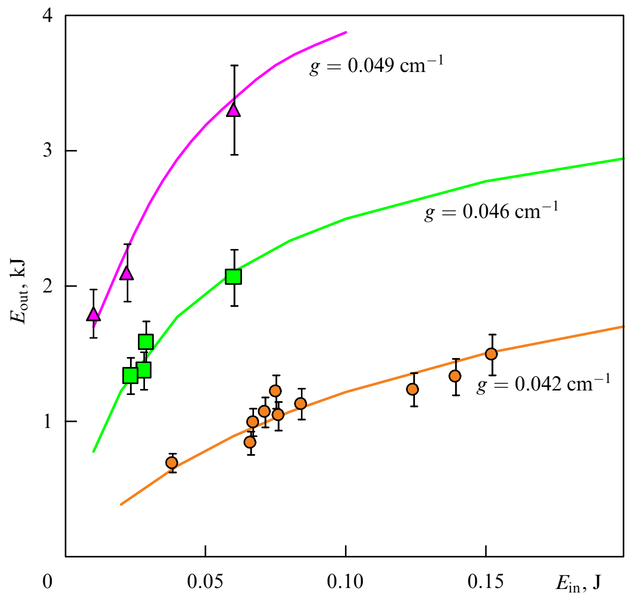


Figure 5. Dependences of the output laser energy $E_{\rm out}$ in one channel of the facility on the input energy $E_{\rm in}$ of power amplifiers for different gains g. Symbols show experimental results, curves correspond to calculations.

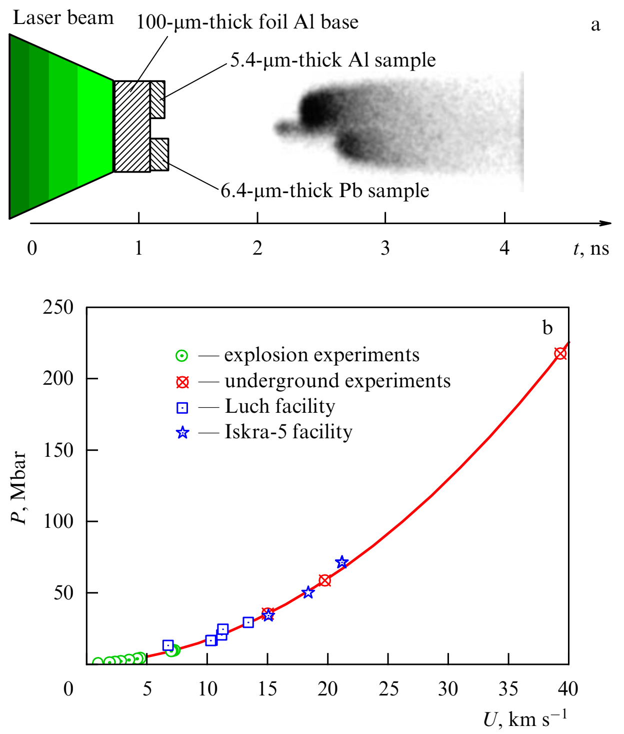


Figure 6. Studies of the shock compressibility of lead at the Luch facility: (a) layout of experiments; (b) the $P - U$ diagram.

Along with studies of laser radiation amplification, the Luch facility is also employed for investigating the behavior of matter under experimental conditions. In particular, an experimental method for studying shock compressibility is being developed. Figure 6a shows the principal experimental layout, and Fig. 6b presents the $P - U$ compressibility diagram obtained for lead. Notice that the pressure reached in laser experiments exceeds 50 Mbar.

7. Petawatt laser complex

Recent years have witnessed considerable progress in the development of solid-state femtosecond lasers. Subpetawatt and petawatt laser facilities emitting 100–500-fs pulses have been started at leading laser laboratories (see, for example, Ref. [63]). Such output power levels in a focused beam provide a power density of up to $10^{18} - 10^{22}$ W cm^{-2}.

The appearance of a new tool led to the development of a number of new research avenues, such as the generation of fast electrons and ions, including proton beams, the generation of hard X-rays, and the initiation of nuclear reactions. The possibility of a 'fast' ignition of a thermonuclear target simultaneously irradiated by nanosecond and femtosecond pulses is considered.

At present, two main approaches for achieving petawatt laser powers are being considered. In the first method, a femtosecond laser pulse with an energy on the order of 1 nJ is stretched up to a few nanoseconds by means of a dispersion optical system (a diffraction grating called a stretcher). Then, the pulse can be amplified by well-known methods. After obtaining the required energy, the pulse is compressed in time with the help of another optical system (a compressor), also consisting of diffraction gratings. If the laser pulse spectrum is not distorted during amplification, the pulse duration can be shortened to its initial value.

However, a neodymium phosphate glass amplifier distorts (narrows) the laser pulse spectrum, and the output pulse of such petawatt laser systems has a 0.5–1-ps duration.

Another system is based on the employment of parametric amplifiers with a considerably broader amplification band. The idea of such a laser system applied to lower radiation power levels was probably first formulated by Soviet researchers more than 25 years ago [64]. However, only at present, after the creation of femtosecond lasers emitting 10-fs pulses and nonlinear crystals with apertures of up to 40 cm, has the realization of this idea for generating record high, multipetawatt powers become possible [65].

Such a system was realized at the Luch facility in collaboration between researchers at RFNC–ARIEP and the Institute of Applied Physics, Russian Academy of Sciences (Nizhny Novgorod). Parametric amplifiers in this system are based on large-aperture DKDP crystals. At present, 1 PW of output power is being achieved [7]. The output energy of the facility is about 50 J for a compressed pulse duration of about 45 fs and a beam diameter of 7.4 cm.

8. Conclusions

The laser stand base built at RFNC–ARIEP is unique. It is the property of the scientific community in Russia and is open for investigations in the field of high-energy-density physics for researchers from different scientific institutes in Russia.

The creation of high-power laser facilities at RFNC–ARIEP for investigations in the field of high-energy-density physics facilitates the development of technologies in the fields of laser science, optics, pulsed power, and measurement techniques.

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PACS numbers: 07.55.Db, **64.30.–t**, **74.25.–q**
DOI: 10.3367/UFNe.0181.201104n.0441

Research in ultrahigh magnetic field physics

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1. Introduction

The history of the achievements of the All-Russian Research Institute of Experimental Physics (VNIIEF in *Russ. abbr.*) in the field of ultrahigh magnetic field (UHMF) generation and applications in fundamental physical studies begins in 1952, when Andrey D Sakharov put forward the idea of magnetic cumulation as one of the possible methods for achieving a controlled thermonuclear reaction [1]. He also proposed two types of magnetocumulative generators of UHMFs (MC-1) and energy (MC-2) [1, 2]. In the first of them, a special device produces the initial axial magnetic field flux in the cavity of a cylindrical metal shell (liner). A converging detonation wave is initiated in a circular explosive charge surrounding the liner so that it arrives at the external boundary of the liner at the instant of time when the initial magnetic field in the liner achieves a maximum. Under the action of pressure of the detonation products, the liner collapses to the center, compressing the initial magnetic flux. If the compression is rapid enough, the magnetic flux in the cavity is preserved, and the magnetic field strength on the liner axis increases inversely proportionally to the squared radius of the liner, achieving a few megagausses. The chemical energy of the explosive is transformed into the magnetic field energy through the kinetic energy of the liner.

Extensive attempts made in many countries to reproduce UHMFs by the explosive compression of a magnetic flux revealed unexplainable difficulties in obtaining magnetic fields exceeding 3 MG, which resulted in the termination of work in this field.

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Uspekhi Fizicheskikh Nauk **181** (4) 441 – 447 (2011)
DOI: 10.3367/UFNr.0181.201104n.0441
Translated by M Sapozhnikov; edited by A Radzig

2. MC-1 cascade generator

A group of researchers at VNIIEF headed by A I Pavlovskii proposed and realized a number of concepts supplementing and developing the magnetic cumulation idea and solved the problem of the reproducible generation of UHMFs.

First, it was proposed to make the shells of the MC-1 generator from a material with a controllable electrical conduction. Such a material in the initial state is either completely nonconducting or conducts current only in one direction. At the required instant, a shock wave is passed through the material, making it conducting in all directions. For example, such a material can be produced from closely packed parallel isolated copper wires glued with an epoxy compound.

Second, unique solenoids of the initial magnetic field in the MC-1 generator were constructed in the form of a cylinder made of a composite material with the internal layer containing wires forming a multiple (≈ 500 entry wires), multilayer (7–13 winding layers) solenoid (Fig. 1). This made it possible to reliably obtain high magnetic fluxes and use the solenoid as a liner: after the passage of a shock wave from an explosive charge, the wires are connected up to form a continuous conducting cylinder capturing and compressing the magnetic flux [3].

Third, because the high initial magnetic flux in the wire solenoid provided UHMF generation in large volumes, the X-ray diffraction analysis of the longitudinal cross section of the MC-1 generator showed that the magnetic field strength is mainly restricted by the instability of the matter–field interface during the deceleration of the shell by the pressure of the strengthened magnetic field [4].

Fourth, the cascade principle of magnetic field strengthening was proposed, which removed this restriction, stopped the development of instabilities, and provided the reproducible generation of multimegagauss magnetic fields [5, 6]. One or two cylindrical cascade shells made of the same composite are located coaxially to the shell solenoid. In the initial state, the cascade shells easily transmit the amplified magnetic field flux inside, but each time the internal boundary of the liner can lose its stability, the liner is replaced by a new one, which compresses the magnetic flux when conduction appears in the cascade material after the impact of one cascades with the other.

The MC-1 cascade ten-megagauss magnetic field generator was developed for many years of research work and then produced in batches (see Fig. 1) [7, 8]. The basic

Figure 1. Appearance of the MC-1 cascade generator prepared for an explosion experiment. The inset shows a part of the cross section of the solenoid shell of the MC-1 generator.