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Laser thermonuclear fusion and physics of pulsed plasma with ultrahigh energy density

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Contents

Abstract. **Research in the field of laser thermonuclear fusion, which began more than 60 years ago at the Lebedev Physical Institute, in 2022 led to a record result in the ignition of a controlled fusion reaction in a laboratory experiment. The paper outlines the modern concept of laser thermonuclear fusion and the most significant results of research into pulsed plasma with an extremely high energy density produced under high-power laser irradiation of matter. A concise summary of the history of research in the field of laser thermonuclear fusion is presented, with emphasis placed on the role of the Lebedev Physical Institute.**

Keywords: lasers, controlled fusion reaction, inertial confinement, laser plasma, shock waves

1. Introduction

Laser thermonuclear fusion (LTF) is based on the so-called inertial method of thermonuclear plasma confinement during the time of its expansion under its own pressure. In this case, plasma is produced due to the collision of high-speed flows of matter at the center of a spherical target or on the axis of a cylindrical one. The inertial method of plasma confinement was first implemented in practice during the development of thermonuclear weapons in the middle of the last century. In order to heat the substance at the center of the target to temperatures of several ten keV, which correspond to the largest cross sections of the fusion reaction between hydrogen isotopes, the compressed substance must be accelerated to speeds of 300–400 km s^{-1}. Such acceleration can be achieved if an enormous pressure of several ten million atmospheres is applied to the surface of the target. In a thermonuclear explosive device, such pressure is achieved due to the explosion of the primer as a result of a chain fission reaction.

In 1962, at a meeting of the Presidium of the USSR Academy of Sciences, N G Basov put forward the idea of harnessing lasers with a unique capability to concentrate light energy in volumes with dimensions on the order of the radiation wavelength to achieve a controlled thermonuclear reaction (CTR). In 1964, N G Basov and O N Krokhin published a fundamental paper [1] with a theoretical substantiation for the possibility of heating deuterium–tritium (DT) matter to thermonuclear temperatures under the action of a laser pulse during the expansion of the resulting plasma. These two scientific events and the experiment that soon followed at the Lebedev Physical Institute (LPI) on generating neutrons from laser deuterium-containing plasma [2] not only became the starting point for LTF research but also laid the foundation for a new scientific line: the physics of high energy densities of laser-plasma interaction. Research in the field of laser thermonuclear fusion began to develop rapidly in the largest scientific centers in the world, such as the Lebedev Physical Institute, the nuclear centers the Russian Federal Nuclear Center All-Russian Scientific Research Institute of Experimental Physics (RFNC–VNIIEF) and the Russian Federal Nuclear Center All-Russian Scientific Research Institute of Technical Physics in Russia, the Livermore (LLNL) and Los Alamos (LANL) laboratories in the USA, the nuclear center of the French Atomic Energy Commission (CEA), the Laboratory for Laser Energetics of the University of Rochester (LLE, USA), and the Institute of Laser Engineering (ILE) of Osaka University (Japan) and in other laboratories.

Modern research in the field of LTF is being developed on the basis of two methods of implosion of a spherical thermonuclear target. One of them, so-called direct drive, is carried out by direct action on the target of radiation from symmetrically located laser beams. The second, so-called

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indirect drive, the use of which began later, involves target irradiation by laser-induced soft X-ray radiation. In the latter case, the conversion of laser radiation into X-ray radiation occurs on the inner surface of the converter, with the thermonuclear target located at its geometric center.

The general setup of a thermonuclear target is as follows. It is a structure in the form of a thin spherical shell consisting of an external layer of an absorber of laser or laser-induced X-ray radiation, an ablator, and a layer of DT or deuterium–deuterium (DD) ice frozen onto its inner surface. Compression of such a target toward the center provides a high degree of energy cumulation. The size of the target ranges from several hundred microns for kilojoule-level laser energy to several thousand microns for megajoule-level energy. With the same laser pulse energy, direct irradiation provides delivery of a significantly greater amount of energy to the target than in the case of indirect irradiation. While inferior to direct irradiation in the energy delivering to the thermonuclear capsule, indirect irradiation has the important advantage of providing a high degree of uniformity of energy input to the thermonuclear target and, as a consequence, the stability of its compression toward the center. This circumstance determines the degree of plasma compression, which is critically important for a binary fusion reaction, whose speed is proportional to the square of the density of interacting nuclei.

The first-ever experiments on direct irradiation of spherical targets [3–6] were performed at the Lebedev Physical Institute in the mid-1970s at the nine-beam Kalmar facility with a pulse energy of the fundamental harmonic of a neodymium glass laser (Nd laser, radiation wavelength of 1.06 μm) of about 100 J at a pulse duration of about 3 ns. These experiments, which were conducted under the supervision of N G Basov and O N Krokhin, brought fundamental results on the direct-drive implosion of spherical shell targets. Use was made of spherical shells with a thickness of several μm and a radius of 50–100 μm containing gaseous deuterium. Even in these experiments, the flight speeds of the shell to the center were measured at about 200 km s^{-1}, 10-fold shell compression by radius was achieved, the yield of neutrons of the deuterium–deuterium reaction was measured at about 10^6 particles per shot, and the high degree of absorption of short-wave laser radiation was substantiated: 60–70%. These experiments, as well as theoretical work at that time by scientists from the LPI in creative collaboration with scientists from the Institute of Applied Mathematics of the Russian Academy of Sciences [7–10], made a decisive contribution to the development of the concept of low-entropy LTF-target compression.

By the mid-1980s, high-power multi-beam laser facilities for LTF research with an energy of several ten kJ were set up, such as Nd lasers Nova (120 kJ, LLNL, USA), Omega (40 kJ, LLE, USA), Gekko-XII (ILE, 20 kJ, Japan), Febos (20 kJ, CEA, France), the iodine Iskra-5 laser (30 kJ, RFNC–VNIIEF), and the CO_2 Helios laser (10 kJ, LANL, USA). In the first decade of the 21st century, research reached the megajoule energy level on the largest Nd laser to date, the NIF (National Ignition Facility, LLNL), with an energy of about 2 MJ.

At the same time, a start was made on indirect-drive implosion research in LTF. In our country, similar studies were conducted at RFNC–VNIIEF under the supervision of S B Kormer and G A Kirillov, and in the USA at the Lawrence Livermore National Laboratory (LLNL) under the supervision of J Nuckols. The use of the indirect compression method [11–13] led to an outstanding result in solving the CTR problem. According to the US Department of Energy, in an experiment at the NIF facility at the Lawrence Livermore National Laboratory in December 2022, ignition of a thermonuclear target was achieved in relation to the energy of a laser pulse: the energy released in fusion reactions was 1.5 times higher than the expended laser energy. The NIF facility [14] was built at the end of the first decade of the 21st century and still remains the largest laser in the world. It provides 10–15-ns-long third-harmonic Nd-laser pulses (wavelength: 0.35 μm) in 192 beams with a total energy of about 2 MJ. In the record experiment mentioned above, about 3 MJ of energy was released in DT reactions. The neutron yield was 10^{18}.

For low-entropy compression of spherical shell targets in the experiments mentioned above, a laser pulse with a smooth power increase was used, in which one shock wave is excited at the initial stage of compression. This method of initiating the reaction at the center of the target is the traditional method of spark ignition in LTF. The higher the degree of target compression, the lower the energy required for ignition. In turn the less the compressed substance is heated, the higher the degree of compression, i.e., the more separated from each other the processes of target compression and heating of its central part [15, 16], the ignition region, which with any ignition method must ultimately be heated to thermonuclear temperatures. Research in this area led to the formulation of two promising ignition methods. One is ignition by a focused shock wave [17], called 'shock ignition' in the foreign literature, proposed at RFNC–VNIIEF in 1983. The second is direct ignition [18], called 'fast ignition' in the foreign literature, proposed at LPI in 1992. Both approaches involve the use of laser pulses at the final stage with a power significantly exceeding that at the compression stage.

High-power pulsed laser irradiation provides a record-breaking energy density in matter for a laboratory experiment both in studies to achieve a CTR and in studies of the properties of matter under extreme conditions. The second section of this paper presents the main provisions of the LTF concept based on the traditional spark ignition scheme. The efforts of the world's largest laboratories are currently focused on implementing this concept. The current state and most important results of research in this area are discussed. The third section is devoted to promising ignition methods, the use of which can provide a significant reduction in the laser energy required for ignition and a significant increase in the energy gain compared to the traditional concept. The fourth section discusses the current state and prospects for further development of high energy density physics using high-power pulsed laser irradiation of matter, in particular, the generation of shock waves with a pressure behind the front of over 1 Gbar [19] for studying extreme states of matter.

2. Classical concept of laser thermonuclear fusion

The efficiency of the fusion reaction in a laser thermonuclear fusion reactor is usually characterized by the total gain G, which is the ratio of the energy E_{th} released in fusion reactions to the total energy expended in plasma creation, $E_{\mathrm{L}}/K_{\mathrm{L}}$, where E_{L} is the laser pulse energy and K_{L} is the laser efficiency. Also used are gains relative to the laser energy $G_{\mathrm{L}} = E_{\mathrm{th}}/E_{\mathrm{L}} = G/K_{\mathrm{L}}$ and relative to the energy of the thermonuclear plasma stored at the onset of fusion burn, $G_P = E_{th}/E_p$. The gain G_P is an indicator of the efficiency of plasma burn, determined by the burnup of the thermonuclear fuel g in fusion reactions, i.e., the proportion of the fuel mass whose nuclei manage to react during the inertial confinement time. In terms of burnup and caloric content q: $E_{th} = gqm$, where m is the mass of the thermonuclear plasma; caloric content q is the energy released if all nuclei of a unit mass of an equimolar mixture of hydrogen isotopes enter into the fusion reaction. The plasma energy E_p is a fraction of the laser pulse energy determined by energy loss in the plasma production. Such loss is characterized, first, in the case of direct irradiation, by the absorption coefficient of the laser pulse in the target $K_{ab(L)} = E_{ab}/E_L$, and in the case of indirect irradiation, by the efficiency of converting the laser pulse into an X-ray pulse $K_{LX} = E_{LX}/E_L$ and the absorption coefficient of the X-ray pulse $K_{ab(X)} = E_{ab}/E_{LX}$ and, second, by the efficiency of hydrodynamic transfer of the absorbed energy into the energy of thermonuclear plasma $K_g = E_p/E_{ab}$, since part of the energy is contained in the energy of the evaporated part of the target (corona) flying outward, towards the heating radiation.

Among all fusion reactions, the DT reaction has the highest maximum cross section (about 10^{-24} cm^2), which is also achieved at the lowest energy of relative motion of nuclei (about 80 keV). In the DT reaction, an energy of 17.6 MeV is released during the production of a helium nucleus (α-particle) with an energy of 3.52 MeV and a neutron with an energy of 14.06 MeV. The energy released in this reaction per nucleon, 3.5 MeV, is significantly higher than in other fusion reactions, which determines its maximum calorific value among other fusion reactions $q = 3.34 \times 10^{11}$ J g^{-1}. Note that the calorific value of the DT reaction is approximately four times higher than that of the fission reaction of uranium-235 nuclei.

The number of binary fusion reactions N_r occurring in a unit volume of plasma and, consequently, the amount of energy released in them ε_r become greater as the reaction cross section σ depending on the plasma temperature T, the square of the plasma density n, and the time τ during which the plasma is retained in a compressed and heated state become greater: $\varepsilon_r \propto n^2\sigma\tau$. In turn, the specific (per unit volume) energy of the plasma $\varepsilon_p \propto nT$. Thus, the ratio $\varepsilon_r/\varepsilon_p$ becomes greater when the product of the plasma nuclear density n and the confinement time τ — the so-called $n\tau$-parameter — increases. The above relationships, taking into account energy losses due to plasma intrinsic radiation, were generalized in the form of a thermonuclear spark criterion proposed by Lawson more than 60 years ago [20]. The Lawson criterion sets requirements for the parameters of uniformly heated and compressed plasma that correspond to achieving the gain factor $G_P = 1$. According to this criterion, in addition to achieving the plasma temperature necessary to overcome the potential of electrostatic repulsion of nuclei, the $n\tau$-parameter must exceed a certain lower limit. The value of such a limit depends on the reaction cross section at a given plasma temperature, and for the DT reaction at a temperature of 10 keV is 10^{14} cm^{-3} s. In the case of inertial confinement, the role of the $n\tau$-parameter is played by the areal density of the compressed plasma nR: the product of the plasma nuclei density n and its size R. This is a consequence of the fact that the inertial confinement time is, by order of magnitude, the ratio of the plasma radius to the velocity of its thermal expansion, i.e., ultimately to the speed of sound. While in the case of magnetic confinement the parameter value of 10^{14} cm^{-3} s corresponds to a characteristic plasma density of $10^{13} - 10^{14}$ cm^{-3} and confinement time of several seconds, in the case of inertial confinement it is $10^{25} - 10^{26}$ cm^{-3} and several ten picoseconds. Typically, used in the case of inertial fusion is the mass areal density ρR, and the criterion for DT plasma is formulated as $T \geqslant 5-7$ keV, $\rho R \geqslant 0.35$–0.4 g cm^{-2} [21].

Current research is aimed at achieving a laser energy gain G_L exceeding unity. It is carried out in a traditional spark ignition setup using a profiled irradiation pulse, whose power smoothly increases with time [22] to values of several hundred TW. In the first part of the pulse, a preliminary compression of the relatively cold target substance occurs; in the second, under maximum pulse power, the plasma in the central part of the target is compressed and heated. To achieve a gain of $G_L = 1$, the energy of a laser pulse with a duration of about 10 ns, either directly irradiating the target or converted into X-ray radiation, should be about 2 MJ [21].

The research is based on the use of a solid-state Nd laser, which is capable of generating a pulse with the characteristics specified above. An important advantage of the Nd laser for LTF is its relatively short radiation wavelength: for the fundamental harmonic, it is $\lambda = 1.06$ µm. Currently, a technique is being developed for this type of laser for efficient conversion (up to several ten percent) of the fundamental harmonic radiation into the second ($\lambda = 0.53$ µm) and third harmonic radiation ($\lambda = 0.35$ µm). Radiation absorption is most efficient in the plasma resonance region, where the plasma density ρ_{ab} is close to the critical density $\rho_{ab} \leqslant \rho_{cr}$. The critical density value is determined from the equality of the radiation frequency and the oscillation frequency of plasma electrons in the ion field and is $\rho_{cr} \approx 1.83 \times 10^{-3} A/Z\lambda_\mu^2$ g cm^{-3} (λ_μ is the radiation wavelength [µm], and Z and A are the ion charge state and the atomic weight of the ions, respectively). Due to the fact that, with decreasing wavelength the critical density increases and radiation is absorbed in denser plasma, the use of short-wavelength radiation provides not only a high absorption coefficient in the case of direct irradiation but also a high degree of transformation of laser radiation into X-rays in the case of indirect irradiation. It should be noted that conversion into X-rays in the LTF scheme is carried out in practice inside a special converter box made of a material based on heavy elements when laser radiation interacts with its inner surface. Repeated conversion of scattered laser radiation under such conditions has the effect that the degree of conversion depends only slightly on the wavelength of the laser radiation.

The general characteristics of the design of a thermonuclear target intended for traditional spark ignition under the action of an Nd laser pulse with an energy of about 2 MJ under direct or indirect irradiation lie in the following approximate ranges [21]: mass, 1–3 mg; radius, 1.1–1.5 mm; thickness of the ablator layer made of different materials indicated above, 50–100 µm; thickness of the DT ice layer, 100–200 µm. The power of the profiled pulse during the first few nanoseconds increases to a value of 400–500 TW, after which it maintains its maximum value for 3–5 ns. The total pulse duration is 10–20 ns. At maximum pulse power, the radiation intensity on the surface of the target with the indicated radius is about $10^{14} - 10^{15}$ W cm^{-2}. This intensity corresponds to the optimal conditions of action both during direct irradiation with an Nd laser pulse and during its conversion into an X-ray pulse. Most of the radiation is absorbed in the outer part of the ablator, the corona, evaporating and heating it to temperatures of about 1–2 keV and thereby producing a 50-to-100 Mbar (50–100 million atmospheres) ablation pressure that compresses the unevaporated part of the target to the center.

The scale of ablation pressure is the product of the substance density in the energy absorption region $\rho_{\rm ab}$ and the square of the sound velocity V_s of the substance in this region. In turn, the sound velocity is expressed in terms of the absorbed energy flux density I as $V_s \propto (I/\rho_{\rm ab})^{1/3}$. Consequently, the ablation pressure $P_{\rm ab} \approx \rho_{\rm ab}^{1/3} I^{2/3}$ increases with increasing intensity of the incident radiation pulse and plasma density in the absorption region. For monochromatic laser radiation with wavelength λ at $\rho_{\rm ab} \approx \rho_{\rm cr}$, this estimate gives the dependence $P_{\rm ab} \propto (I/\lambda)^{2/3}$ for the ablation pressure, which shows an increase in pressure with decreasing radiation wavelength. For direct irradiation, the ablation pressure of fully ionized CH-plastic plasma is $P_{\rm ab} \approx 35(I_{15}/\lambda_\mu)^{2/3}$ Mbar [11, 23] (I_{15} and λ_μ are, respectively, the laser radiation intensity in units of 10^{15} W cm^{-2} and the wavelength in μm). When exposed to a third harmonic Nd laser pulse with an intensity of 10^{15} W cm^{-2}, the pressure is about 70 Mbar. When exposed to an X-ray pulse induced by a laser pulse with the above parameters, the ablation pressure reaches values approximately twice as high: about 150 Mbar. This increase is due to the absorption of X-rays in denser layers of the target compared to the absorption of laser radiation. Under the action of the ablation pressure, the unevaporated portion of the shell together with the DT fuel is compressed toward the center of the target at a speed of 300–400 km s^{-1}, exceeding by 40–50 times the first cosmic velocity. It is this speed that ensures the heating of the DT substance to a temperature of about 10 keV during the deceleration of the substance flows converging toward the center of the target. Only a small part of the energy absorbed in the target is spent on the formation of thermonuclear plasma with traditional spark ignition. The efficiency of hydrodynamic transfer — the ratio of the kinetic energy of the substance accelerating toward the center of the target to the total energy absorbed in the target — depends on the ratio of the masses of the evaporated and nonevaporated parts of the target in accordance with the momentum conservation law and is about 10% for a target with the above parameters [11, 23].

It should be noted that the pulse intensity of 10^{14}–10^{15} W cm^{-2} is the limit for traditional spark ignition using Nd-laser radiation. At such an intensity, the absorption of the radiation of the first three harmonics of the Nd-laser occurs due to collisional inverse bremsstrahlung with an absorption coefficient of $K_{\rm ab(L)} \approx 0.6-0.8$ [21]. When the interaction parameter $I\lambda^2$ exceeds the value of 10^{14} W μm^2 cm^{-2}, one of the most striking effects of high-energy-density physics of laser-plasma interaction, direct laser acceleration of charged plasma particles, begins to manifest itself to a significant extent. As a result, collisionless absorption mechanisms caused by the development of plasma instabilities, such as stimulated Raman scattering (SRS) and two-plasmon decay (TPD), begin to contribute to the absorption of laser radiation [24, 25]. As a consequence, a part of the laser energy is transformed into the energy of fast (suprathermal) electrons. In traditional spark ignition, the generation of fast electrons is a negative process, since the transfer of energy from such particles to the target can lead to its preheating, with a consequential decrease in the compression ratio.

The spark ignition concept is underlain by the phenomenon of energy cumulation during compression of matter in a spherical geometry. This effect results in the formation of a nonuniform DT plasma with a central part (ignition region) with a temperature of about 10 keV and a density of several ten g cm^{-3} surrounded by relatively cold fuel compressed to a density of several hundred g cm^{-3}, whose mass significantly exceeds the mass of the ignition region. The described plasma configuration is a necessary condition for the implementation of the most energetically favorable burn mode, when the input energy is spent on the formation of thermonuclear plasma with parameters satisfying the Lawson criterion in a small mass of fuel, after which the burn spreads to the main mass of the initially cold DT substance [7, 8, 26]. This burn mode of larger targets designed for irradiation with a laser pulse with an energy of about 10 MJ in the traditional spark ignition scheme can lead to a gain factor $G_{\rm L}$ of several hundred [26]. It is this gain that is required in the LTF scheme, not only to compensate for energy losses associated with low hydrodynamic compression efficiency, but also to compensate for the relatively low laser efficiency and obtain the final energy gain. Increasing the laser efficiency to at least 10% and ensuring the frequency mode of laser operation are two of the most important scientific and technical challenges in LTF. The solution to both problems lies in the use of ceramic materials with high thermal conductivity characteristics as an active medium and pumping these media by the radiation of semiconductor lasers [27, 28]. The use of light-emitting diodes (LEDs) can provide an efficiency of an Nd laser, of about 10% (the intrinsic efficiency of LEDs ranges up to 50%) and a pulse repetition rate of 10 Hz, which is necessary for the operation of an LTF thermonuclear reactor. However, LED matrices are still extremely expensive.

The greater the shell radius-to-thickness ratio (the aspect ratio), the greater the cumulation effect. However, the shell cannot be too thin: its aspect ratio should not exceed 5–10. Otherwise, its motion will be too sensitive to fluctuations in the compression symmetry, and the shell may collapse before reaching the center. The collapse is caused by the development of hydrodynamic instabilities, in particular, the Rayleigh–Taylor instability [29], which occurs when the pressure and density gradients of the adjacent media have opposite directions. The source of the initial disturbances can be density inhomogeneities and distortions of the shell shape, as well as spatial and temporal nonuniformity in the energy contribution to the target. The greater the difference between the densities of adjacent media, the greater the growth rate of the initial disturbances. Conditions for the development of Rayleigh–Taylor instability arise both at the stage of target acceleration, toward the center under the pressure of a low-density corona, and at the stage of compression, when the peripheral dense layers of matter are decelerated on the less dense matter of the central part of the target. Reducing the degree of the negative influence of hydrodynamic instabilities on the compression of a thermonuclear target is the most important task in LTF. The methods for solving it are improving target manufacturing technologies, improving the quality of laser beams, multi-beam irradiation, and using the method of indirect irradiation with laser-induced X-ray radiation.

At the instant of highest compression, a pressure of 200–300 Gbar (200–300 billion atmospheres) develops in the central part of the target, which is ten thousand times greater than the ablation pressure compressing the target. The specific energy of the substance reaches colossal values: 10^9 J g^{-1}. Behind the combustion wave front, the pressure reaches values that are an order of magnitude higher: several thousand Gbar. This means that the effect of high-power laser irradiation provides the opportunity to study high-density energy physics phenomena in a laboratory experiment under conditions that are realized during uncontrolled nuclear fission and fusion reactions in explosive devices and astrophysical objects.

Over the 60-year-long period of research in the field of laser thermonuclear fusion, a huge amount of knowledge has been accumulated concerning the physics of hydrodynamic, plasma, and radiation phenomena occurring at energy flux densities from 10^{14} to 10^{19} W cm^{-2}. With the commissioning of the NIF facility with an energy of about 2 MJ at the Lawrence Livermore National Laboratory, research in the field of laser thermonuclear fusion has reached the level of demonstrating the ignition of a thermonuclear reaction with respect to laser energy. The research program at this facility initially assumed indirect irradiation of a thermonuclear capsule with laser-induced X-ray radiation [11, 12]. For this purpose, a spherical capsule is positioned with the help of special suspensions at the geometric center of a hollow cylinder made of a substance of heavy elements, in which laser radiation is converted into X-rays by focusing laser beams on its inner surface. The beams are introduced through two end holes and are fan-shaped focused, as a rule, within four rings on its inner surface, arranged in pairs symmetrically relative to the cross section of the cylinder, in the middle of which is the center of the thermonuclear capsule. Heavy substances such as gold or depleted uranium are used as the converter material. The length and radius of the converter are about 9 mm and 5 mm, respectively, the radius of the input holes is about 1.5–2 mm.

The choice of the converter size and material was the result of fine optimization of the multiparameter problem of the injection of laser beams and their interaction with the inner surface of the converter in the presence of a thermonuclear capsule under the necessary condition of minimizing the converter size [12, 30, 31]. The energy of the X-ray radiation acting on the thermonuclear capsule is determined by the ratio of the surface areas of the capsule and the converter. With a degree of laser-to-X-ray radiation conversion of about 80%, a thermonuclear capsule with a radius of about 1 mm [30, 31] is exposed to an X-ray pulse with an energy that is 10–12% of the laser energy, i.e. about 150–200 kJ.

Over the ten-year period of research, the DT neutron yield in experiments at the NIF facility was increased from 10^{15} in 2013, first to 4.8×10^{17} in the 2021 experiment [31], and then to 10^{18} in the record-breaking experiment in December 2022. The main problem along this path was violation of the spherically symmetric compression of the target due to the development of hydrodynamic instabilities during the development of low-mode perturbations associated with the method of fixing the thermonuclear capsule and the two-sided injection of laser beams into the cylindrical converter. It was solved by improving various aspects of the indirect compression scheme, including the development of target manufacturing technology, improvement of the target fixing system in the converter, and the optimal choice of the location of the laser beam focusing areas on the inner surface of the converter. The research was accompanied by a large volume of computational and theoretical studies based on numerical simulations using two-dimensional and three-dimensional radiation hydrodynamics codes [32–36].

Prior to the time of writing this paper, the details of the record-breaking experiment had not been published in the scientific press. However, the parameters of the target and the characteristics of its compression in this experiment can be estimated using information contained in publications devoted to previous experiments, for example, in Refs [13, 31, 37]. The dimensions of the thermonuclear capsule with an ablator made of high-density carbon were close to the following values: outer radius of about 1.1 mm, ablator thickness of about 80 μm, DT ice layer thickness of about 70 μm. With a degree of conversion of laser energy of 2 MJ into X-ray energy of 0.8–0.9 and a ratio of the areas of the thermonuclear capsule with a radius of 1.1 mm and a cylindrical converter with a length of 8–10 mm and a cross-sectional diameter of 5–6 mm, the energy of the X-ray pulse can be estimated as $E_{\rm XL} \approx 200$ kJ. During one-dimensional spherically symmetric compression of such a target, which occurs at a shell flight speed to the center of 370–380 km s^{-1}, about 10% of the laser energy is converted into DT plasma energy, i.e., the plasma energy can be estimated as $E_{\rm p} \approx 20$ kJ. The central region of initial ignition satisfies the Lawson criterion: the ion temperature reaches a value of 9 keV, and the areal density is 0.35–0.37 g cm^{-2} (with a density of about 100 g cm^{-3} and a radius of about 35 μm). The density of the surrounding cold DT fuel is close to 800 g cm^{-3}. The above extremely optimistic estimates of one-dimensional target compression correspond to the propagation of a wave of fusion reactions into cold fuel due to the energy transfer by α-particles with a final yield of thermonuclear energy of about 12 MJ, which means achieving a gain $G_{\rm L} \approx 6$. The achieved ignition of a fusion reaction by laser energy with a gain $G_{\rm L} = 1.5$ is an outstanding scientific result, which is comparable in its significance to the launch of the first fission reactor 80 years ago. At the same time, it should be understood, of course, that, given the currently low efficiency of the NIF laser, the released energy of 3 MJ amounted to less than 1% of the total energy expended. Therefore, in any case, the path to an energetically favorable fusion reaction in LTF involves a radical increase in laser efficiency, as discussed above.

Currently, nearing completion in France is the construction of the LMJ laser, another facility designed for experiments near the ignition threshold [38]. This facility, whose energy should be 1.5 MJ, is equivalent to the NIF facility in all other respects. It was expected that, by the end of 2022, the energy of the facility would reach 300 kJ. The construction of a megajoule facility for research in the field of laser thermonuclear fusion is also underway at the Laser Physics Research Institute (LPRI) of the Russian Federal Nuclear Center VNIIEF [39, 40]. This facility is designed to generate a second-harmonic laser pulse of Nd laser radiation with an energy of 2.8 MJ in 192 beams. Just as at the NIF facility, the maximum power of the profiled pulse will reach 500 TW with a pulse duration of 10–20 ns. The main differences between the facilities are the use of a second-harmonic pulse of Nd laser radiation and a system of spherically symmetric focusing of laser beams. The choice of the second harmonic is aimed at increasing the energy of the facility by 1.5 times over the NIF setup due to the higher efficiency of the fundamental harmonic radiation conversion, which is 55–60% for the second harmonic when using modern KDP crystals, while for the third harmonic it is 35–40%. Despite the lower efficiency of the energy impact of the second harmonic radiation compared to the third, an increase in the laser pulse energy to 2.8 MJ will allow using targets with a greater mass, which can provide broader opportunities for optimizing its drive and ignition. The irradiation geometry corresponding to the cube-octahedron symmetry will make it possible to conduct experiments with spherical irradiation of the target from six directions both with direct and indirect irradiation, and, in the latter case using a spherical converter, which is extremely important for producing a uniform X-ray radiation field.

One of the versions of the direct implosion target intended for experiments at the megajoule facility of the Russian project is presented in a joint publication of LPI and RFNC–VNIIEF [41]. For a laser pulse of the second harmonic of an Nd laser with an energy of 2.8 MJ, a two-layer shell with an outer radius of 1595 μm has an ablator layer made of 35-μm-thick CH plastic and a 120-μm-thick layer of DT ice frozen onto its inner surface [41]. In such a target, 57% of the laser pulse energy is absorbed. The total pulse duration is 10 ns. Over the course of 7 ns, the power smoothly increases to a maximum value of 400 TW, which is maintained for the remaining 3 ns. The gain of such a target with respect to the laser energy, obtained in one-dimensional numerical calculations in the approximation of the absence of fast electron generation, is $G_{\mathrm{L}} = 18$ [41].

In subsequent studies, the effect of hydrodynamic instabilities [42–44] and fast electron generation [45, 46] on the gain was investigated using two-dimensional numerical simulations. In studies of the stability of target compression, all factors of target heating uniformity violation were taken into account: a finite number (192) of irradiating laser beams (base factor), energy imbalance between beams, beam misses relative to the target center, target shifts from the focal point, and beam arrival mismatches on the target. Base irradiation nonuniformity leads to a threefold decrease in the gain. Among the additional factors, the most significant effect on irradiation uniformity is exerted by target shifts from the laser beam aiming point. So that the presence of additional factors does not lead to deterioration of the basic nonuniformity, the target shift should not exceed 2% of the target radius, the random beam miss should not exceed 5% of the target radius, the time mismatch of laser pulses should not exceed 3% of the pulse duration, and the energy imbalance in laser clusters should not exceed 12%. The design characteristics of the laser system of the RFNC–VNIIEF facility satisfy the above conditions with a safety margin, which indicates the possibility of conducting successful experiments on ignition at this facility, not only in the indirect but also in the direct irradiation scheme.

As for fast electrons, the scale of their energy for all production mechanisms is the average energy of electron oscillations in the laser radiation field: $\varepsilon = m_{\mathrm{e}}c^2[(1+a^2)^{1/2}-1]$ (here, $a = eE_{\mathrm{f}}/m_{\mathrm{e}}c\omega$ is the dimensionless vector potential of the laser radiation field, m_{e}, e are the mass and charge of the electron, respectively, E_{f} is the field intensity, c is the speed of light, and $\omega = 2\pi c/\lambda$ is the laser radiation frequency). From this follow the relationships for the energy of a fast electron in the relativistic (at $I_{19}\lambda_{\mu}^2 > 1$) ($I_{19}$ is the intensity in units of 10^{19} W cm^{-2}, λ_{μ} is the wavelength in microns) and nonrelativistic (at $I_{19}\lambda_{\mu}^2 < 0.1$) electron acceleration modes in the laser radiation field, respectively: ε [MeV] $= 1.2(I_{19}\lambda_{\mu}^2)^{1/2}$ and ε [MeV] $= 0.45(I_{19}\lambda_{\mu}^2)^{1/3}$ [47, 48]. The characterization of fast electrons for the traditional spark ignition scheme at $I\lambda^2 \sim 10^{14}$ W cm^{-2} is based on the above nonrelativistic scaling and the experimental results [49], according to which the energy of fast electrons with a temperature $T_{\mathrm{h}} \approx 30-50$ keV contains about 1% of the laser energy.

The numerical simulations performed in Refs [45, 46] using these data yielded the following results at the influence of energy transfer by fast electrons on the operation of the spark ignition target intended for experiments at the Russian project facility. At a temperature of $T_{\mathrm{h}} < 35$ keV and a conversion degree of less than 2%, fast electrons do not have a significant effect on the compression and gain of the target. For $T_{\mathrm{h}} > 35$ keV, the critical threshold for the degree of laser energy conversion into fast electron energy is 1%.

3. Promising methods of ignition in laser thermonuclear fusion

The focused shock wave ignition method [17] involves the irradiation of a traditionally designed target by a two-stage laser pulse, which provides a stronger separation of the target compression and heating stages than traditional spark ignition does. The first part of the pulse, as in the case of the traditional approach, is intended for smooth low-entropy compression of the target over 10–20 ns to a density of several ten g cm^{-3}. During the second stage, the pulse power increases quite rapidly (in tenths of a nanosecond) to about 500 TW and is maintained for approximately one ns. It is this second part of the laser pulse that is intended to generate a powerful igniting shock wave with a pressure behind the front of several hundred Mbar. The central ignition region is formed at a high energy density resulting from the collision of one or more diverging and converging (igniting) shock waves [17, 50, 51]. The focused shock wave ignition method can provide a gain of $G_{\mathrm{L}} = 50-70$ with a laser pulse energy of about 1 MJ [17, 50–53].

To generate an igniting shock wave, the intensity of laser radiation on the surface of a pre-compressed target must be at least $(5-10) \times 10^{15}$ W cm^{-2}, which is an order of magnitude higher than the peak intensity of a laser pulse with traditional spark ignition. The interaction of radiation of so high an intensity with plasma is accompanied by intense generation of fast electrons. The degree of laser energy conversion into the energy of fast electrons and the characteristic energy of these particles increase with an increase in interaction parameter $I\lambda^2$. While in the case of traditional spark ignition, as indicated above, about 1% of the laser energy is converted into the energy of fast electrons with a temperature of 30–50 keV [49], in the case of ignition by a focused shock wave these figures can be 50–100 keV and 20–40% (of the energy of the igniting part of the pulse) [54–56]. However, in the period preceding the generation of the igniting shock wave, the target is compressed, that prevents the heating of the central part of the target by fast electrons. Under such conditions, a positive effect of energy transfer by fast electrons takes place due to the fact that at the final stage of target compression they make a significant contribution to the production of the ablation pressure, which is several times higher than the ablation pressure during traditional spark ignition. This effect has been confirmed in a number of experiments [57–63]. Specifically, in experiments of Refs [57, 58] with flat CH targets and an iodine laser pulse of 5×10^{15} W cm^{-2}, the ablation pressure increased from 30–40 Mbar in the absence of fast electrons, when third harmonic radiation was employed, to 80–90 Mbar when using the fundamental harmonic, which was accompanied by high-intensity generation of fast electrons. In experiments in Ref. [60], the ablation pressure was increased to 70 Mbar with an increase in the Nd-laser intensity to 10^{16} W cm^{-2}. In experiments in Ref. [63] with a petawatt-power laser, a shock wave pressure of 140 Mbar was recorded.

The direct ignition method [18] involves a radical separation of the stages of compression and heating of thermonuclear plasma by using an additional energy source: an ignition pulse (an electron or ion beam) with an intensity of 10^{18}–10^{19} W cm^{-2}, which should transfer its energy to the pre-compressed plasma during its inertial confinement time of several ten ps. It was proposed to use spherical shell targets equipped with symmetrically located hollow conical channels for introducing the ignition pulse radiation. In Ref. [64], in connection with rapidly developing research in the mid-1990s on the development of petawatt-power lasers [65] based on the 'chirping' technique [66], it was proposed to form a channel for delivering the ignition pulse due to the ponderomotive action of the laser beam radiation with an intensity of $10^{20} - 10^{21}$ W cm^{-2}.

The scenario proposed in Ref. [64] involved using two laser pulses at the ignition stage, each with a duration of about 10 ps. The radiation of the second pulse penetrates the target through the channel produced by the action of the first pulse, where, as a result of its interaction with dense plasma layers, an ignition beam of fast electrons is generated. At present, the set of ignition pulse versions under consideration includes the already mentioned beam of laser-accelerated electrons, a beam of laser-accelerated protons and light ions [67–70], a pulse of laser-induced X-ray radiation [71], and a hydrodynamic pulse of a laser-accelerated macroparticle [72, 73]. When the ignition criterion $T_{\rm ig} \approx 10$ keV, $\rho_{\rm ig} R_{\rm ig} \approx 0.35$–$0.4$ g cm^{-2} is met, the energy of the ignition region $E_{\rm ig} \propto (\rho_{\rm ig} R_{\rm ig})^3 T_{\rm ig}/\rho_{\rm ig}^2$ decreases with increasing density of the ignition region according to a quadratic law. The theoretical and simulation research performed in Refs [18, 64, 74, 75] has shown that fast ignition can reduce the total energy of the compression and ignition pulses required for ignition when reaching $G_{\rm L} = 1$ to values of about 100 kJ, while with a total energy of 10 MJ the gain factor of the fast ignition target can be $G_{\rm L} = 1.5 \times 10^3$, which is more than 5 times higher than the most optimistic prediction for traditional spark ignition. Among the results of experiments devoted to the study of fast ignition physics, it is worth noting the results of experiments of Refs [76–79] on the Gekko-12 facility at the Institute of Laser Engineering (ILE) at the University of Osaka (Japan), in which an increase in the neutron yield by more than an order of magnitude was recorded with additional heating of the compressed plasma of a spherical target, both by a beam of laser-accelerated electrons [76, 77] and by the impact of a laser-accelerated macroparticle [78, 79].

4. Ultrahigh-power laser-induced shock waves

The most fruitful avenue for studying the equation of state of matter is the shock-wave experiment in plane geometry due to the possibility of using a wide range of diagnostics in this case [39, 40, 80]. As mentioned in the foregoing, with direct irradiation of the target by terawatt pulses of short-wavelength laser or laser-induced X-ray radiation, record pressures of a quasi-stationary shock wave in a solid substance with a pressure of several ten Mbar have been achieved in a modern experiment [11, 12, 39, 40, 81]. A method for achieving even higher pressures at this level of radiation power is cumulative energy transfer to the target by impacting a macroparticle accelerated as a whole under irradiation by a terawatt-power pulse of laser or laser-induced X-ray radiation. Using this 'collisional' method, which is more complex to implement experimentally, record shock wave pressures of several hundred megabars have been achieved [78, 82–84].

In experiments in Refs [78, 82] at the Gekko-12 facility (ILE), a macroparticle-impactor made of CH plastic 20 μm thick was accelerated to a velocity of about 700 km s^{-1}under irradiation by the third Nd-laser harmonic pulse with an intensity of about 10^{14} W cm^{-2}. As a result of the impact, the propagation of a shock wave with a pressure behind the front of about 200 Mbar was recorded in a test target made of the same material 300 μm thick. In experiments with a similar impactor and test target irradiated with the pulse of a KrF laser (wavelength of 0.25 μm) with the same radiation intensity of about 10^{14} W cm^{-2} at the Nike facility at the Naval Research Laboratory (USA), the propagation of a shock wave with a pressure behind the front of about 500 Mbar was recorded [83]. Moreover, the impactor was accelerated to a speed of about 1000 km s^{-1}. Finally, in an experiment in Ref. [84] at the Nova facility (LLNL, USA), a record shock wave pressure of 740 Mbar for laboratory conditions was achieved. A two-layer impactor consisting of a 50-μm-thick CH-ablator layer and a 3-μm-thick gold layer was accelerated to a speed of about 100 km s^{-1} under irradiation by an X-ray pulse, into which the third harmonic radiation pulse of an Nd laser was preliminarily converted. The impactor collided with a test target made of 6-μm-thick gold. The shock wave velocity in the test target was 50 km s^{-1}.

The possibility of generating shock waves with even higher pressure is associated with the use of beams of laser-accelerated electrons and ions. In Refs [19, 85–87], a simulation and theoretical substantiation for the generation of a quasi-stationary plane shock wave with a pressure of several gigabars and even tens of gigabars under the action of a beam of relativistic electrons accelerated in the radiation field of petawatt-power lasers are presented. The physical prerequisite is the properties of energy transfer from fast charged particles to a solid target, which occurs as a result of Coulomb collisions with the electrons of the substance. As a result, the density of the region of charged particle energy absorption in the substance is not limited by the critical density of the plasma, which takes place in the absorption of electromagnetic radiation. Energy transfer to a dense substance is the reason why the effect of a flow of laser-accelerated fast electrons or ions is capable of providing a higher ablation pressure and, consequently, the generation of a more powerful shock wave in a solid substance. Specifically, since, as shown in the previous Section, $P_{\rm ab} \approx \rho_{\rm ab}^{1/3} I^{2/3}$, a beam of charged particles of the same intensity is capable of providing a pressure in a target with a density of ρ_0 that is approximately $(\rho_0/\rho_{\rm cr})^{1/3}$ times higher than that of a laser beam. Considering, for example, the radiation of the fundamental harmonic of an Nd laser ($\lambda \approx 1.06$ μm, $\rho_{\rm cr} \approx 3.6 \times 10^{-3}$ g cm^{-3}) and an aluminum target ($\rho_0 \approx 2.7$ g cm^{-3}), the increase in pressure is approximately 10-fold.

In modern experiments on the interaction of petawatt-power laser radiation with matter, fast electrons and ions have been accelerated to energies that exceed 1 MeV and 100 MeV/nucleon, respectively, with the degree of laser energy conversion into the energy of these particles being

20–30% and 7–10%, respectively (see, for example, review Refs [88, 89]). By providing an energy flux density on the target surface comparable to the intensity of the laser pulse, beams of laser-accelerated electrons are capable of generating shock waves with a pressure of several Gbar, a record for a laboratory experiment. Obtained in Refs [90–92] was experimental evidence of the generation of shock waves with a pressure of several hundred Mbar due to the heating of small masses of substance by fast electrons accelerated by petawatt-power laser pulses.

A transition to pressures of several Gbar in a laboratory experiment will be a significant step in the development of studies of the equation of state of matter. Studies at pressures of several hundred and thousands of Mbar were supported by the capabilities of underground nuclear tests during the period of their implementation. Some results of these studies are presented in a series of reviews published in *Uspekhi Fizicheskikh Nauk* [93–96]. Under the conditions of a moratorium on nuclear tests, the most promising technique for generating a gigabar-pressure shock wave involves irradiation of a substance by laser-accelerated charged particle streams, which can provide a record energy density input into matter under laboratory conditions. Moreover, such an approach is capable of providing a gigabar level of pressure of a plane shock wave in open geometry, which is especially important for the use of various diagnostics.

5. Conclusion

Ignition of the indirect-drive LTF target confirmed the fundamental possibility of implementing a controlled fusion reaction in laboratory conditions. An important scientific task for the near future is to demonstrate ignition in the direct irradiation scheme, which can be implemented at a megajoule facility of the Russian project. Direct irradiation is simpler and less energy-consuming than is indirect irradiation. Furthermore, the use of presently known promising ignition methods for the direct irradiation scheme seems more realistic from a technical point of view than in the indirect irradiation scheme. The continuation of the path to thermonuclear energy based on LTF is associated with solving scientific and technological problems regarding improving the efficiency of lasers with a power of several hundred terawatts and implementing their pulse-periodic operation mode.

In the area of high energy density physics, compressing LTF targets at an ultra-high energy density in matter, as well as generating ultrahigh-power shock waves under irradiation by petawatt and exawatt power lasers, makes it possible to study the extreme properties of matter in laboratory conditions. In particular, an important step in this area will be the transition to studying the equation of state of matter at gigabar pressure levels.

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