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Explosions, Powerful Shock Waves, and Extreme States of Matter

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Abstract—Extreme states arise when a substance is exposed to powerful shock, detonation and electric explosive waves, concentrated laser radiation, electron and ion beams, during powerful chemical and nuclear explosions, hypersonic motion of bodies in dense planetary atmospheres, high-speed impact, and in many other situations characterized by extremely high pressures and temperatures. The study of matter under extreme conditions is one of the most urgent and intensively developing fundamental scientific disciplines, located at the intersection of plasma physics, nonlinear optics, condensed state, nuclear, atomic and molecular physics, and relativistic and magnetic hydrodynamics. In our country, research in the field of physics of high energy density and extreme states of matter is dynamically developing thanks to the active cooperation of the Russian Academy of Sciences and the Rosatom State Atomic Energy Corporation.

Keywords: extreme states of matter, high energy density, shock waves, nonideal plasma, powerful magnetic fields.

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INTRODUCTION

The first decades of the 21st century were marked by many striking scientific achievements in the study of the structure of the atom and the atomic nucleus. Based on the results of work in this area of a number of leading physicists of the world, I.V. Kurchatov,

Ya.B. Zeldovich, Yu.B. Khariton, and others already in 1939 substantiated the possibility of a chain reaction of nuclear fission in uranium, and, consequently, the possibility of practical use of a fundamentally new, nuclear, energy source, millions of times more powerful than traditional chemical reactions. Soon after that, the conditions for the realization of an explosive-type nuclear chain reaction (discovered earlier by Academician N.N. Semenov for chemical reactions) were formulated with the release of an unprecedented amount of energy [1, 2]. This meant that scientists approached the threshold of creating weapons of extraordinarily destructive power [2, 3].

In the middle of the 20th century, the development of physics of high energy densities received a powerful impetus in connection with the entry of our civilization into the atomic and space era. The first step in this direction was the creation of nuclear and thermonuclear weapons [2–7]. In nuclear charges, high energy densities generated by powerful shock waves are used

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to initiate nuclear chain reactions in compressed nuclear fuel. In thermonuclear charges, high-energy states are the main tool for compression, heating of thermonuclear fuel and initiation of thermonuclear fusion reactions in it. That is, the operation of nuclear devices with quasi-controlled (atomic and hydrogen charges) and with controlled (inertial controlled thermonuclear fusion) energy release is based on the initiation of nuclear fusion reactions in a mixture of deuterium and tritium in highly compressed and heated nuclear fuel.

A great contribution to the development of the science of the extreme state of matter at this stage was made by outstanding scientists, Academicians Ya.B. Zel'dovich, A.D. Sakharov, Yu.B. Khariton, E.I. Zababakhin, A.I. Pavlovskii; Corresponding Member of the USSR Academy of Sciences S.B. Kormer; Doctor of Physical and Mathematical Sciences L.V. Altshuler, and others. The research they began in the mid-1950s within the framework of nuclear defense projects of the USSR subsequently developed significantly with the advent of new devices for generating high energy densities, such as lasers, charged particle beams, high-current Z-pinchs, explosive, electric explosive generators of powerful shock waves, multistage light gas cannons, and diamond anvils. These complex and expensive technical devices made it possible to advance significantly on the scale of energy concentrations available for physical experiments and to obtain, in laboratory or quasi-laboratory conditions, states of mega- and gigabar pressure ranges that are unattainable for the traditional equipment of physical experiment. In addition, a stable pragmatic incentive for such research was the practical application of states with high energy concentrations in nuclear, thermonuclear, and pulsed power engineering, high voltage and high power electrophysics for the synthesis of superhard substances, hardening and welding of materials, antimeteorite protection of spacecraft, and, of course, defense needs.

The physics of high energy densities has turned today into an extensive and rapidly developing branch of modern science, where the most advanced generation tools, diagnostic methods, and computer modeling are applied on the most powerful supercomputers. "High" is traditionally considered to be the concentration of energy in a substance, exceeding 10^4 – 10^5 J/cm³, which corresponds to the binding energy of valence electrons of several eV and pressures from about 100 kbar to 1 Mbar [3, 8, 9]. These pressures significantly exceed the limits of the mechanical strength of substances, which makes it necessary to take into account their compressibility during hydrodynamic motion as a result of pulsed energy release.

The state of matter characterized by extremely high temperatures and pressures and, consequently, extremely high energy concentrations has always attracted researchers with the prospects of obtaining in

laboratories such exotic conditions under which our Universe arose as a result of the Big Bang. The exotic state is characteristic even today for the overwhelming (90–95%) mass of baryonic (visible) matter in stellar and interstellar objects and in planets and exoplanets [10].

As a rule, a substance under conditions of high energy densities is in a plasma (ionized) state, since the processes of thermal ionization and/or ionization by pressure take place in it. In astrophysical objects, such compression and heating is carried out by gravitational forces and nuclear reactions, and in laboratory conditions, it occurs by powerful shock waves, for the excitation of which a wide range of "drivers" is used, from two-stage gas guns to lasers and high-current Z-pinchs with a power of hundreds of terawatts [3, 10]. At the same time, if in astrophysical objects the lifetime of extreme states varies from milliseconds to billions of years, allowing their detailed observation and measurement using space probes and orbital and ground-based telescopes of various wavelengths, then in terrestrial conditions we are talking about micro-, femto-, and attosecond ranges of durations [3, 11], which requires the use of specific extremely fast diagnostic tools.

It is important to note that in experiments with laboratory plasma of extreme states, it is already possible to reproduce partially on a small scale many phenomena and processes occurring in astrophysical objects, information about which has become available as a result of the use of terrestrial and space observational facilities. This is information about hydrodynamic mixing and various instabilities, shock-wave phenomena, strongly emitting, relativistic and magnetized flows and jets, solitons, relativistic phenomena, equations of state, the composition and spectra of compressed nonideal plasma, as well as characteristics of interstellar cosmic plasma and dust.

PHASE DIAGRAM OF MATTER IN AN EXTREME STATE

Figure 1 shows a diagram expressing extreme conditions that are realized in a number of physical objects of nature and in technology [10, 12]. The emergence of extreme states in nature is caused by gravitational forces, which have a long-range and, in contrast to Coulomb ones (in electromagnetic plasma), unshielded nature. These forces compress and heat matter either directly or by stimulating exothermic nuclear reactions in massive astrophysical objects, which was also manifested in the early stages of the evolution of the Universe [9, 12].

Plasma as the most widespread state of matter in nature (95% of the mass of the Universe excluding "dark" matter) occupies almost the entire area of the phase diagram (see Fig. 1). In this case, a particular difficulty in the physical description of such a medium

Fig. 1. Extreme states [3] in nature and in the laboratory. The numbers in brackets indicate the logarithm of the density (in g/cm^3). The “statics” region corresponds to the static method; “Dynamics,” to the dynamic method of obtaining high pressures; “High temperatures,” to the experiments at high temperatures. Lines 1–6 denote the states of the electronic component of matter for carbon: 1, boundary of the nuclear degeneracy region; 2, border of the region of ideality; 3, melting curve; 4, border of the region in which the lattice can be considered classical; 5, boundary of the region of electron degeneracy; 6, boundary of the region of relativism of electrons.

Source: [4].

is presented by the region of the nonideal plasma where the energy of the interparticle Coulomb interaction $e^2 n^{1/3}$ is comparable to or exceeds the kinetic energy of particle motion E_k . In this area, where the parameter of nonideality $\Gamma = e^2 n^{1/3} / E_k > 1$, the effects of plasma nonideality cannot be described by perturbation theory [8, 12], and the use of machine parameter-free Monte Carlo techniques or molecular dynamics [13] is associated with difficulties in choosing the adequate pseudopotentials and correctly accounting for quantum effects.

The quantum effects are determined by the degeneracy parameter $n\lambda^3$ ($\lambda = \sqrt{\hbar^2 / 2mkT}$ is the thermal de Broglie wavelength). For a degenerate plasma, $n\lambda^3 \gg 1$, the scale of kinetic energy is the Fermi energy $E_F \approx \hbar^2 n^{2/3} / 2m$, which grows with increasing plasma density, making it in the course of compression, $n \rightarrow \infty$, more and more perfect: $\Gamma = me^2 / (\hbar^2 n^{1/3}) \rightarrow 0$. The condition of relativism corresponding to the condition $mc^2 \approx E_F \approx 0.5 \text{ MeV}$ gives the density $\rho \approx 10^6 \text{ g/cm}^3$.

The effects of relativism of electrons in the equation of state and transport properties of plasma, when

$mc^2 \approx kT$, correspond to $T \approx 0.5 \text{ MeV} \approx 6 \times 10^6 \text{ K}$. Above this temperature, matter becomes unstable with respect to the spontaneous production of electron–positron pairs.

The scale of extreme conditions realized in nature is capable of striking the wildest imagination (see Fig. 1). At the bottom of the Mariana Trench (11 km), the water pressure reaches 1.2 kbar, at the center of the Earth, it is 3.4 Mbar, $T \approx 0.5 \text{ eV}$, density $\rho \approx 10$ – 20 g/cm^3 ; in the center of Jupiter $P \approx 40$ – 70 Mbar , $\rho \approx 30 \text{ g/cm}^3$, $T \approx 2 \times 10^4 \text{ K}$; at the center of the Sun $P \approx 240 \text{ Gbar}$, $T \approx 1.6 \times 10^3 \text{ eV}$, $\rho \approx 150 \text{ g/cm}^3$; and in cooling stars like white dwarfs $P \approx 10^{10}$ – 10^{16} Mbar , $\rho \approx 10^6$ – 10^9 g/cm^3 , $T \approx 10^3 \text{ eV}$. In targets of controlled thermonuclear fusion with inertial plasma confinement, $P \sim 200 \text{ Gbar}$, $\rho \approx 150$ – 200 g/cm^3 , $T \sim 10^8 \text{ eV}$. Neutron stars, which are elements of pulsars, magnetars, and sources of γ -bursts, apparently have record high parameters: $P \approx 10^{19} \text{ Mbar}$, $\rho \approx 10^{11} \text{ g/cm}^3$, $T \approx 10^4 \text{ eV}$ for the mantle and $P \approx 10^{23} \text{ Mbar}$, $\rho \approx 10^{14} \text{ g/cm}^3$, $T \approx 10^4 \text{ eV}$ for the nucleus at a giant magnetic field strength of 10^{11} – 10^{16} G .

In collisions of heavy nuclei accelerated in modern accelerators to relativistic velocities, there arise super-compressed quark–gluon plasma states with ultra-extremal parameters $P \approx 10^{30}$ bar, $\rho \approx 10^{15}–10^{16}$ g/cm³, $T \approx 10^{14}$ K, which exceed the conditions realized in extreme astrophysical objects [10].

METHODS FOR GENERATING HIGH ENERGY DENSITIES IN MATTER

Although modern experimental capabilities are rapidly increasing, they allow only partial penetration of the field of ultra-extreme astrophysical states. The strength of a substance fundamentally limits the use of static methods for studying high energy densities, since the overwhelming majority of structural materials are unable to withstand the high pressures of interest to experimenters. An exception is diamond, which has the record holder for hardness ($\sigma_n \approx 500$ kbar), which allows using it in diamond anvils to reach pressures of 3–5 Mbar in static experiments [10]. The palm of victory now belongs to dynamic methods [3, 8, 14, 15], based on the impulse cumulation of high energy densities in matter. The lifetime of such high-energy states is determined by the time of the inertial expansion of the plasma, which has a characteristic scale of $10^{-10}–10^{-6}$ s, which requires the use of diagnostic tools with a high temporal resolution.

The use of shock waves generated by sources of high local energy densities makes it possible to expand dramatically the range of pressures and temperatures available for the experiment and to penetrate into the region intermediate between the parameters of chemical explosives and the unique parameters of underground nuclear explosions. Already in the first experiments with laser beams and electrodynamic shock waves, it was possible to obtain important experimental data on the equation of state of hydrogen, deuterium, copper, iron, carbon, and water and use them to analyze the structure of the giant planets of the Solar System and exoplanets [3, 8, 11].

The range of experimental devices for generating high energy densities is very wide. It includes diamond anvils for static compression of matter, powder and light-gas throwing devices (“guns”), explosive generators of powerful shock waves, electric explosive devices, magnetic cumulative generators, lasers, high-current generators of powerful pulses of electric current, charged particle accelerators, and the possible combinations of these devices. Table 1 shows the parameters of the most powerful of the existing types of installations and those under construction: lasers, pulsed electrical devices, Z-pinches, and charged particle accelerators [10, 11]. The accelerators of relativistic charged particles (electrons and ions), created for conducting plasma research in the interests of defense and high-energy physics, today are also used success-

fully for work in the fundamental physics of high-energy-density plasmas.

SHOCK-WAVE DYNAMIC METHODS

Advancement on the scale of high energy densities is associated with the transition to dynamic research methods [8, 9, 15, 16], based on impulse cumulation of energy in the studied substance using powerful shock waves or using electromagnetic or corpuscular radiation of various nature. The resulting plasma temperatures and pressures significantly exceed the thermal strength limits of the construction materials of the facilities, which leads to limitations on the characteristic plasma lifetime in dynamic experiments. The lifetime is determined by the target expansion dynamics and is approximately $10^{-10}–10^{-5}$ s. With the dynamic approach, there are no fundamental restrictions on the magnitude of the maximum energy and pressure densities created in the target; they are limited only by the power of the energy source, i.e., the “driver.”

The most common tool for creating high energy densities is powerful shock waves [3, 14, 15], characterized by a viscous compression shock wave, in which the kinetic energy of the incident flow is converted into thermal energy of compressed and irreversibly heated plasma. Shock waves arise as a result of nonlinear hydrodynamic phenomena in a substance during its motion caused by pulsed energy release. Such a wave not only compresses, but also heats the substance to high temperatures, which is especially important for obtaining plasma, the ionized state of matter. A number of dynamic techniques used in the experimental study of strongly nonideal plasma are considered in [8, 10, 15].

The shock compression of matter in the solid or liquid initial state makes it possible to obtain behind the shock front the state of nonideal degenerate (Fermi statistics) and classical (Boltzmann statistics) plasma, compressed to maximum pressures of about 4 Gbar and heated to temperatures of about 10^7 K [10, 16] at which the internal plasma energy density is comparable to the nuclear energy density, and the temperatures are close to the conditions when the energy and pressure of equilibrium radiation begin to play a significant role in the overall thermodynamics and dynamics of such high-energy states.

To reduce the effects of irreversible heating, it is advisable to use the compression of matter by incident and reflected shock waves in a certain sequence, then it becomes close to the “softer” isentropic one, which makes it possible to obtain significantly higher (by a factor of 10–50) compression ratios and lower (approximately by a factor of ten) temperature compared to a single shock wave impact. Multiple shock compression has been used successfully to study experimentally plasma ionization by pressure [10, 17, 18] and substance dielectrization [10] at megabar pres-

Table 1. Energy sources and experimental devices used in the physics of high energy concentrations

Primary energy source	Final form of the energy source	Energy density, MJ/cm ³	Temperature, eV	Pressure, 10 ⁵ Pa	Total energy, MJ	Duration, s	Power, W
Chemical explosives	Chemical explosives	10 ⁻²	0.5	5 × 10 ⁵	10 ²	10 ⁻⁷	10 ¹⁰
	Metal plates	0.3	60	10 ⁷	3	10 ⁻⁶	10 ¹⁰
	Magnetic field 1 ME	4 × 10 ⁻³	0.3	5 × 10 ⁴	5	10 ⁻⁶	5 × 10 ¹²
	Magnetic field 25 ME	2.5	200	2.5 × 10 ⁷	1	10 ⁻⁷	10 ¹³
	Explosive plasma generators	10 ⁻²	60	10 ⁵	30	10 ⁻⁶	10 ¹²
Nuclear explosives	Nuclear explosives	10 ⁴	10 ⁷	10 ¹⁰	10 ¹¹	10 ⁻⁶	10 ²²
	Neutron heating	10	50	2 × 10 ⁷	10 ³	10 ⁻⁶	10 ¹⁵
	Shock waves in a solid	5	50	5 × 10 ⁷	10 ⁴	3 × 10 ⁻⁶	10 ¹⁵
	Shock waves in gas	0.3	40	2 × 10 ⁵	10 ⁷	10 ⁻⁵	10 ¹⁸
Compressed gas	Adiabatic compression	2 × 10 ⁻⁵	0,3	150	10 ³	6 × 10 ⁻³	10 ⁵
	Pneumatic shock tubes	10 ⁻⁴	1	250	10 ⁻²	10 ⁻⁴	3 × 10 ⁸
	Shock tubes on combustion	10 ⁻⁶	2	10	2 × 10 ⁻²	3 × 10 ⁻⁴	10 ⁸
	Shock tubes, electric discharge	10 ⁻⁷	2	1	10 ⁻²	10 ⁴	10 ⁸
Laser	—	10 ⁻⁶	—	—	0.5 × 10 ⁻³	—	10 ¹³
	Target	10 ⁴	10 ⁶	10 ⁸	0.5	10 ⁻¹⁰	5 × 10 ¹⁴
Electron beam	—	10 ⁻⁶	—	—	1	10 ⁻⁸	10 ¹⁴
	Target	5 × 10	5 × 10 ³	10 ⁷	0.1	10 ⁻⁸	10 ¹³

Source: [10].

tures. Quasi-adiabatic compression is also realized in explosive highly symmetric cylindrical and spherical compression of deuterium, helium, and inert gases [10, 18–20]. In this case, record plasma parameters were obtained in deuterium. At the initial pressure of gaseous deuterium $p_0 = 267$ atm and $T_0 = 10.5^\circ\text{C}$, the density of the shock-compressed deuterium plasma was recorded $\rho = (4.3 \pm 0.7) \text{ g/cm}^3$ at a pressure of $P = 1830$ GPa. Under these conditions, the plasma turns out to be highly nonideal ($\Gamma \approx 4.5 \times 10^2$), with a degenerate ($n\lambda_e^3 \approx 2.8 \times 10^2$) electron component and the number of electrons $n \approx 2.8 \times 10^{23} \text{ cm}^{-3}$ (Fig. 2).

Figure 3 shows the diagram of an experiment at VNIIEF to measure the compressibility of gases for simulating extreme astrophysical phenomena in laboratory conditions using a unique X-ray complex of this institute and experimental devices of cylindrical and spherical geometry that transform shock-wave compression into quasi-isentropic compression. The compression of the resulting plasma in such devices is car-

ried out by a system of shock waves reverberating in its volume, and steel shells converging to the center under the action of the explosion products of a powerful condensed explosive with a mass of up to ≈ 85 kg of trinitrotoluene. The process is called quasi-isentropic, because after the passage of the first shock wave, further compression of the plasma occurs practically without its significant heating with a longer retention of the substance in a compressed state. The purpose of the experiment is to register the $R(t)$ trajectory of the shells of the experimental device and determine the size of the internal cascade at the moment of “stopping” when the maximum compression of the test substance is reached. Its density is calculated from the expression $\rho = \rho_0 (R_0/R_{\min})^n$, where ρ_0 is the initial gas density, R_0 and $R_{\min}$ are the inner radius of the shell in the initial state and at the moment of its “stopping,” respectively; and $n = 2$ for cylindrical or 3 for spherical geometry.

Fig. 2. Quasi-isentropic compression of gaseous deuterium at pressures up to 10 Mbar. (1) Isentrope $S = 23.5$ J/g, (2) isentrope $S = 26.0$ J/g K, (3) numerical simulation of the RAS Joint Institute of High Temperatures [10]. The step in pressure is tied to the plasma phase transition (PPT).

Source: [19].

An experimental device of spherical or cylindrical geometry with a test gas is placed in front of a concrete structure, in which a complex is mounted, developed under the leadership of Corresponding Member of the RAS V.D. Selemir, consisting of three ironless pulsed betatrons BIM234.3000 with a boundary electron energy of ≈ 60 MeV. The use of such betatrons makes it possible to transmit through objects with a mass thickness of ~ 230 g/cm², which is equivalent to a ~ 200 mm thickness of lead. A feature of the VNIIEF's betatrons is the ability to operate in the mode of sequential generation of three X-ray pulses with a duration of ~ 150 – 180 ns. This makes it possible to register simultaneously up to nine phases of plasma compression in the experiment. In the experiments, an optoelectronic detection system is used, which is activated synchronously with the betatron pulses. Monocrystals of sodium iodide and lutetium silicate are used as converters of X-ray radiation into visible radiation. To eliminate the effect of scattered radiation on highly sensitive detectors, the size of the registration field in each of the projections is limited by lead collimators. Aluminum cones are used to protect betatrons and optoelectronic X-ray recorders. In dynamic experiments with devices of cylindrical geometry, an anomaly in the compressibility of deuterium plasma caused by a phase transition was recorded, which is accompanied by a density jump of $\sim 15\%$ in the pressure range $P \approx 150$ GPa at a temperature $T \approx 3700$ K [19].

Today, the use of the experimental technique of powerful shock waves to study the extreme states of

Fig. 3. Schematic course of the VNIIEF experiment to measure the compressibility of gases.

Shock compression of deuterium and helium up to 185 Mbar, $\rho = 14$ g/cm³.

matter is the main source of information on the behavior of highly compressed strongly nonideal plasma in the region of record high temperatures and pressures of the megabar and gigabar ranges. Being exotic for terrestrial conditions, ultra-extreme states are quite typical for most astrophysical objects, determining the structure, evolution, and luminosity of stars and planets of the Solar system, as well as more than 100 recently discovered exoplanets [10].

In addition, promising energy projects for controlled thermonuclear fusion with inertial plasma confinement and the realization of high-temperature states in compressed hydrogen are associated with plasma of the ultra-megabar range. These circumstances are a constantly acting stimulating factor in the experimental study of the properties of highly compressed nonideal plasma of hydrogen, deuterium, and inert gases using powerful shock waves, for the excitation of which light-gas [17] and explosive plane, spherical, and hemispherical devices and powerful lasers and electrodynamic accelerators are used [10, 18, 21].

A UNIQUE PHYSICAL PHENOMENON: THE NUCLEAR EXPLOSION

Physicists and, first of all, developers of nuclear weapons, fully appreciated the possibilities of nuclear explosions as an unprecedented source of generation of super-powerful shock and radiation waves in condensed media and the study of ultra-extreme states of matter with their help [10, 22–24]. To obtain the necessary information about the physical properties and

Fig. 4. Schematic course of the experiments on the generation of powerful shock waves in the near zone of a nuclear explosion.
Sources: [10, 16, 24].

gas-dynamic features of the behavior of matter under conditions of a nuclear explosion, a large-scale complex of experimental and theoretical works was launched, which gave rise to a new science, the physics of high energy densities [8, 16, 22, 23, 25] and dynamic physics of high pressures.

Along with measurements of the integral characteristics of a nuclear explosion and its impact, experiments were carried out to study the physical properties of matter at extreme pressures and temperatures. The set-up and the main physical results of such experiments are contained in a comprehensive review [24] and are presented in Fig. 4 [10, 26, 27]. The world record of the pressure level at which the parameters of the equation of state of a highly compressed and multiply ionized plasma were measured is $P \approx 4$ billion atmospheres. It was obtained in the near zone of a nuclear explosion.

The set of experimental data on shock-compressed aluminum plasma is given in [10, 16, 24], where the highest values of pressures correspond to record-breaking parameters under terrestrial conditions. The internal energy density of such a plasma is $E \approx 10^9 \text{ J/cm}^3$, which is close to the energy density of nuclear matter, and the pressure $P \approx 4 \text{ Gbar}$ is close to the pressure in the inner layers of the Sun. The plasma under these conditions ($n_e \approx 4 \times 10^{24} \text{ cm}^{-3}$, $T \approx 8 \times 10^6 \text{ K}$) is nondegenerate, $n\lambda^3 \approx 0.07$, twelvefold ionized, and the nonideality parameter is small, $\Gamma \sim 0.1$, which serves as an experimental illustration of the thesis on the simplification of the physical properties of plasma in the limit of ultrahigh energy densities. The range of parameters investigated is adjacent to the region where the contribution of the energy and pressure of equilibrium light radiation is noticeable in the thermodynamics of the system: $E_R = 4\sigma T^4/c$; $P_R = E_R/3 = 4/3\sigma T^4/c$. Thus, a plasma dynamics mode close to the radiation-gasdynamic one is realized [4, 27].

In addition to the possibility of obtaining ultrahigh energy densities, these experiments have a number of other unique features. This is the widest range of

pressure changes, one-dimensionality, and good symmetry of measurements using large samples, the dimensions of which are orders of magnitude larger than laboratory ones. As a result, a significant amount of invaluable experimental information was obtained in the region of ultrahigh pressures, the lower range of which is now being approached by the technique of high-power lasers [10]. The plasma energy densities recorded in terrestrial conditions were obtained precisely in the near zone of a nuclear explosion.

EXTREMELY STRONG MAGNETIC FIELDS

The study of the mechanisms of the formation of ultrahigh energy densities of electric and magnetic fields is an important task facing researchers. Russian science since the time of Academician P.L. Kapitsa has held a leading position in the generation of strong magnetic fields. The conservation of the magnetic flux in a closed conductor during its symmetric compression by an explosion allowed Academician A.D. Sakharov to propose a method of magnetic cumulation (MC) for the implementation of extremely strong magnetic fields [28]. He also developed the principle of operation of the first explosive magnetic generators. Its essence is as follows. In a radial generator (field generator), the initial magnetic flux with induction B_0 is radially compressed by a metal cylinder, accelerated towards the center by the detonation of a condensed explosive. Provided the magnetic flux is maintained $S = H_0\pi R_0^2 = H\pi R^2$, the magnetic field strength inside the cylinder $H = H_0(R_0/R)^2$ reaches many megagauss [29]. Under the leadership of Academician A.I. Pavlovskii, generators of reproducible extremely strong magnetic fields of the ten-megagauss range were developed, and the magnetic field record was brought to 17 MG [30].

Since the beginning of the 21st century, a generator of reproducible extremely strong magnetic fields (MK-1) has been used in the series of international experiments "Kapitsa." The unique experimental base of Rosatom in the field of extremely strong magnetic

Fig. 5. Schematic course of the experiment on isentropic compression of hydrogen by an extremely strong magnetic field. (1) Solenoid-shell of MK-1, (2) cascade, (3) metal tube with the test substance, (4) cylindrical explosive charge.

Sources: [30, 31].

fields, in this case acting as a center for collective use, was provided for studying the electronic structure of various materials, including organic metals, heterostructures, magnetic materials, determining the characteristics of phase transitions and the critical magnetic fields in high-temperature superconductors [31]. The placement in the internal volume of the MK-1 generator of extremely strong magnetic fields of a coaxial hollow cylinder made of a conductive material allows it to be converted into a generator for isentropic compression of substances at pressures up to 7 Mbar. This generator was used to study the equations of state for isentropic compression of hydrogen isotopes, which are important for determining the characteristics of giant planets [31], and as an applied problem, the equations of state for isentropic compression of structural materials.

A team led by Corresponding Member of the RAS V.D. Seleznev is conducting work to improve generators of extremely strong magnetic fields. In the “nesting doll” from the MK-1 generators nested inside each other, the maximum possibilities of using the energy of explosives are realized, and in macrovolumes of $\sim 3 \text{ cm}^3$, a magnetic field of 28 MG was obtained, which is the maximum value that has been achieved in macroscopic volumes on Earth thus far (Fig. 5). These explosive devices currently hold records for the magnitude of a pulsed electric current of $\approx 300 \text{ MA}$, which corresponds to extremely high electromagnetic energy $H^2/8\pi \approx 3 \text{ MJ/cm}^3$. Explosive magnetic generators are the most powerful energy devices today, and their power reaches $\approx 100 \text{ TW}$ [32].

Progress into the region of extremely strong magnetic fields of the hundred-megagauss range, at which the pressure in macrovolumes of the order of several

cm^3 reaches 400 million atmospheres, will require the use of the energy of an atomic explosion [33].

The study of the method of magnetic cumulation for the formation of current pulses has made it possible to create powerful, up to 100 TW, energy devices [34]. These generators are used to convert the energy of an explosion into the energy of powerful plasma formations, coherent and incoherent light radiation, and powerful microwave radiation [32]. Thanks to the unique energy capabilities of magneto-cumulative generators, it was possible for the first time to simulate the effect of a lightning pulse with a current amplitude of hundreds of kA on grounding devices [35] and to create mobile complexes for applications in practical power engineering [36].

DEVICES OF HIGH-CURRENT PULSED ENERGY

Devices of high-current pulsed energy ($10^5\text{--}10^7 \text{ A}$) are used to obtain plasma of high energy densities in experimental set ups. Electric energy can carry out direct pulsed Joule heating (electric explosion) of conductors or magnetodynamic compression and heating of plasma formations. The stored energy can be used to generate intense flares of soft X-ray radiation (with a radiation temperature of 200–300 eV) with the subsequent generation of powerful shock or radiation heat waves by this radiation, or for electrodynamic generation of shock waves, as well as for the electrodynamic acceleration of metal liners.

The highest plasma parameters are currently obtained in powerful Z-pinch of the terawatt power range, in which the electric energy of the capacitors carries out the electrodynamic acceleration of the plasma with the subsequent focusing of its kinetic energy on the cylinder axis [37–39]. In these experiments, a cylindrical plasma shell (liner) is created by the electric explosion of hundreds of thin (6–50 μm) tungsten conductors with a current of 20 MA with a rising edge of about 100 ns. When collapsing around the axis, a tungsten plasma was obtained with an ion density of the order of 10^{20} cm^{-3} and an ionization degree of more than 50.

In experiments at the Angara installation [38–40] (Fig. 6), a pulsed current of $\approx 4 \text{ MA}$ accelerated the xenon plasma liner to a speed of $\approx 500 \text{ km/s}$. The highly symmetric impact of this liner on the surface of a highly porous cylindrical target excited a thermal radiation wave in it, emitting soft X-ray radiation with a temperature of about 100 eV. This radiation was used for highly symmetric generation of plane shock waves with a pressure amplitude of $\approx 5 \text{ Mbar}$ to excite thermal radiation waves with a propagation velocity of $\sim 100 \text{ km/s}$, as well as to accelerate metal strikers to 10–12 km/s.

Fig. 6. Pulse generator Angara-5, State Research Center of the Russian Federation Troitsk Institute for Innovative and Thermo-nuclear Research of the Rosatom State Corporation.

Source: [35].

GENERATION OF MACROSCOPIC VOLUMES OF HOT PLASMA

An important positive feature of accelerated charged particle beams is the volumetric nature of their energy release [41]. This is how they differ from laser radiation, where the main energy release with the frequency ω_l is limited to a narrow critical zone [42–44], $\omega_l \sim \omega_p \sim 4\pi e^2 n_e / m_e$, and then is transferred into the depth of the target due to electron thermal conductivity. As a result of deceleration of charged particles, a layer of isochorically heated plasma arises, the subsequent expansion of which generates a shock wave deep into the target or a cylindrical shock wave diverging from the beam axis. In modern research in the field of high energy density physics, both of these techniques are used—isochoric heating and compression by shock waves generated by corpuscular beams.

The accelerators of relativistic heavy ions created for experiments in high-energy physics turned out to be promising devices not only for controlled thermonuclear fusion with inertial confinement, but also for experiments on compression and heating of dense plasma [45, 46], that is, for work on the fundamental physics of plasma of high energy densities. Heavy ion beams with a kinetic energy of 3–300 MeV per nucleon were used in experiments on heating condensed and porous targets, measuring the stopping power of ions in the plasma, and also on the interaction of charged beams with shock-compressed plasma

produced using explosive generators and mini-explosive shock tubes [10, 13].

Of particular interest is the use of the GSI heavy ion accelerator in combination with the powerful petawatt PHELIX laser system (Fig. 7), which qualitatively expands the experimental capabilities of such a device. Prospects for the use of the GSI accelerator

Fig. 7. Schematic course of the HIHEX experiment of the FAIR project using a relativistic heavy ion beam and a petawatt laser.

Sources: [37, 42].

complexes in Darmstadt (Germany) are presented in papers [41, 43]. Intense relativistic beams of heavy ions are promising for the generation of high energy density plasma, as well as for pulsed thermonuclear fusion.

* * *

Shock-wave experimental techniques play a leading role in the physics of high energy densities today, making it possible to obtain maximum dynamic pressures of the megabar and gigabar ranges for many chemical elements and compounds. The maximum reached is six orders of magnitude higher than the pressure at the impact of a bullet, three orders of magnitude higher than the pressure at the center of the Earth, and close to the pressure in the central layers of the Sun and targets of inertial thermonuclear fusion. Such exotic states of matter appeared during the birth of our Universe a few seconds after the Big Bang [9, 10]. In a certain sense, we can assume that by successively increasing pressure and temperature in dynamic experiments, we seem to be moving backward along the time axis, approaching the moment of the birth of the Universe—the Big Bang.

Studying the evolution of the early Universe provides a unique opportunity to explore high-energy phenomena that cannot be recreated in a laboratory. According to modern concepts [47], the evolution of the Universe in time was extremely uneven. It is relatively slow now, but in the early stages it was amazingly fast, so that serious qualitative changes in the state took a fraction of a second. The currently observed Universe arose about 13.7–14 billion years ago from some initial singular state with infinitely high temperature and density, and since then has been continuously expanding and cooling to its present size, on the order of 10^{28} cm, with average temperatures of about 2.7 K. According to the Big Bang theory, further evolution depends on the current expansion rate of the Universe and the average density of matter in it.

The science of the structure of matter at high energy densities and cosmophysics are closely related and intertwined. And although the limiting pressures of laboratory plasma so far differ from the maximum astrophysical values by 20–30 orders of magnitude, this gap is rapidly narrowing, and physical processes in the laboratory and in space often demonstrate striking diversity and, at the same time, deep analogies, indicating at least the unity of the physical principles of the behavior of matter in the widest range of densities (about 42 orders of magnitude) and temperatures (up to 10^{13} K).

The achieved level of development of the physics of high energy densities already today presents unique opportunities for scientists of the Russian Academy of Sciences, Rosatom, and higher education institutions to solve a number of interesting fundamental and applied problems. Studies of the isentropic compres-

sion of a number of substances are extremely important for determining the structure of both the planets of the Solar System and exoplanets. Without studying the electronic structure of materials, progress in the development of new materials for electronic engineering, new high-temperature superconductors, is impossible. It is possible that the first controlled thermonuclear reaction will be carried out with inertial thermonuclear fusion. The pressures, magnetic field strengths, and temperatures required for these studies can be realized only by methods of high energy density physics.

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