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IN MEMORY OF VLADIMIR EVGEN'EVICH FORTOV

Use of powerful shock and detonation waves to study extreme states of matter*

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Contents

Abstract. This article is written on the basis of a report given 10 January 2003 at the International Scientific Conference, The Nuclear Age: Science and Society, dedicated to the 100th anniversary of the birth of Igor' Vasil'evich Kurchatov. It presents the results of work on the experimental study of substance properties under high pressure shock waves, briefly describes the use of super-strong magnetic fields for the study of substances at high pressure, presents the results of computational and theoretical research methods, and presents some results of studies of substance properties using liner systems in high-power pulsed electrophysical facilities (VNIIEF disk explosion-magnetic generators and USA Pegasus and ATLAS capacitor banks).

Keywords: extreme states of matter, shock waves, detonation, liner systems

From the editorial board. The editorial board of the journal *Physics–Uspekhi* (*Uspekhi Fizicheskikh Nauk*, *UFN*) expresses its gratitude to Svetlana Vladimirovna Fortova, who drew the attention of the *UFN* editorial board to this interesting publication, which had not been previously translated into English and, therefore, most likely, was little known to the international scientific community. We hope that the reproduction of this paper in the memorial issue of *UFN*, dedicated to the memory of Vladimir Evgenievich Fortov, will give a 'second life' to this publication, which outlines numerous results. By virtue of the genre of this paper (report at a conference), the material in it was presented in an extremely laconic form (mainly in a vivid illustrative form adopted for the presentation of reports). Therefore, for the convenience of the readers of the journal *UFN*, this publication is supplemented with a list of some reviews and papers, in which the interested reader can find more detailed information both on the research results presented in this paper at the time of publication of this report in 2004 [1–28] and on the future development of research in this field at VNIIEF and in other Russian and foreign scientific centers [29–59].

The editorial board of *UFN* expresses its gratitude to A M Buiko, S F Garanin, M V Zhernokletov, E L Kobryanskaya, S A Monakhova, V D Selemir, N I Sokolova, and V G Sultanov for their help in preparing this paper for publication in the *UFN* journal.

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* The paper was written on the basis of a report presented by R I Il'kaev on January 10, 2003 at the plenary session of the International Scientific Conference, The Nuclear Age: Science and Society, dedicated to the 100th anniversary of the birth of Igor' Vasil'evich Kurchatov. The conference was held on January 10–11, 2003 at the Russian Scientific Center, Kurchatov Institute, on the eve of Igor' Vasil'evich Kurchatov's birthday (January 12, 2003). Together with other reports presented at the conference, this paper was first published in the collection of the *International Scientific Conference, The Nuclear Age*: *Science and Society* (Moscow: IzdAT, 2004) p. 64. Currently, the collection is posted on the website of the electronic library, History of Rosatom, at http://elib.biblioatom.ru/text/yaderny-vek_2004/ (*Editor's comment*).

1. Investigation of substance properties at high pressures of shock waves

The need to study the properties of substances at high pressures of shock waves — the so-called equations of state — arose simultaneously with the implementation of the Atomic Program of the Soviet Union. Outstanding Soviet scientists E I Zababakhin, Ya B Zeldovich, Yu B Khariton, the still living L V Al'tshuler, and others stood by the cradle of a new, dynamic area in high-pressure physics. Methods were proposed for determining the kinematic parameters of shock waves, which are related by conservation laws:

with shock compression pressure $P = \rho_0 D U$,
density $\rho = \rho_0 D (D - U)^{-1}$
and energy $E = 0.5P(\rho_0^{-1} - \rho^{-1})$.

Here, D and U are the velocity of the shock wave and the velocity of substance motion behind its front, that is, in the dynamic method, thermodynamic quantities are determined in terms of kinematic parameters.

Naturally, the first quantities whose compression was studied in shock waves were those used in the first nuclear charges: aluminum, iron, and uranium. In 1947, the density of their shock compression was recorded at pressures of 500,000 atmospheres.

In the 1950s–1960s, special measuring devices were made that provided pressures in heavy metals up to 30 million atmospheres. These devices, in the order of increasing generated pressure, are shown in Fig. 1. On the left side, the

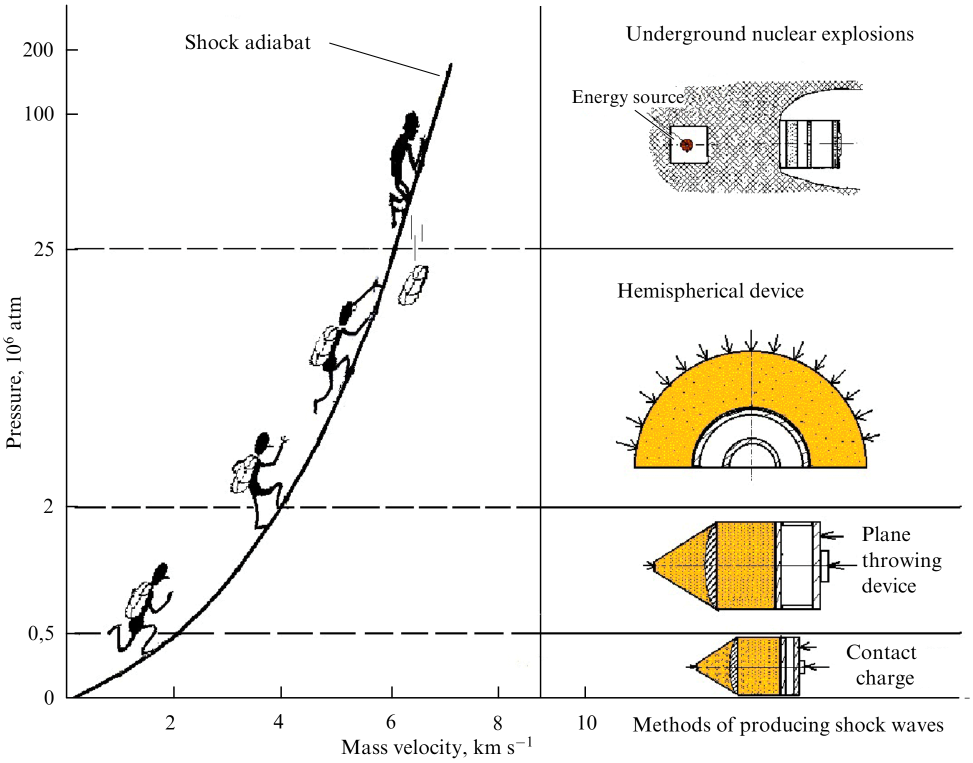


Figure 1. Diagram of explosion measurement devices and recorded shock compression pressure ranges (for heavy metals).

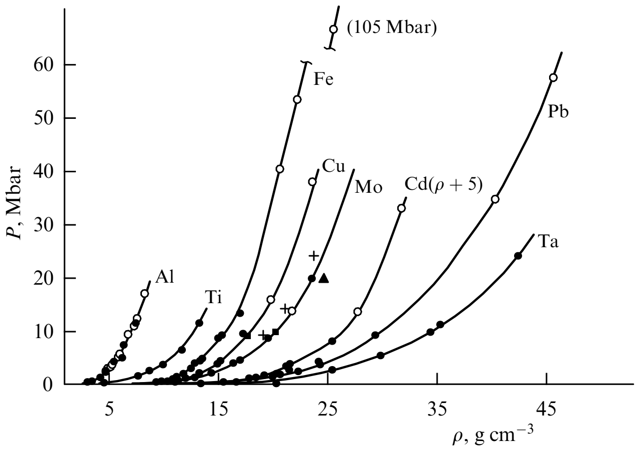


Figure. 2. Pressure–density diagram. Area of maximum parameters. o, +, ▲ — points obtained during underground explosions (o — Russia): • — laboratory data. Adiabat C is shifted by +5 g/cm^3.

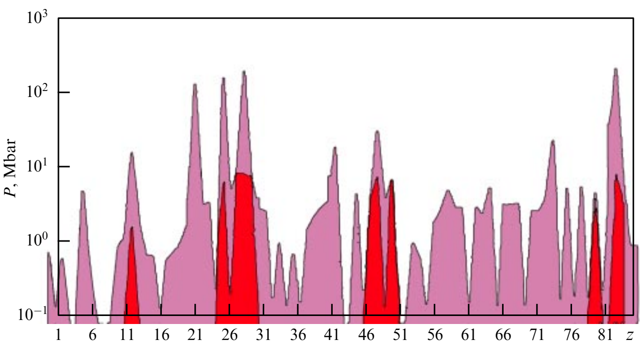


Figure 3. Diagram of pressures for elements of the periodic system (depending on pressure). Results obtained at VNIIEF during the lifetime of Igor Vasil'evich Kurchatov are marked in red. Current state is shown in lilac. (Beginning of 2003 — *Editor's comment.*)

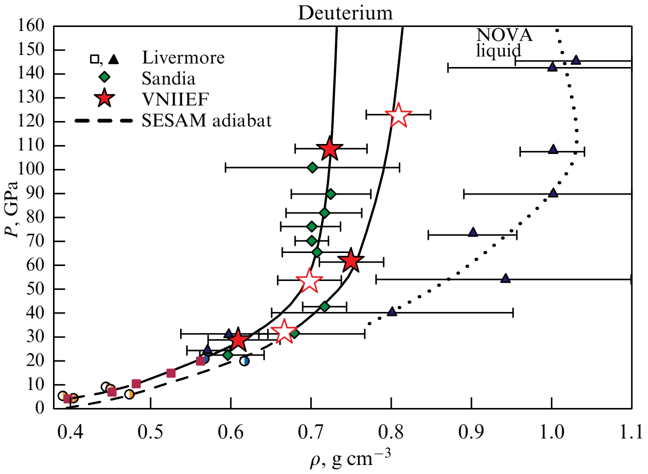


Figure 4. (Color online.) Comparison of shock adiabats obtained in the USA (Livermore, Sandia) and at VNIIEF.

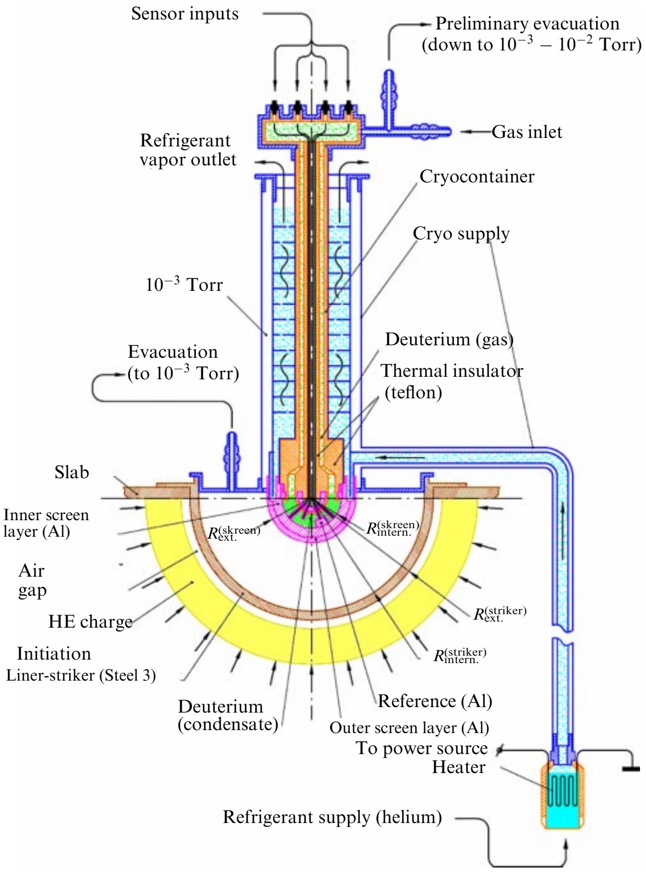


Figure 5. (Color online.) Sketch of experimental device.

iron shock adiabat is shown, along which a researcher makes his way up to the higher pressure. Shown schematically on the right are measuring devices for producing pressure in the substances under study. Topping this column are underground nuclear explosions, which have enabled a series of unique measurements of compressibility at ultrahigh pressure. The simplest systems, presented in the lower right column, provide a pressure of 2 million atm. These are so-called 'throwing' systems. A researcher making his way along the adiabat (left part of the picture) allows himself to calmly overcome this frontier.

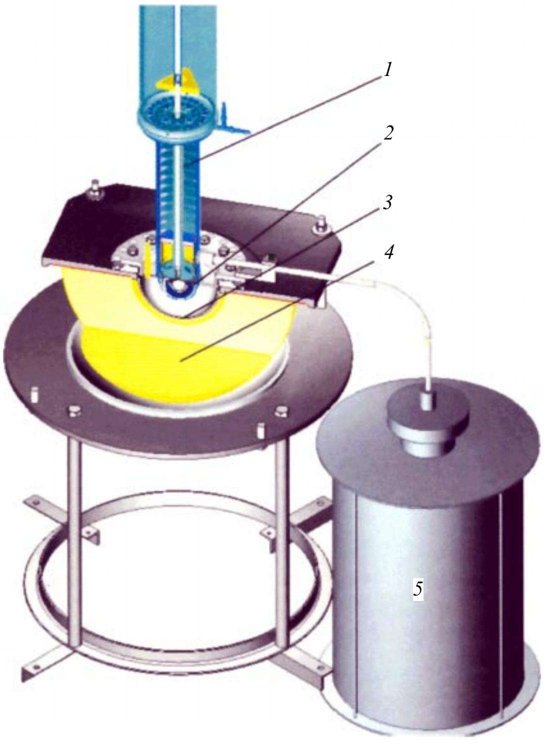


Figure 6. (Color online.) Device for the shock study of deuterium. *1* — cryostat, *2* — condensed deuterium, *3* — liner-striker, *4* — hemispherical HE charge, *5* — vessel with liquid helium.

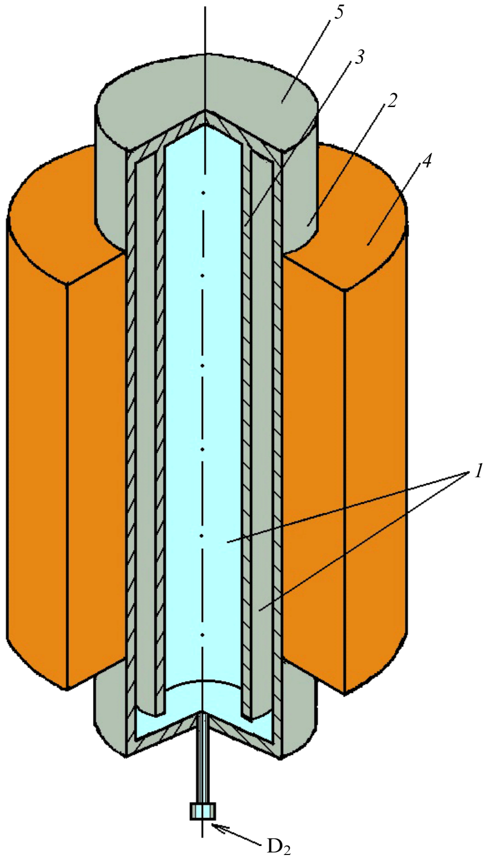


Figure 7. (Color online.) Investigation of quasi-isentropic compressibility of gases in the megabar pressure range. *1* — gaseous medium, *2* — outer shell, *3* — inner shell, *4* — HE, *5* — flange.

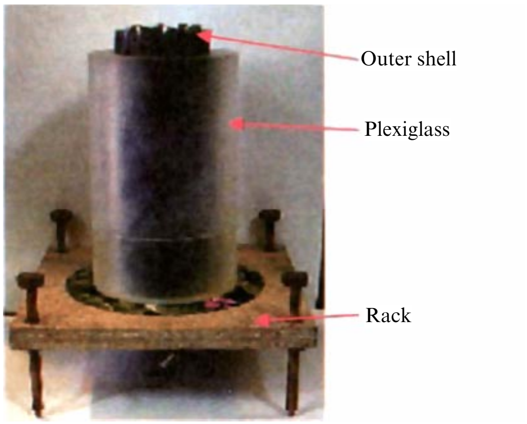
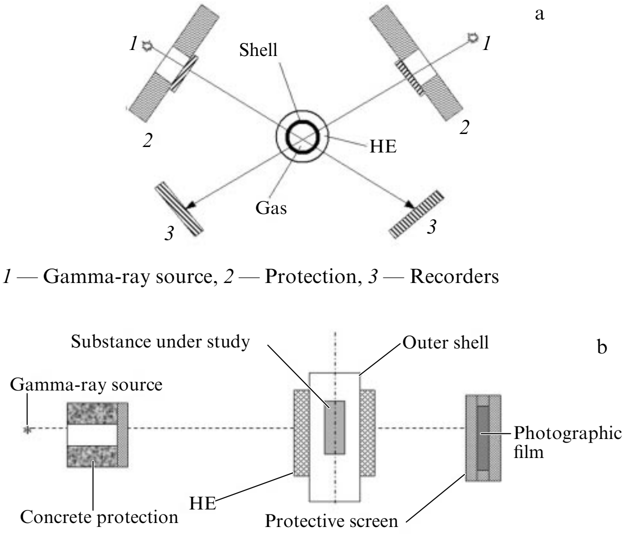


Figure 8. Photograph of the experimental device without the HE charge.



1 — Gamma-ray source, *2* — Protection, *3* — Recorders

Figure 9. Schematic of an experiment to measure the quasi-isentropic compressibility of gaseous deuterium.

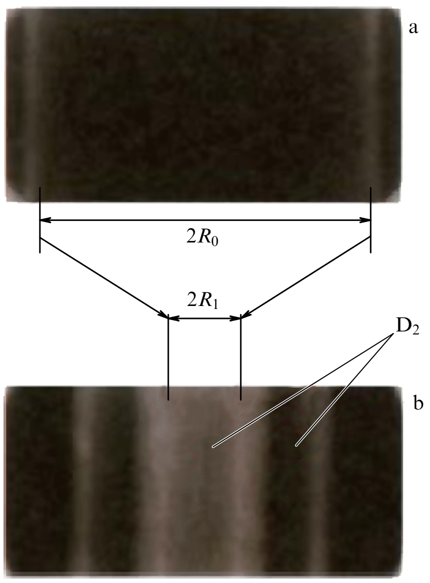


Figure 10. X-ray images of cylindrical shells in the compression of deuterium gas at a pressure of $\sim$ 150 GPa. (a) Shadow image of the shell in its original state. (b) Shadow image of shells at the instant a gamma-ray photograph is taken.

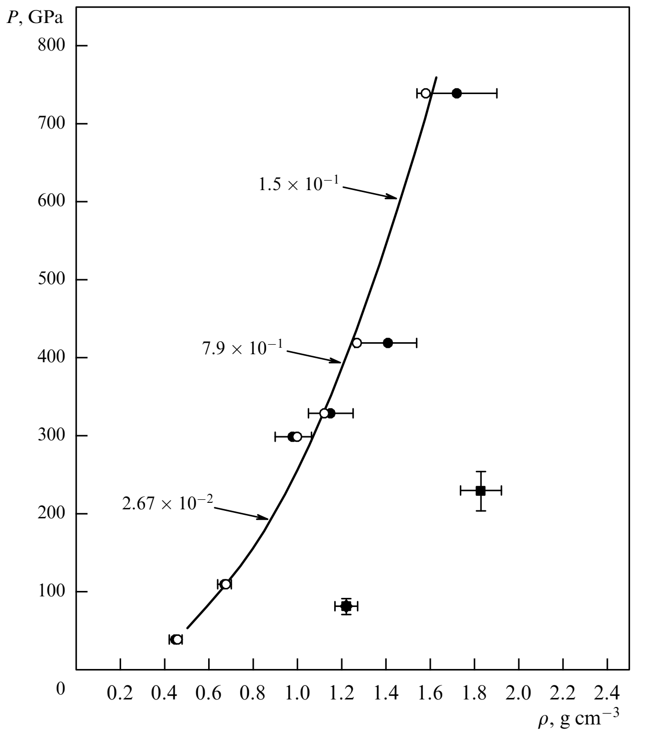


Figure 11. Quasi-isentropic compressibility of hydrogen and deuterium gases. Deuterium: experiment. Hydrogen: experiment and calculation [Kormer] — calculation for hydrogen by EoS in modified Van der Waals form. Arrows indicate the degree of dissociation at these pressures.

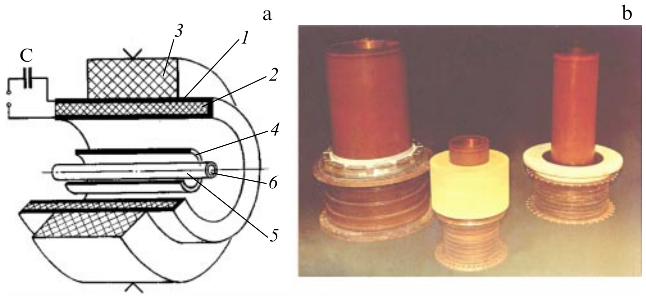


Figure 12. (Color online.) Isentoropic compression of substances by the pressure of a superstrong magnetic field. MK-1 cascade generator of superstrong magnetic fields. (a) Diagram of the MK-1 cascade generator: *1* — solenoid liner, *2* — insulator, *3* — HE charge, *4* — 2nd stage, *5* — 3rd stage, *6* — strongest-field volume. (b) Appearance of solenoid shells of three sizes: 150, 200, and 360 mm.

The next stage is hemispherical systems. Such systems exist only in Russia, and they have made it possible to ensure the priority of our research in the million-pressure range. In hemispherical devices, the explosion products of a spherically converging detonation wave smoothly accelerate an iron striker-liner, which 'converges' to the center of the system. Near the center, its pressure ranges up to about 30 million atm.

Finally, the highest pressures were reached in the immediate vicinity of the explosion site of a nuclear device during underground tests and, according to our measurements, are 200 million atm. In this area of the diagram, our researcher is no longer up to running: let's hope he can stay on all fours on the adiabat! To lighten the weight, even the backpack had to be jetisoned!

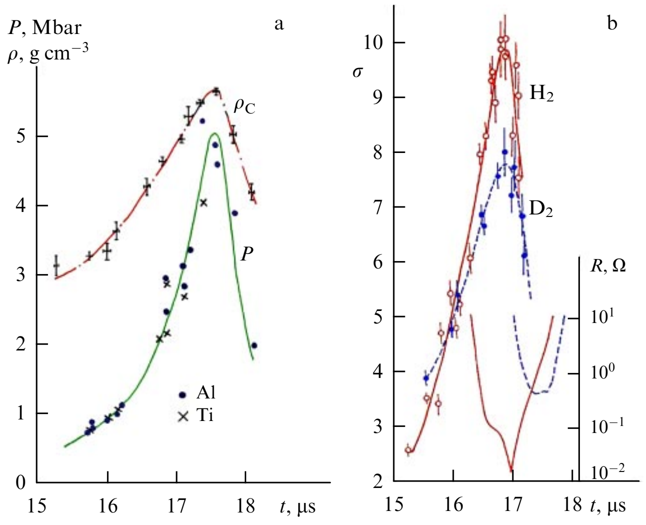


Figure 13. (Color online.) Isentropic compression of substances by the pressure of a superstrong magnetic field. Results of studies of graphite and condensed deuterium and hydrogen. (a) Pressure pulse $P(t)$ with a maximum of 5 Mbar and compressibility curve of graphite $\rho(t)$ in the compression device. (b) Compressibility curves of hydrogen and deuterium $\sigma(t) = \rho/\rho_0$ and variation in the resistance $R(t)$ of the sample after the occurrence of conductivity.

Let us now see (Fig. 2) what the compressibility is of some metals obtained using the measuring devices considered.

Data are given in pressure–density coordinates. The highest pressures were obtained on iron — 105 million atm (these are absolute measurements, i.e., those in which D and U are measured simultaneously). Lead shrinks best. At a pressure of 60 million atm, it contracts by a factor of 4.2.

Figure 3 shows the dependence of pressure on the ordinal number of an element in the periodic system. Shown in red are the data obtained at our institute during the lifetime of Igor Vasilyevich, who, realizing their importance, was always interested in these studies. The position at the present time is shown in lilac. One can see that the vast majority of elements have been studied (including, in particular, a number of transuranic elements, which are not shown in the diagram).

To date, we have studied the shock compression of more than 250 different substances. In addition to elements, this number includes alloys, hydrides, nitrides, oxides, minerals, and other substances.

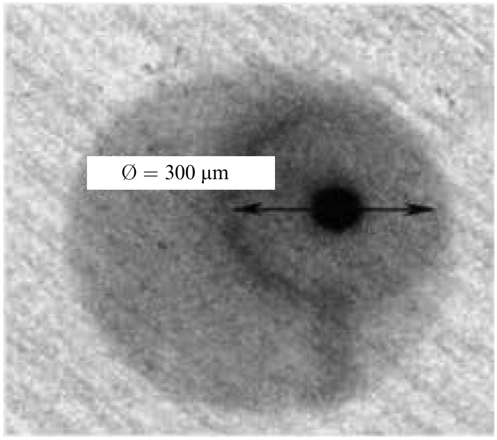


Figure 14. In experiments at the ISKRA-5 facility, a high degree of compression symmetry of X-rayed glass microspheres with DT gas was realized. A pinhole camera image of the glass microsphere.

Table.

Minimum number of points on the target surface	$250 \times 250 - 6 \times 10^4$
Minimum number of points along the radius	200
Minimum number of groups in photon energy and alpha-particle energy	20
Number of particle flight directions in the phase space	1000
Number of arithmetic operations required to calculate one point in the phase space at one time step	2×10^3
Total number of arithmetic operations for all points required to calculate one time step	4.4×10^{14}
Number of time steps	10^4
Required performance of a supercomputer for calculating the compression stage of a thermonuclear target	~ 10 Tflops (time costs: ~ 100 h for one simulation)
Required performance of a supercomputer for full-scale simulations of the operation dynamics of the laser thermonuclear facility	> 100 Tflops

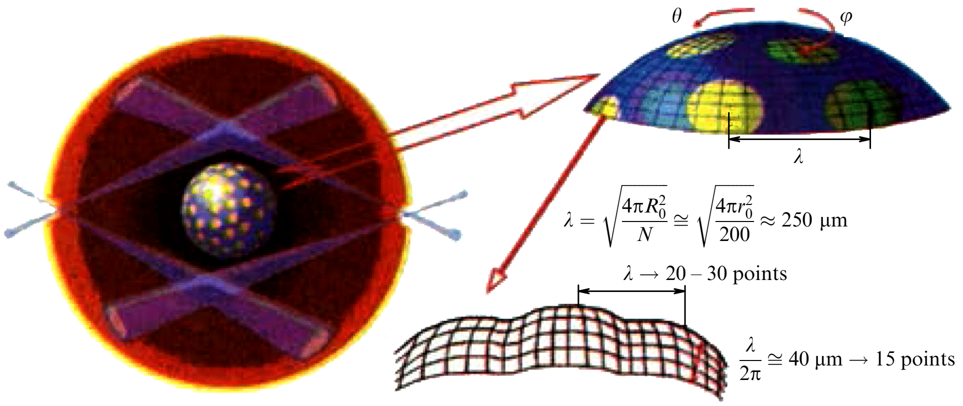


Figure 15. (Color online.) Simulation of target dynamics under irradiation by a multi-beam laser.

- Three-temperature hydrodynamics:

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{1}{\rho}\,\mathrm{grad}\,(P+Q)\,; \quad \frac{\mathrm{d}z}{\mathrm{d}t} = u\,; \quad \frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho\,\mathrm{div}\,u\,;$$

$$\frac{\mathrm{d}E_\gamma}{\mathrm{d}t} = -\rho_\gamma\,\frac{\mathrm{d}(1/\rho)}{\mathrm{d}t}\,; \quad \frac{\mathrm{d}E_\mathrm{e}}{\mathrm{d}t} = -\rho_\mathrm{e}\,\frac{\mathrm{d}(1/\rho)}{\mathrm{d}t}\,;$$

$$\frac{\mathrm{d}E_\mathrm{i}}{\mathrm{d}t} = -(p_i+Q)\,\frac{\mathrm{d}(1/\rho)}{\mathrm{d}t}\,.$$

- Multi-group spectral radiation transfer:

$$\frac{\partial U_\nu}{\partial t} + \mathrm{div}\,\frac{c}{3\chi_\nu^{\mathrm{abs}}}\,\mathrm{grad}\,U_\nu = j_\nu - c\chi_\nu^{\mathrm{abs}}U_\nu\,;$$

$$\rho\,\frac{\mathrm{d}E_\mathrm{e}}{\mathrm{d}t} = c\sum_\nu\left(\chi_\nu^{\mathrm{abs}}U_\nu - \frac{j_\nu}{c}\right).$$

- Electron and ion energy transfer:

$$\frac{\partial E_\mathrm{e}}{\partial t} = -\frac{1}{\rho}\,\mathrm{div}\,(\chi_\mathrm{e}\,\mathrm{grad}\,T_\mathrm{e})\,; \quad \frac{\partial E_\mathrm{i}}{\rho}\,\mathrm{div}\,(\chi_\mathrm{i}\,\mathrm{grad}\,T_\mathrm{i})\,.$$

- Alpha-particle energy transfer in space in a multi-group diffusion approximation.
- Kinetics of thermonuclear reactions.
- Kinetics of ionization and recombination.
- Laser energy import into the target.

Figure 16. Main processes included in the simulation.

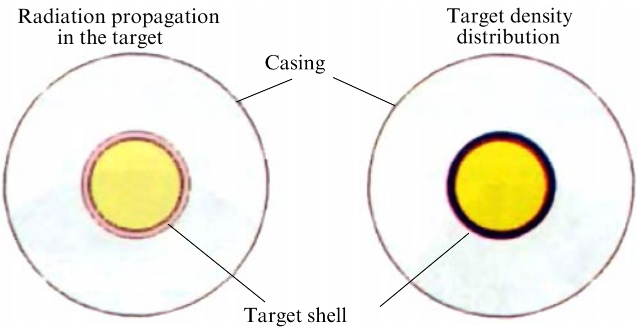


Figure 17. (Color online.) Schematic showing radiation propagation and target density distribution.

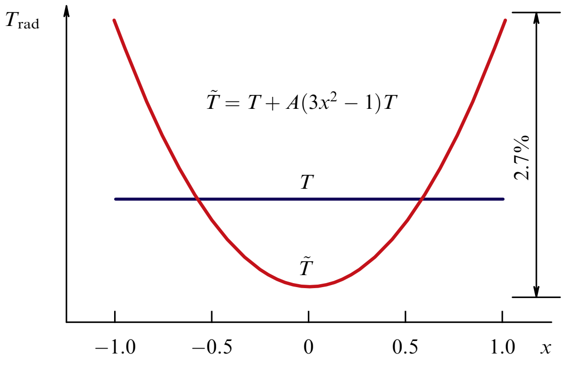


Figure 18. (Color online.) Perturbation shape.

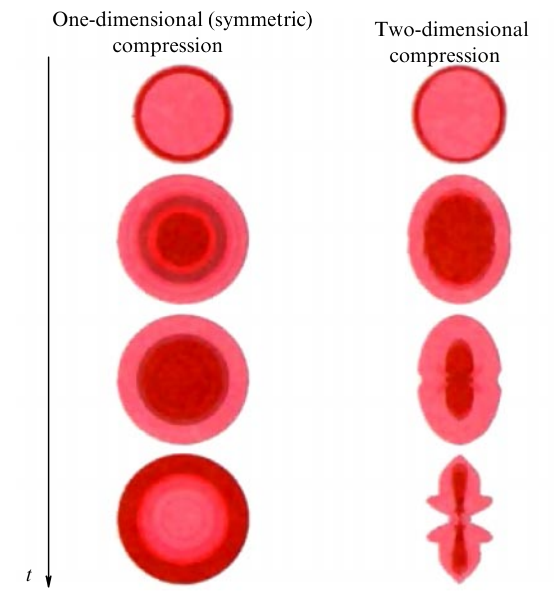


Figure 19. (Color online.) Compression dynamics of laser fusion targets.

Let us dwell in somewhat more detail on the study of the shock compression of condensed deuterium, in whose behavior researchers at the Livermore Laboratory discovered an anomaly associated with a sharp increase in the density on its shock adiabat. They investigated liquid deuterium. The data are shown in Fig. 4. Coordinates: pressure–density. Pressure was produced by irradiating a deuterium target with a powerful laser beam at the NOVA facility. On the irradiation side, a plane sample of deuterium was covered with aluminum foil, which transmitted a shock wave of megabar amplitude to the deuterium.

Up to a pressure of 0.3 Mbar, data were obtained with the so-called two-stage gas gun (Livermore); at megabar pressures (experiments are indicated by triangles), using NOVA at the same place.

The increase in density at a pressure of 500 kbar is so unusual that many scientists, both here and abroad, expressed doubts about the correctness of the Livermore results. These doubts are based both on an insufficiently clear recording of the mass velocity and on the influence on the recorded parameters of the possible nonequilibrium of processes at the screen–deuterium interface. Such processes, with a thickness of the studied samples in tenths of a millimeter, may indicate the values of the compression of deuterium. And although there seemed to be no direct measurement errors, the unusual position of the compression curve called for independent verification using other technical options.

Such options are provided to us, in particular, by explosive systems with the convergence of hemispherical shells to the center. In existing devices, the flight speed of the shell near the center of the system reaches 24 km/s. When it strikes a nucleus containing deuterium, pressures of approximately 1.1 Mbar arise in the latter. The advantage of spherical systems is that the samples (deuterium) are significantly thicker (by a factor of 10–20).

We started experiments with deuterium in 2000. For technical reasons, we began measurements with solid deuterium, assuming that the conclusions obtained with it apply equally to liquid deuterium.

At the present time, we have obtained data on the compression of solid[1] deuterium at pressures of 0.6 and

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[1] Here and wherever solid and liquid deuterium are referred to, we mean their initial state.

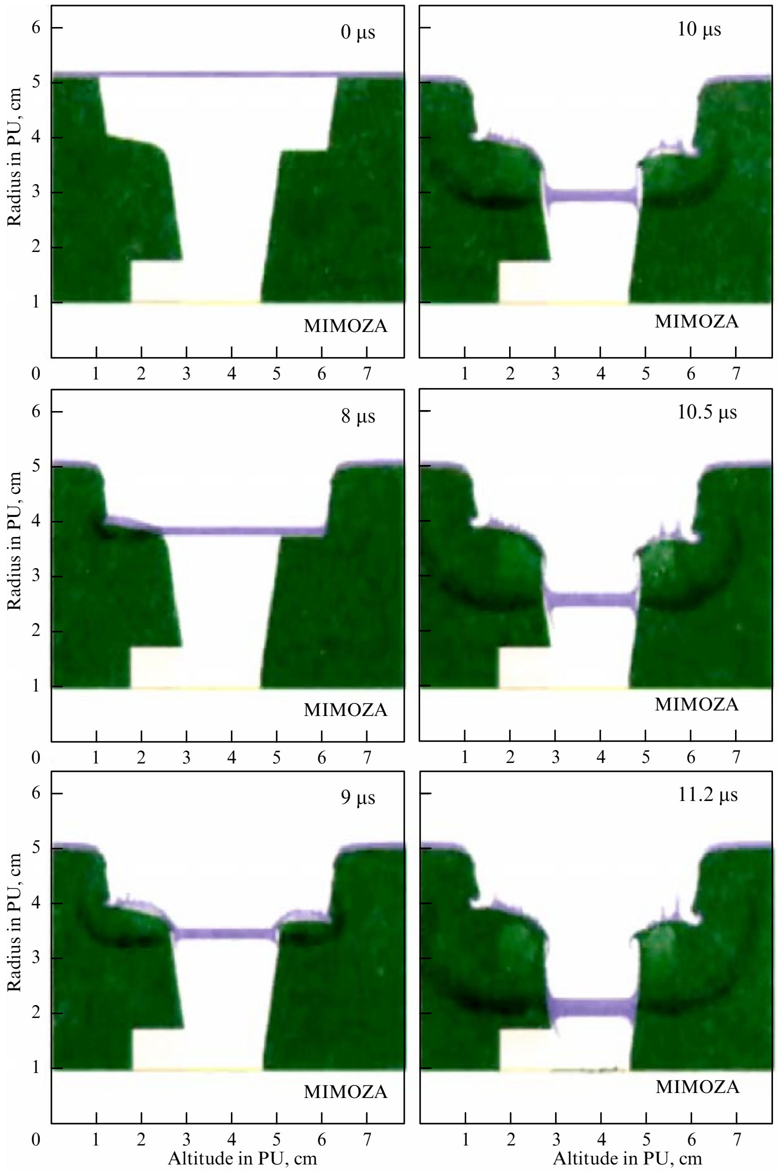

Figure 20. (Color online.) Two-dimensional MHD simulation of the compression of a cylindrical A1 liner in a ponderomotive unit (PU) with different shapes of end-face PU electrodes (Cu): significant interaction of the liner with the electrodes is possible, which prevents the liner from being efficiently used. Isodensity maps at successive points in time. Characteristics of the liner in the simulation: radius $R = 5$ cm, thickness $\Delta = 2$ mm, current $I_{\max} = 22$ MA ($\tau_{1/4} = 6$ µs, ATLAS bank, USA, planned experiment RUS-8), speed ~ 7 km/s at a radius of ~ 2 cm.

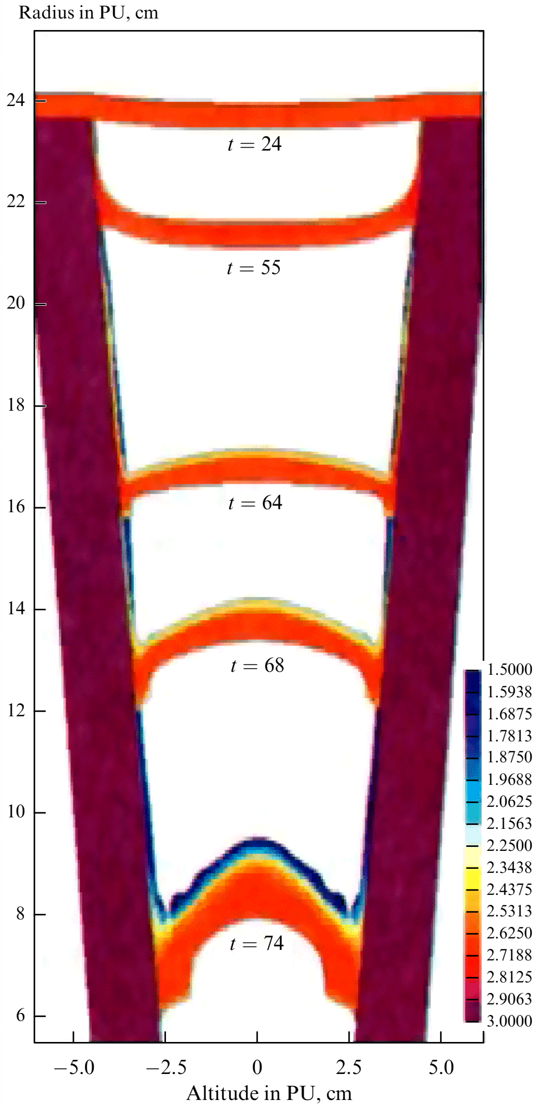

Figure 21. (Color online.) Results of a two-dimensional MHD simulation of the acceleration of a cylindrical Al liner, confirmed by the joint VNIIEF–LANL experiment HEL-1. Isodensity maps of the liner at different times, µs. The liner was accelerated by a current of $\sim$ 100 MA directly from a 5-module DEMG ∅ 1 m in diameter and had the following main characteristics: $R = 24$ cm, $\Delta = 4$ mm, $H = 10$ cm, velocity $\sim$ 8 km/s at a radius of $\sim$ 6 cm.

1.1 Mbar. The points, red asterisks, are the data averaged over several experiments. They are shown in Figure 4. Recently, verification measurements were carried out on liquid deuterium at a pressure of 500 kbar. The preliminary data are consistent with the measurements on solid deuterium.

One can see that our data are indicative of smooth monotonic dependences without an anomalous increase in density.

Figure 4 also shows the calculated adiabat of deuterium according to the well-known equation of state (EoS) SESAM, which is a standard in the USA. In addition, green points show the Sandia Laboratory data obtained (at about the same time as our experimental point for solid deuterium at a pressure of 600 kbar) on a system with a striker accelerated by a strong magnetic field. Despite the significant 'scatter' of the experimental points, their data do not confirm the NOVA measurements, either.

It is possible, apparently, to assert with a high degree of confidence that the experiments on NOVA are faulty.

Nevertheless, our plans include the completion of condensed and liquid deuterium studies and the beginning of research on the compressibility of protium.

A device for experimental investigations of deuterium properties is shown in Figs 5 and 6. For a number of years, work has been underway on the quasi-isentropic compressibility of hydrogen and deuterium gases.

To this end, cylindrical explosive devices are used, in which a metal shell accelerated by an exploded HE quasi-entropically compresses a cavity with gaseous hydrogen or

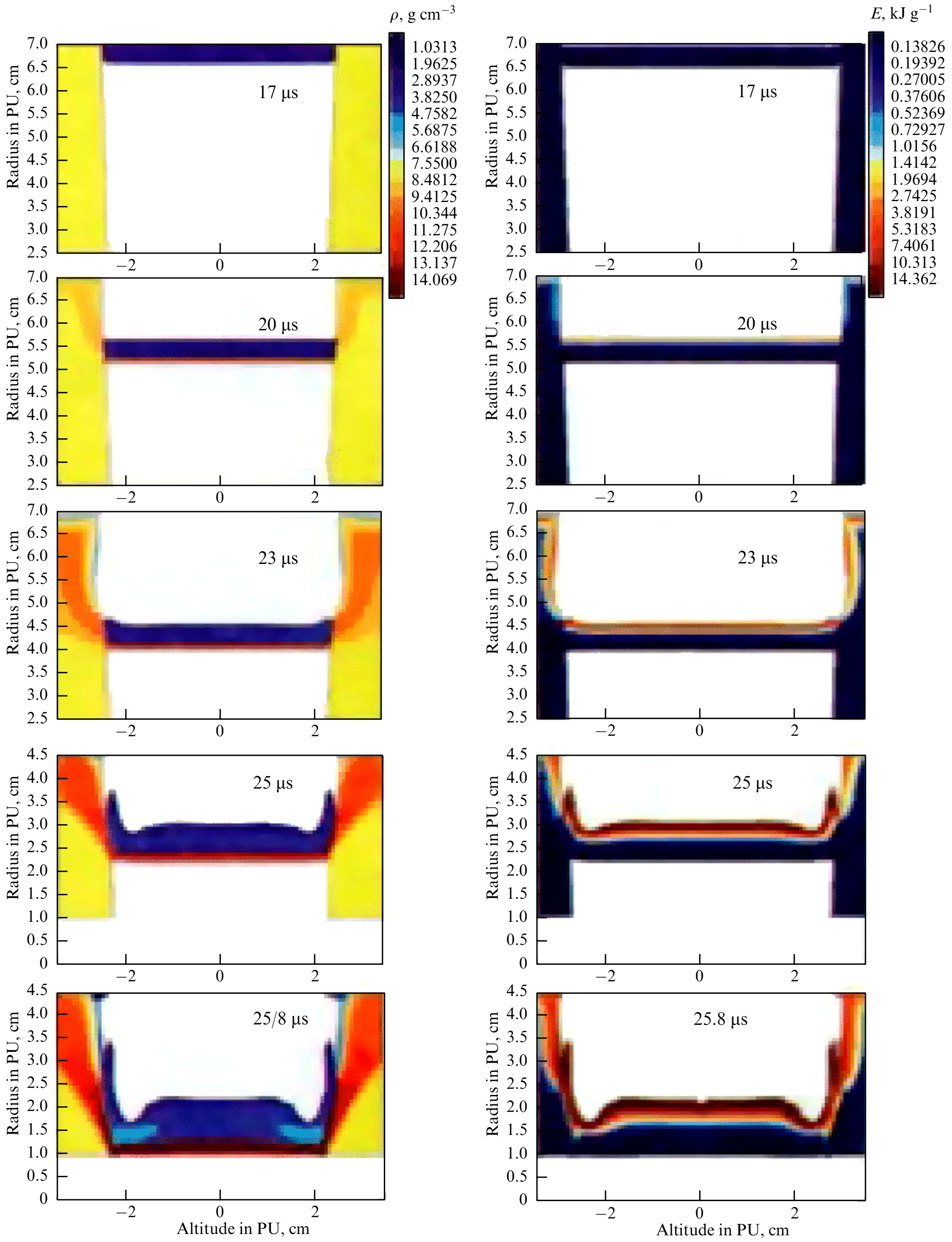

Figure 22. (Color online.) Results of a two-dimensional MHD simulation showing the efficient acceleration of a cylindrical two-layer liner by the current directly from a 25-module DEMG ∅0.4 m in diameter (for the planned shock wave experiment HEL-2). Liner parameters: $R = 7$ cm, $\Delta = 3.5$ mm, Al + 0.7 mm Mo, $H = 7$ cm, $I_{\max} = 80$ MA, speed of 14.5 km/s at a radius of 1 cm.

deuterium. The geometry of the compressed gas is determined by X-ray radiography.

A sketch of the device, a photograph, the experimental setup, experimental X-ray radiographs, and a graph are shown in Figs 7–11.

2. Use of superstrong magnetic fields to study substance properties at high pressures

The MK-1 generator of superstrong magnetic fields, proposed by Andrei Sakharov, is widely used in research on the physics of high pressures and temperatures. As a result of the long-term work of a group of VNIIEF staff members, it was possible to make a cascade generator of reproducible magnetic fields in the 10 megagauss (10 MGs) range.

Based on this generator, a device was developed for the isentropic compression of substances, including frozen gases, using the megabar pressure of a superstrong magnetic field.

A schematic of the MK-1 cascade generator and some research results are presented in Figs 12 and 13.

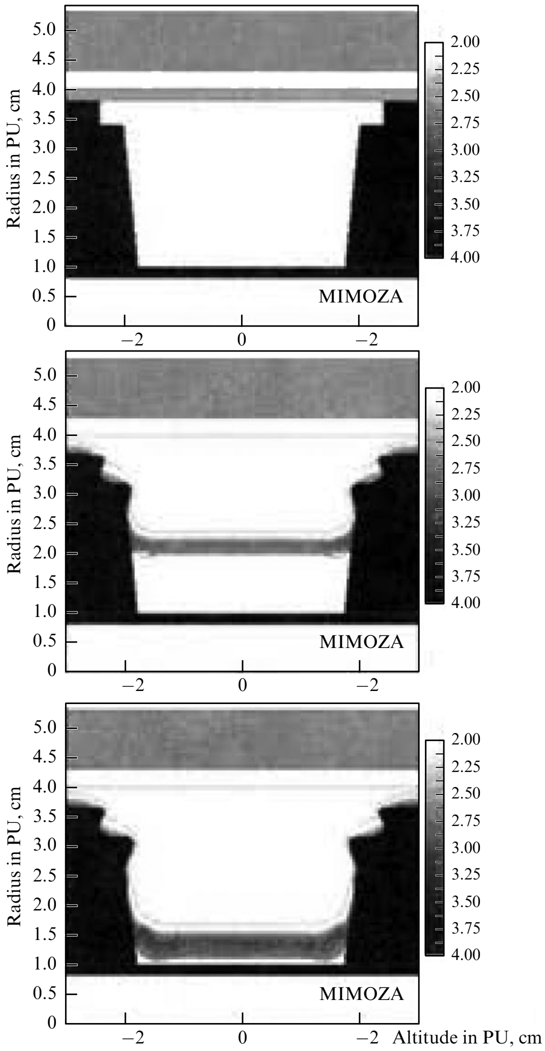

Figure 23. Results of two-dimensional MHD simulations of the acceleration of a cylindrical Al liner, which were borne out by joint VNIIEF-LANL experiments ALT-1, 2. The liner had an almost synchronous collision with a cylindrical target ∅2 cm in diameter. The liner was accelerated by a current from a 10-module DEMG ∅0.4 meters in diameter with a foil opening switch (FOS), $I_{\max} = 31-32$ MA, had a velocity $v_{\max} = 11-12$ km/s with initial parameters: $R = 4$ cm, $\Delta = 2$ mm, $H = 4$ cm. ID — inductive sensor; TL — transmission line; PU — ponderomotive unit; CMU — central measuring unit.

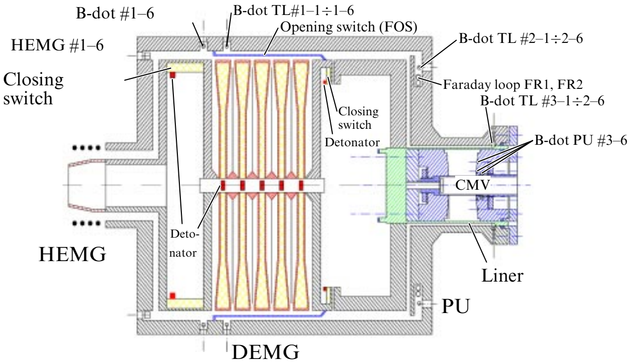

Figure 24. (Color online.) Diagram of an explosive magnetic liner device in the ALT-1 experiment. Main units: spiral EMG (HEMG, current preamplifier), 10-module DEMG with a diameter of ∅0.4 m (DEMG, main current amplifier), FOS, liner PU with a diameter of ∅8 cm with a central measuring unit ∅2 cm in diameter, explosive closing keys in HEMG–DEMG and FOS–PU circuits.

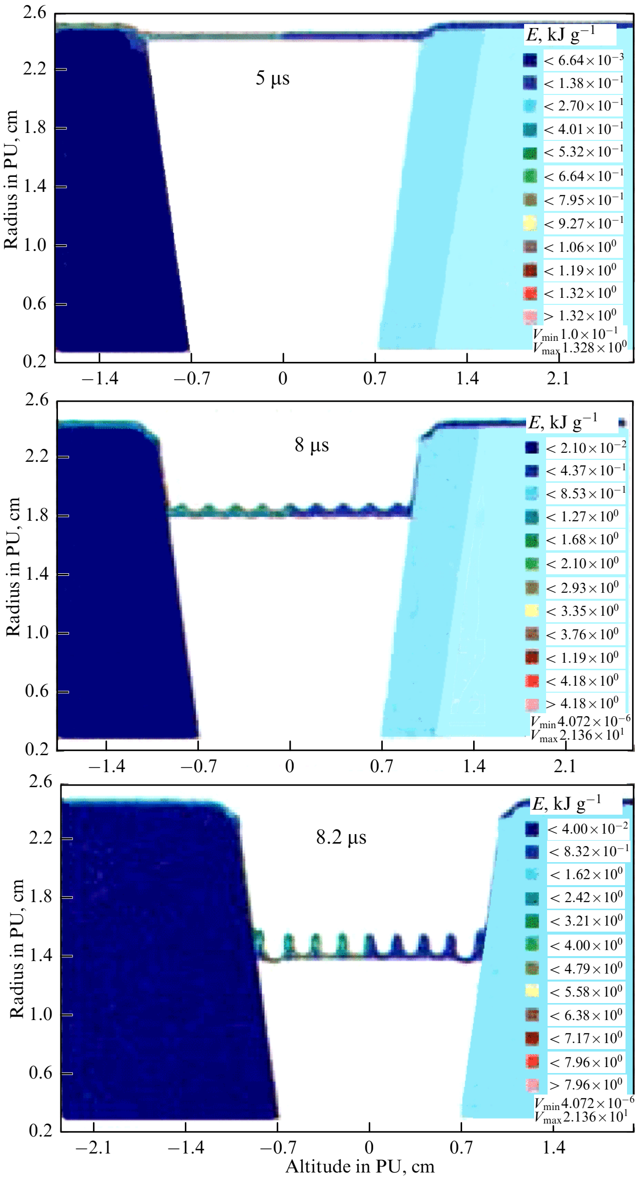

Figure 25. (Color online.) Two-dimensional MHD simulation of the growth of perturbations of a current-carrying liner in the PU for the RUS-1 experiment on the Pegasus-2 (LANL) capacitor bank; current of 6.5 MA. The liner is made of chemically pure aluminum (A995). Liner radius $R = 24$ mm and average thickness $\Delta = 0.5$ mm; $\lambda = 2$ mm and $A_0 = 25$ μm are wavelength and initial peak-to-valley amplitude of axially symmetric perturbations of outer liner surface.

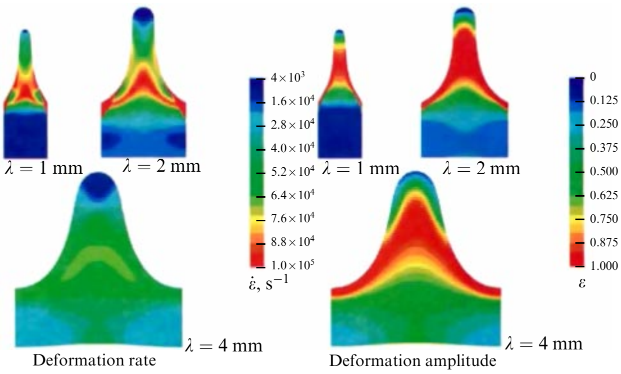

Figure 26. (Color online.) Typical conditions for deformation simulations for the materials under study: deformation $\varepsilon \sim 100\%$, deformation rate $\dot{\varepsilon} \cong 10^5 - 10^6$ s^{-1}.

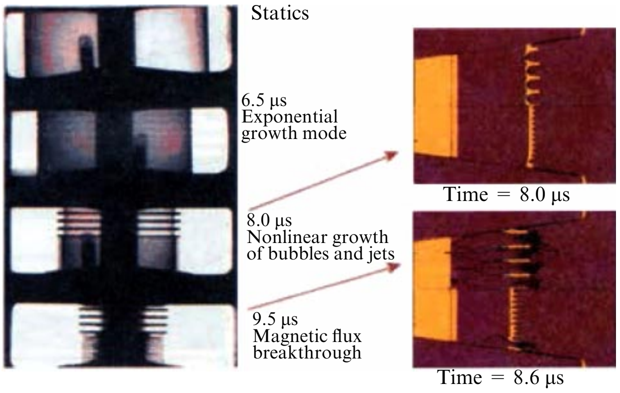

Figure 27. (Color online.) Results of LANL studies of technically pure aluminum (A1-1100). X-ray images were obtained at the stages of exponential growth of single-mode initial perturbations ($\lambda = 2$ mm, $\lambda = 0.75$ mm, $A_{\text{pp}} = 50$ μm), their nonlinear growth, and after magnetic flux breakthrough at a current of 6.2 MA.

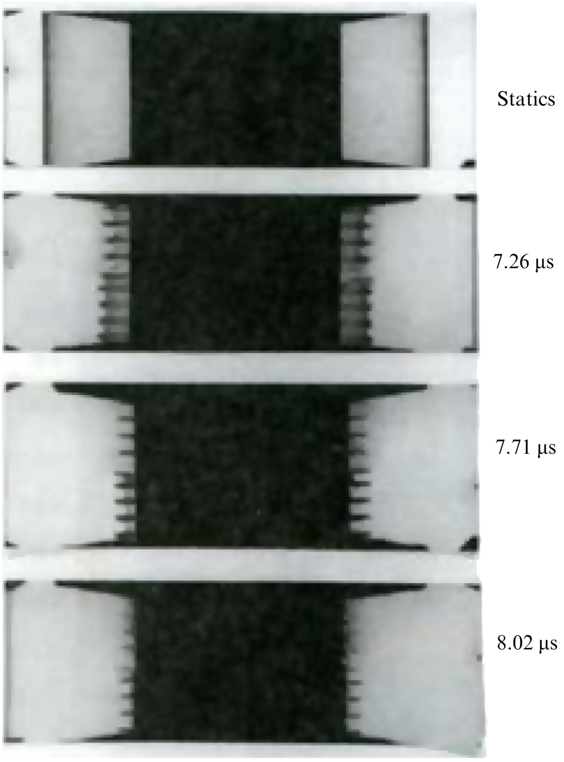

Figure 28. Copies of X-ray images of the liner in the RUS-1 experiment at a current of 6.5 MA. The liner was made of chemically pure aluminum (A995, lower half of liner) and AMg-6 (upper half of liner). Liner radius $R = 24$ mm and average thickness $\Delta = 0.5$ mm; $\lambda = 2$ mm and $A_0 = 25$ μm are wavelength and initial peak-to-valley amplitude of axially symmetric perturbations of the outer liner surface. Measured amplitudes of these disturbances: $A_1 = 0.9$ mm ($t_1 = 7.26$ μs) and $A_2 = 1.7$ mm ($t_2 = 7.71$ μs) for A995; $A_1 = 1.7$ mm ($t = 7.26$ μs) for AMg-6.

3. Computational and theoretical research methods

Calculations using powerful computing systems have become, especially in recent years, an indispensable tool for researchers to gain new knowledge about the operation of complex hydrodynamic devices. We consider how computational methods are used in the problem of spherical target compression under the action of laser radiation.

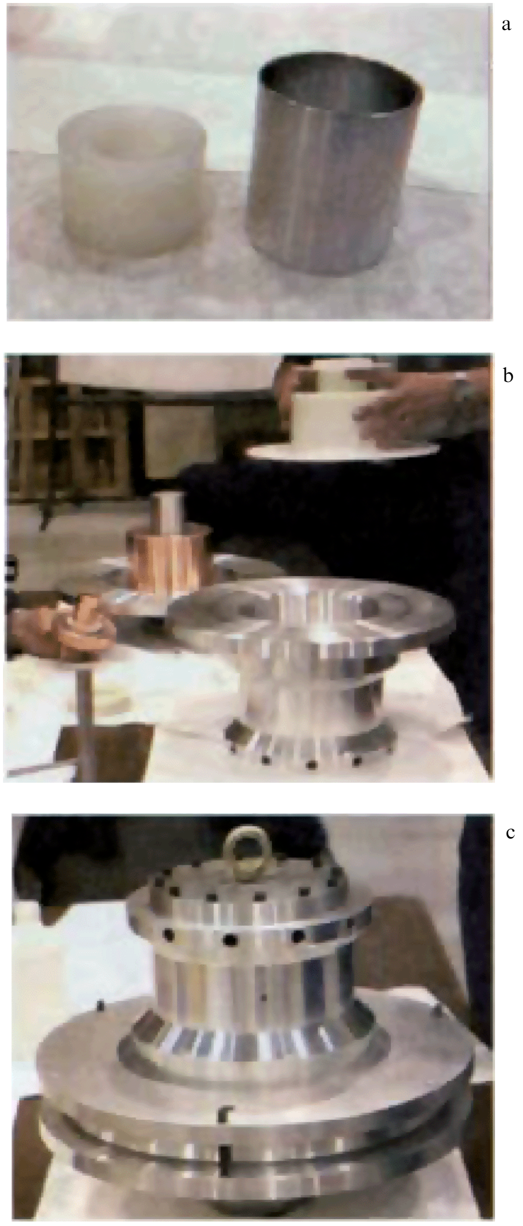

Figure 29. (Color online.) Cylindrical liner PU for RUS-6, 7 experiments at the ATLAS facility for studying the dynamic strength of copper. (a) Outer (current-carrying) Al liner of radius $R = 31$ mm and thickness $\Delta = 2$ mm. On the left is an intermediate polyethylene layer of a three-layer liner system. (b) PU assembly process. On the right (in the hands) is a part of a PU with a Cu liner, on which axisymmetric initial perturbations are applied. (c) PU assembly with a reverse current line.

VNIIEF conducts experiments to investigate the compression of spherical targets of various designs. Figure 14 shows some experimental data obtained at the ISKRA-5 facility. ISKRA-5: 12 channels, energy of 10 kJ, pulse duration of 0.3 ns.

Data obtained in the experiments: shell velocity — 3×10^7 cm/s; DT gas temperature — 1.5–4 keV; density — 1–2 g/cm^3; neutron output — 2×10^{10} n/s.

To correctly calculate the target compression on a modern laser facility with a large number of beams (such as NIF or ISKRA-6), it is necessary to use a supercomputer with a speed of > 100 Tflops (Fig. 15 and Table).

We therefore restrict ourselves to the simplest one-dimensional and two-dimensional simulations with the initial data shown in Figs 16–18. Presented are the results of two simulations.

In both simulations, use was made of a spherical geometry, and the radiation temperature in one of them was assumed to be spherically symmetric. Assumed in the other simulation was the angular dependence of the temperature in the form of the second harmonic with $\Delta T/T - 2.7\%$ (Fig. 18).

The simulation data suggest that a target with a spherically symmetric temperature value is ignited, and a target with an asymmetric temperature provides low fuel compressions, has strong shape distortions during compression, and does not provide a thermonuclear flash. This means that the $\sim 2.7\%$ level of symmetry in temperature is unsatisfactory.

The dynamics of compression of laser thermonuclear targets are depicted in Fig. 19.

4. Investigation of substance properties using liner systems in powerful pulsed electrophysical facilities (VNIIEF disk EMGs, Pegasus and ATLAS capacitor banks in the USA)

Simulations of liner interaction with end walls of different shapes (Figs 20–23).

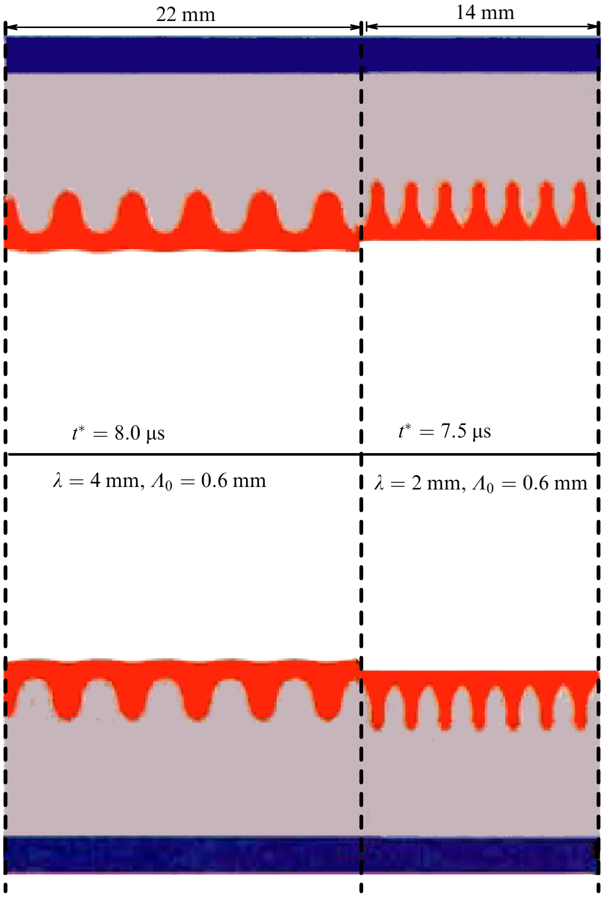

Figure 30. (Color online.) Pattern of maximally grown perturbations of the inner copper layer in a three-layer liner system — according to the calculations for the RUS-6, 7 experiments on the ATLAS capacitor bank ($I_{\max} = 19-22$ MA, intermediate layer is made of polyethylene, radii of the three layers are 16–18–29–31 mm). Characteristic simulation pressure on the layer of the material under study ($P_{\text{char}} \approx 100-150$ kbar) increases in ~ 1 μs and is maintained for 2–3 μs.

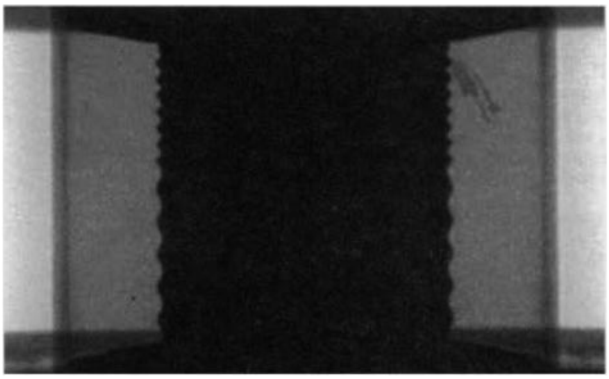

Figure 31. Static X-ray diffraction pattern of a three-layer liner system with initial perturbations of the inner Cu layer of the liner: $\lambda = 2$ and 4 mm, $A_0 = 0.6$ mm (for the RUS-6 experiment).

Development of explosion-magnetic facilities for studying the equation of state of substances in large volumes at pressures up to 30 Mbar (Figs 22–24).

Studies of the dynamic strength of materials based on the growth of initial liner perturbations (Figs 25–31).

In the similar RUS-2 and RUS-5 experiments, an investigation was made of the dynamic strength of aluminum alloy V95 and technically pure aluminum ADO. The initial and measured amplitudes of perturbations in these experiments were as follows:

$$A_0 = 9\ \mu\text{m}, \quad A_1 \approx 0.3\ \text{mm}\,(t_1 = 7.24\ \mu\text{s})\,,$$
$$A_2 \approx 0.7\ \text{mm}\,(t_2 = 7.63\ \mu\text{s})\ \text{for V95}\,,$$
$$A_0 = 40\ \mu\text{m}, \quad A_1 \approx 0.3\ \text{mm}\,(t_1 = 6.0\ \mu\text{s})\,,$$
$$A_2 \approx 0.7\ \text{mm}\,(t_2 = 6.7\ \mu\text{s})\ \text{for ADO}\,.$$

Some of the experimental data were predicted by pre-experimental simulations (for AMg-6 alloy, ADO); other results are used to improve the shear strength models of materials.

It turns out, in particular, that the four materials under study exhibit similar dynamic strength in experiments, although their quasi-static yield strengths differ by up to 40 times.

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