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IN MEMORY OF VLADIMIR EVGEN'EVICH FORTOV

V E Fortov and dynamic methods in nonideal plasma physics. Chernogolovka

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Contents

Abstract. Vladimir Evgen'evich Fortov made an enormous contribution to the physics of extreme states of matter, high energy density physics, the physics of shock and detonation waves, thermal physics, chemical physics, energetics, and several other realms of physics and technology. Among this amazingly broad spectrum of V E Fortov's scientific interests, special place is occupied by dynamic methods in the physics of nonideal plasmas. His scientific activity commenced in precisely this area, and it remained at the focus of his attention throughout his life. We have endeavored to briefly generalize V E Fortov's investigations in the area of explosion-produced nonideal plasmas and reveal the logic of their origination.

Keywords: nonideal plasma, shock waves, extreme states of matter, Chernogolovka

1. Introduction

It is difficult to write about a great man, a Scientist with a capital letter, whom we worked with for almost 50 years. These years were marked by outbursts of brilliant scientific ideas, great joy in their realization, ongoing disputes in the formulation of scientific problems, inspired hard round-the-clock work without sleep to realize the emerging ideas and implement them in real life, and shared experiences of failures, which in turn gave rise to new ideas.

When we are dealing with a personality of academician V E Fortov's stature, a personality with so remarkable a creative life, evidently many scientific teams and scientific disciplines fall within view. Chernogolovka and the dynamic methods of nonideal plasma generation stand out prominently among them. No wonder that in V E Fortov's first interview as president of the RAS, in reply to the question, "Your first trip?" he promptly said: "To Chernogolovka, to the scientific center in Chernogolovka...."

In this paper, we endeavor to recall how it all began, to recite the history of the onset of nonideal plasma research, exhibit the logic of the emergence of new ideas, and remember the people whom this research began with. Of course, this presentation is bound to be somewhat subjective, since the story will primarily deal with research we were directly involved in.

2. Setting up research on nonideal plasmas

The nontrivial story of how V E Fortov found himself in Chernogolovka is nicely described in the book [1] *Trajectory. Vladimir Fortov*, which was carefully prepared by his daughter Svetlana and published in 2015 on Vladimir Evgen'evich Fortov's 70th birthday. His fate was decided by his brilliant report to the Third All-Union Symposium on combustion and explosion in Leningrad in 1971, where he was noticed by an outstanding physicist, academician Ya B Zel'dovich, who recommended him to the Nobel Laureate academician N N Semenov. The latter, in turn, suggested that V E Fortov work in the Chernogolovka Division of the Institute of Chemical Physics (DICP) [1] of

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[1] Since 1997, Institute of Problems of Chemical Physics RAS.

Figure 1. Vladimir Fortov and his teachers in Chernogolovka: (a) Ya B Zel'dovich, (b) A N Dremin, (c) N N Semenov (on the left), and F I Dubovitskii at a May Day celebration at the House of Scientists in Chernogolovka (1975). (d) V E Fortov at the same celebration. (Borrowed from book [1].)

the USSR Academy of Sciences (AC). F I Dubovitskii,[2] Director of the DICP, N N Semenov's pupil and assistant, enrolled Fortov as a junior researcher in the laboratory of one of the first heads of laboratories in Chernogolovka, A N Dremin,[3] who was engaged in the physics of explosion and detonation.

So V E Fortov began work in Chernogolovka, which was an amazing place in the early 1970s. The work here was carried out in '24/7' mode, i.e., 24 hours a day, seven days a week (this was his principle) — all conditions were created for such intensive scientific work. It was easy to work due to the proximity of the Institute of Solid State Physics RAS, Landau Institute for Theoretical Physics RAS, and others, and one could get scientific advice by coming to any institute or meeting with the right scientist at the lake or on a walk in the forest. Actively pursued at that time in the DICP was research on powerful explosives, solid rocket propellants, and the processes of detonation and combustion.

V E Fortov's first work in Chernogolovka was devoted to the equations of state of condensed matter at high dynamic pressures, estimates of critical point parameters, and the kinetics of evaporation and condensation in the isentropic expansion of metals [2–8]. However, here he also brought his love for nonideal plasma, a love which later led to the emergence of a new field of science — the physics of extreme states of matter and dynamic processes at high energy densities. Fortov's paper, "Hydrodynamic Effects in Nonideal Plasma" [9], which was published in the journal *High Temperature* in 1972, was devoted precisely to the problems of studying the behavior of nonideal plasma in fast processes.

V E Fortov began studying nonideal plasma physics as a student and graduate student at the Moscow Institute of Physics and Technology (MIPT) at the Research Institute of Thermal Processes (RITP)[4] under the supervision of V M Ievlev.[5] V E Fortov, together with B N Lomakin, carried out a series of studies on the properties of nonideal cesium plasma using a preheated shock tube [10, 11]. This work was summarized in 1980 in the book, *Thermophysical Properties of Working Media of a Gas-Phase Nuclear Reactor*, edited by V M Ievlev [12].

When in Chernogolovka, Fortov realized that the technique of shock waves generated by the energy of condensed high explosives is a unique tool for generating high-density plasma with strong interparticle interactions. Calculations were made of the states of matter behind the front of powerful shock waves, which was reflected in the first joint work of V K Gryaznov, I L Iosilevskii, and V E Fortov [13]. They showed that a shock-compressed plasma of inert gases with high nonideality parameters is produced in these gases at an increased initial pressure and shock wave velocities of ~ 5 km s^{-1}, which are easily realized using explosive shock tubes.

Although V E Fortov was a pronounced theorist, he was aware that nonideal plasma, for which there was no rigorous theory due to the absence of a small parameter, called for setting up experimental work to construct theoretical models on its basis. Furthermore, for an adequate interpretation of experiments, it was necessary to understand the hydrodynamics of explosive flows and to be able to carry out their complex three-dimensional simulations with real parameters of matter at high pressures and temperatures.

The first support in organizing an explosive experiment on nonideal plasma in Chernogolovka was provided by V V Yakushev's group. A pupil in this group, a laboratory assistant for physical and mechanical tests, N A Afanas'ev, became the first employee of Vladimir Fortov's group. The study, "On 'anomalous' effects in the exit of a detonation wave to a free surface" [14], showed the possibility of generating dense air plasma behind the front of shock waves formed during the detonation of condensed explosives. Great

[2] F I Dubovitskii (1907–1999), Soviet and Russian physicochemist, corresponding member of the RAS (1991; corresponding member of the USSR AS beginning in 1979). Twice a laureate of the USSR State Prize (1970, 1986), a laureate of the Prize from the USSR Council of Ministers (1981).

[3] A N Dremin (1930–2008): an Honored Scientist, professor, doctor of physicomathematical sciences, a laureate of the Prize from the USSR Council of Ministers.

[4] Presently the State Research Center of the Russian Federation, M V Keldysh Research Center.

[5] V M Ievlev (1926–1990): Soviet scientist in mechanics and thermal physics, corresponding member of the USSR Academy of Sciences (1964).

Figure 2. First graduate students and students: (a) V K Gryaznov, (b) Yu V Ivanov, (c) V E Bespalov, (d) V B Mintsev, (e) A A Leont'ev.

technical support in the organization of experimental work was provided by E F Lebedev's group from the Institute for High Temperatures of the USSR Academy of Sciences (IHT),[6] which conducted experiments in Chernogolovka to study explosive magnetohydrodynamic generators [15].

V E Fortov conceived the idea to carry out a wide range of experiments to study explosion-generated nonideal plasmas. People were needed, and he selected the first graduate students and students to join his group. The tasks of making an explosive nonideal plasma generator based on explosive shock tubes and studying its thermophysical properties was posed to the corresponding graduate student Yu V Ivanov — V E's fellow student at MIPT. A postgraduate student at Tomsk University, A A Leont'ev, was entrusted with investigating isentropic expansion of condensed matter in the region of strong interparticle interaction and the equations of state for a nonideal plasma of inert gases. V K Gryaznov, a graduate student of V M Ievlev's department at MIPT, began to calculate the properties of shock-compressed plasma using different nonideal plasma models. A student in the Department of High Temperatures at MIPT, V E Bespalov, was entrusted with experiments to study the compressibility of argon plasma behind the front of powerful shock waves. At the same time, a fourth-year student in the MIPT Department of Combustion and Explosion (Chair: F I Dubovitskii), V B Mintsev, was also accepted into the group. According to the memoirs of the author of this paper, V B Mintsev:

"I remember well my first meeting with V E Fortov. At that time, students had the opportunity to meet with different active scientists and had the right to choose a scientific supervisor. Vladimir talked to me for more than two hours. He vividly described the scientific task, opening up to me a new unexplored world of problems arising in a highly heated substance with strong interparticle interaction. He was especially enthusiastic about possible specific plasma phase transitions and metallization of matter at high pressures, referring to the only joint work of our great scientists L D Landau and Ya B Zel'dovich of 1945 [16]. V E Fortov described in detail how he saw the solution to these problems and what specific tasks had to be solved first. He gave me two books — one by Zel'dovich and Raizer [17] and the other by Frank-Kamenetskii [18] — and said: "Study, young man, and come back in a week, choose what you are most interested in." This is how my first task became the study of electrical conductivity of a nonideal plasma."

[6] Presently the Joint Institute for High Temperatures (JIHT).

3. Dynamic methods in nonideal plasma physics. The onset

The intensive, friendly work of V E Fortov's entire group began. First of all, it was necessary to understand the methods of generating explosive nonideal plasma. The fact is that, in order to measure the thermophysical properties of the medium behind a shock wave front and obtain a uniform plasma bunch, it was necessary to ensure the one-dimensionality and stationarity of the flow. Then, the parameters of a shock-compressed substance turn out to be related to the kinematic parameters of the flow by simple algebraic relations expressing the laws of mass, momentum, and energy conservation, which makes it possible to determine the caloric equation of the state of matter in the form of a dependence of internal energy on pressure and specific volume: $E = E(P, V)$ [17, 19]. However, the internal energy is not a thermodynamic potential with respect to the variables P and V, and in order to construct a closed thermodynamic system, it is necessary to additionally reveal the dependence of temperature, $T = T(P, V)$, on these variables.

By the time our work began, explosive methods of generating shock waves in low-density gases were intensively developing in the USSR and the USA. A wide range of devices was created — from simple 'linear' explosive shock tubes to special cumulative devices that permitted obtaining shock wave velocities up to 100 km s^{-1}. These devices are described in detail in the review, "Explosion-driven shock tubes" [20]. Another technique — based on acceleration of a metal flying plates with the aid of condensed high explosives (HEs) — had been widely used to study the equations of state of condensed matter at high dynamic pressures [21]. It was also decided to use this technique to study nonideal plasmas.

In the developed high explosive linear shock tube (Fig. 3) [22], an ionizing shock wave is formed when the detonation products of condensed HEs expand into the gas under study. The use of a specially profiled detonation lens and the choice

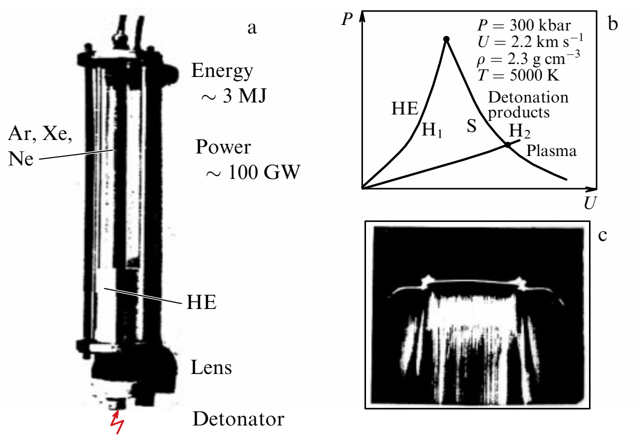

Figure 3. (a) Photograph of explosive nonideal-plasma generator [22]. (b) Diagram of generator operation in variable pressure P and mass velocity U: H_1 — shock adiabat of high explosive (HE), S — detonation product release isentrope, H_2 — plasma shock adiabat. (c) Photo of the flow in the explosive generator taken to determine the shock curvature. (From V E Fortov's 1977 presentation.)

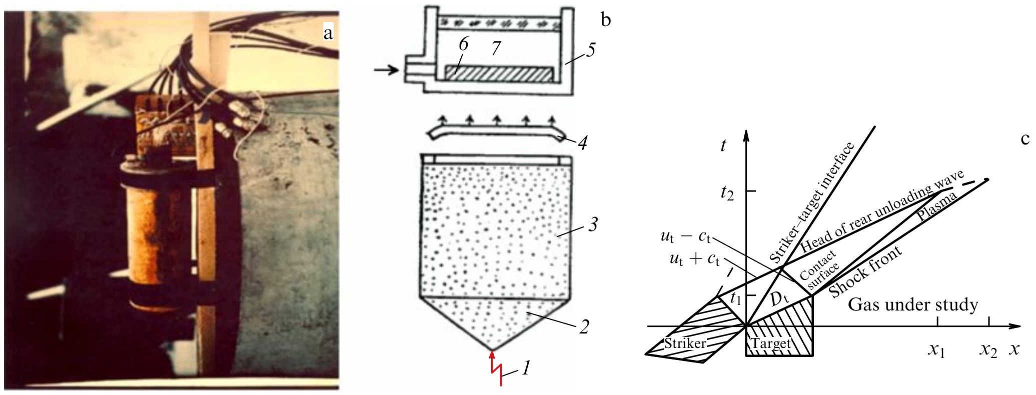

Figure 4. (a) Photo of the explosive generator of a rectangular shock wave. (b) Diagram of the device [24]: *1* — detonator, *2* — detonation lens, *3* — HE charge, *4* — metal striker, *5* — experimental assembly, *6* — target, *7* — test gas. (c) Diagram of the generator operation in the coordinates of time–distance ($t-x$): D_t is the velocity of the shock wave in the target, t_1 and t_2 are the moment when the unloading wave reaches the rear surface of the striker and the moment the rear unloading wave catches up with the contact surface, respectively, x_1, x_2 are the coordinates of the contact surface and the shock front at the moment the rear unloading wave catches up with the contact surface, respectively.

of the appropriate dimensions of the active HE charge ensured the one-dimensionality and stationarity of the parameters of the detonation front in its exit from the HE into the gas under study. The total energy release in each experiment was $\sim 3 \times 10^6$ J for a power of $\sim 10^{11}$ W, which, of course, led to the destruction of the entire device and the need to work in specially protected rooms in compliance with safety measures. The results of photographic, electrophysical, and radiographic measurements showed the one-dimensionality and quasi-stationarity of the plasma flow, which was ensured by the inertial confinement of the shock-compressed plasma by the massive walls of the shock tube channel.

The velocity of the shock front was measured by optical and electrocontact basic methods using high-speed film cameras and ionization sensors with an accuracy of $\sim 1-1.5\%$. Within this error, the ionization front coincided with the shock glow front and the position of the hydrodynamic shock wave. The density of the shock-compressed argon plasma was recorded with an accuracy of $\sim 8\%$ by pulsed X-ray radiography [22, 23], which does not disturb the plasma flow and has a high temporal ($\sim 10^{-7}$ s) and spatial (~ 2 mm) resolution.

Due to the transparency of the gas ahead of a shock wave and the small size of the viscous shock wave front, thermal radiation can freely leave the plasma volume and provide information on the equilibrium temperature and absorption coefficients of the shock-compressed plasma. With the brightness method of temperature measurement (accuracy 5–10%), the intensity of this radiation was determined by photometric comparison of the time scans of the glow of the shock-compressed plasma and reference light sources. The combined measurement of the front velocity and density determines, in accordance with the conservation laws, the caloric equation of state for a nonideal plasma $E = E(P, V)$, which, together with the measured dependence $T = T(P, V)$, gives thermodynamically complete information about argon plasma at a pressure up to 600 MPa and temperature $T = 15.5-23$ kK.

To measure the thermodynamic and optical characteristics of plasma at higher pressures than those in shock tubes, advantage was taken of explosive generators of rectangular shock waves (Fig. 4) of various intensities and durations. In these facilities, an ionizing shock wave emerged when metal or polymer targets, preliminarily compressed to pressures of $\sim 10^6$ bar, expanded into the gases under study (argon, xenon). Powerful shock waves in the targets were excited by linear explosive acceleration devices [24], whose action is based on the acceleration of flat metal impactors by the detonation products to speeds of 2–6 km s^{-1}. The typical energy release in the experiments was $2-30 \times 10^6$ J at a power of 10^{11} W.

In experiments using these generators, two kinematic parameters were independently recorded using electrical contact and optical basic methods: the front velocity D and the mass velocity U of the plasma. Open electrocontact sensors recorded the front velocity D with high-speed oscilloscopes with an accuracy of $\sim 1\%$. The U velocity was measured (with an accuracy of 1–2%) using closed sensors of a special design, which did not react to the shock wave in the plasma and were triggered at the instant of arrival of the heavy contact surface of the plasma–target interface. In the optical recording technique, a plexiglass barrier was placed at a given distance from the target, through which the radiation of the shock-compressed plasma was recorded with the help of high-speed film cameras or electron-optical converters: the nature of the change in this glow made it possible to judge the motion of the shock wave and the contact surface of the plasma. The results obtained on the equation of state for nonideal argon and xenon plasmas refer to a wide range of parameters: $P \sim 0.03-3$ GPa, $T \sim 18-22$ kK, in which developed ionization and strong Coulomb interaction are realized, with the coupling parameter $\Gamma \sim 1-5$.

An analysis of the thermodynamic data obtained for a highly compressed plasma revealed effects that are not described by the standard plasma theory, in which the Coulomb interaction of charged particles is taken into account and atoms are usually considered an ideal subsystem. The inclusion of the interaction of neutral particles in the framework of virial expansion did not help to adequately describe the experimental data, either. In fact, in the region of high plasma densities considered, the average interparticle distances are comparable to the characteristic size of atoms, a significant fraction of which (due to the high plasma density) is in excited states. An idea arose to try to take into account the contribution of excited atoms to the thermodynamic properties of the plasma, whose interaction with the surrounding particles deforms their excitation spectrum. These effects, by the way, were also discovered in the first experiments on shock compression of cesium plasma, carried out earlier by V E Fortov together with B N Lomakin at RITP [11].

In order to estimate the possible effects associated with deformation of the atomic excitation spectrum, V E Fortov conceived the idea to cooperate with mathematicians at DICP, who worked under the leadership of Avigeya Nikolaevna Ivanova and at that time had unique experience in calculating the structure of many-electron atoms. A N Ivanova and her colleagues were the first in the world to develop a method for calculating the electronic structure of many-electron atoms based on the Hartree–Fock method, which had the necessary stability and convergence. The work of A N Ivanova et al. [25] was published in the *Lithuanian Physics Collection* in 1963, several months earlier than the work of Charlotte Froese Fischer [26], who is considered a pioneer in this field. So, as a result of this cooperation, a confined atom model appeared, which took into account the influence of the external environment on the internal structure of atoms. This model was used to explain in [23, 24, 27] the appearance of the effect of additional repulsion in unique shock-wave experiments, in which a highly compressed plasma of megabar pressures was generated.

The electrical conductivity in an explosive shock tube was measured by the four-point probe method with a high spatial resolution and relative ease of implementation under the conditions of a one-time dynamic experiment (Fig. 5) [28]. The electrical conductivity of the plasma of inert gases was measured in a broad range of nonideality parameters, from $\Gamma \sim 0.3$, where the difference between the theories is small and there is a significant amount of experimental data, up to the region of extremely high $\Gamma \sim 5-10$, at which most of the theoretical approximations diverge. The resultant set of experimental data definitely indicated an underestimation of the measured values of electrical conductivity in comparison with those predicted by Spitzer's theory [28]. The quantitative discrepancy between the results of different groups of experiments was attributed both to the features of high-temperature plasma behavior and to the actual discrepancy between the primary data and the difficulties in separating the Coulomb component in a weakly ionized plasma.

To describe the experimental data, a model was proposed [29], whereby ionic correlations were described in the Ziman approximation borrowed from the theory of liquid metals and semiconductors, and charge scattering was calculated in the Born approximation with a screened Coulomb potential. The relations obtained have the correct Spitzer asymptotic form at $\Gamma \ll 1$ and acceptable extrapolation properties, do not have nonphysical divergences, and satisfactorily describe a 'low-temperature' experiment up to the region of extremely high Γ.

In addition to organizing an experiment on a nonideal explosion-produced plasma and directly participating in it, V E Fortov continued to study the equations of state of condensed matter, the equation of state of metals using the method of isentropic expansion and the 'plasma phase transition' in detonation phenomena, and hydrodynamic effects in nonideal media. Research results were published in leading journals, such as the *Journal of Experimental and Theoretical Physics* (*ZhETF*), *Reports of the USSR Academy of Sciences* (*Doklady AN SSSR*), *and High Temperature* (*TVT*), (see the list of references).

In the winter of 1977, V E Fortov successfully defended his doctoral dissertation, "Investigation of nonideal plasma

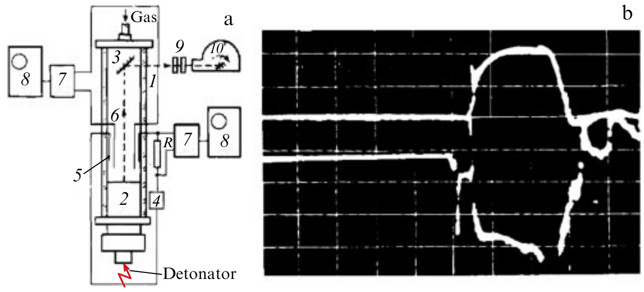

Figure 5. Setup for measuring electrical conductivity: *1* — explosive shock tube channel, *2* — HE charge, *3* — mirror, *4* — direct current source, *5*, *6* — current and potential electrodes, *7* — differential amplifiers, *8* — oscilloscopes, *9* — optical system, *10* — high-speed film camera. (b) Typical current and voltage waveform, 2.5 μs sweep per division [28].

by dynamic methods," at a specialized council at IHT. Academician Ya B Zeldovich was his advisor during the work on the dissertation. The referees were Professor L V Al'tshuler, whose name occupies a prominent place among the creators of Soviet nuclear weapons, and Academician E P Velikhov, an internationally renowned specialist in the field of plasma research. The referees noted that the framework of studies carried out by Fortov marked the emergence of a new scientific discipline — the dynamic physics of nonideal plasma. Indeed, soon, a series of reviews appeared in *Physics–Uspekhi* [30–33]. Published in co-authorship with I T Yakubov was the book, *Physics of Nonideal Plasma* [34].

On December 1, 1977, an order was signed to establish, on the basis of an already existing group, the Laboratory of Physical Gas Dynamics under the leadership of V E Fortov (Fig. 6). It additionally included experimenters V Ya Ternovoi and A P Zharkov, as well as theorists G A Pavlov, Ph D, and a graduate of the Kuibyshev Polytechnic Institute, A A Ovchinnikov. The first deputy for the laboratory was V E Bespalov. A little later, in connection with the need to carry out massive gas-dynamic calculations, A L Ni and A V Shutov joined the laboratory. For active work with models of equations of state of matter, A V Bushman, L V Al'tshuler's pupil, was invited. He came with his student, I V Lomonosov, who is currently the acting director of our Institute for Problems of Chemical Physics (IPCP) RAS. In the mid-1980s, in connection with the work on the Vega project, the group of G I Kanel' was incorporated into the laboratory. After defending his doctoral dissertation in 1982, A L Ni became deputy head of the laboratory. In 1991, this work was entrusted to V B Mintsev, and, in 2001, to V K Gryaznov.

4. Progress in dynamic methods

After defending his doctoral dissertation, V E Fortov did not stop; he was full of strength, energy, and ideas, and the scope of work on the study of nonideal plasma and processes under the influence of powerful shock waves on dense media was significantly expanding. Together with colleagues from Sarov, experiments were being carried out on the thermodynamics of the nonideal plasma of inert gases in a wider range of parameters: at pressures up to $P \sim 4$ GPa and temperatures up to $T \sim 56$ kK [27] (Fig. 7). These experiments confirmed the tendencies found earlier in the shock compression of cesium [11, 35] and argon [23] plasmas. To describe this effect on the basis of the chemical model of

Figure 6. Laboratory of Physical Gas Dynamics of the DICP of the USSR Academy of Sciences (1981). Upper row (left to right): V Ya Ternovoi, V E Bespalov, V K Gryaznov, V B Mintsev, V E Fortov, N A Afanas'ev. Middle row (left to right): A L Ni, N S Gutseva, G A Pavlov, A A Ovchinnikov, A V Bushman, S V Dudin, A P Zharkov. Bottom row (left to right): P V Skachkov, S V Razorenov, G I Kanel', L G Ermolov, M I Kulish, Yu B Zaporozhets, V P Patlazhan, A V Shutov, A S Filimonov, D I Gerasimov.

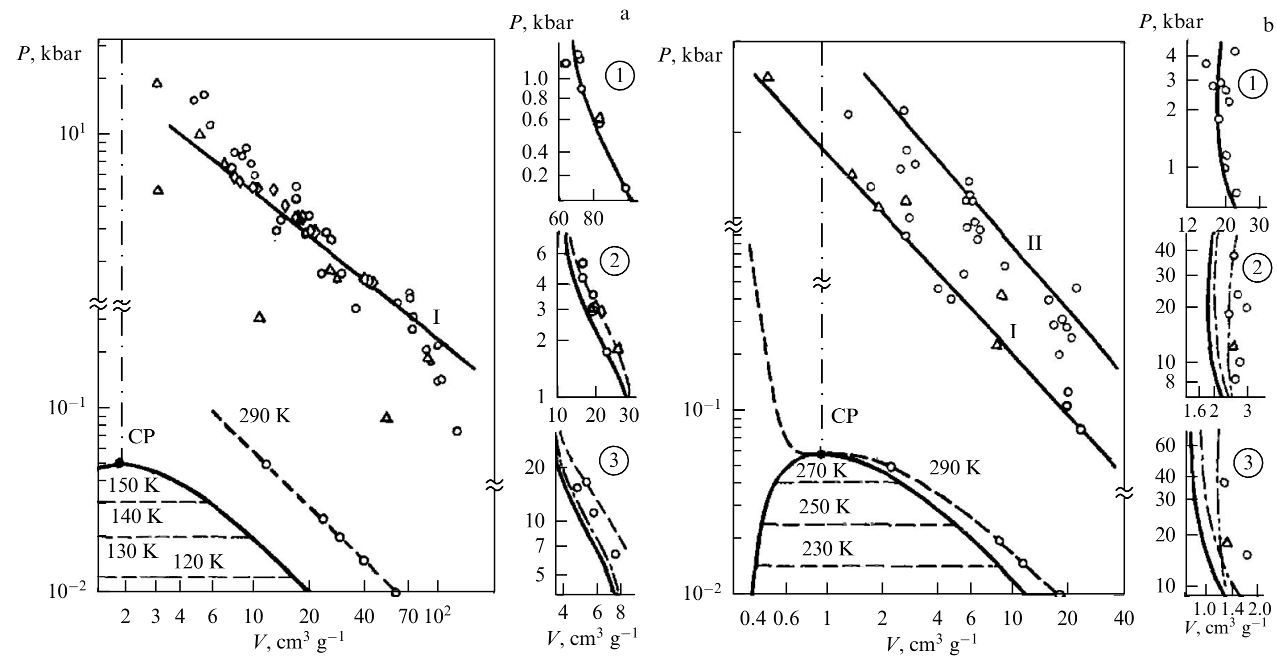

Figure 7. Phase diagrams of argon (a) and xenon (b) [27]. Indicated in the left parts of Figs 7a and 7b are boundaries of the two-phase region and critical points, CP, dashed lines are isotherms of initial states, dashed-dotted lines are isochores, V_{CP}, lines I and II are boundaries of single and double ionization, circles are results of dynamic experiments (see [27]). On the right-hand sides of Figs 7a and 7b, experimental shock adiabats (symbols) are compared with the results of theories. Solid curves: inclusion of the interaction of charged particles in the annular Debye approximation [13]; dashed-dotted lines: additional inclusion of the interaction of atoms in the second virial coefficient approximation [27]; dashed curves: calculation by the 'bounded' atom model [27]; dashed-double-dotted lines: interaction of charges according to the model [27] with a pseudopotential. Right part of Fig. 7a shows shock adiabats of argon at $P_0 =$ 1 bar 1 , $P_0 =$ 5 bar 2 , $P_0 = 20$ bar 3; right part of Fig. 7b shows shock adiabats of xenon at $P_0 = 1$ bar 1, $P_0 = 10$ bar 2, $P_0 = 20$ bar 3.

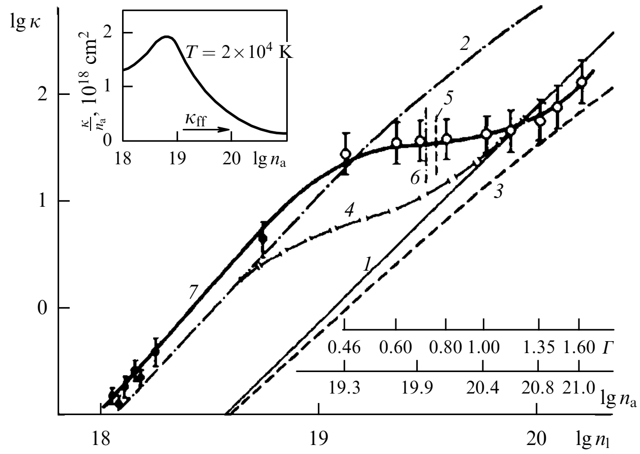

Figure 8. Absorption coefficient of nonideal argon plasma as a function of density [37]. Circles — data from Ref. [37], dark dots — data from other studies (see references in Ref. [37]). Calculation results: *1* — free-free transitions ($\kappa_{\rm ff}$), *2* — photoionization taken into account, *3* — free-free transitions with the inclusion of plasma screening, *4* — calculation by the bounded atom model [37], *5, 6* — estimate based on results of other studies (see references in Ref. [37]); curve *7* connects experimental points reduced to radiation frequency $h\nu = 2.14$ eV and temperature $T = 2 \times 10^4$ K. Inset: absorption coefficient $\kappa/n_{\rm a}$ per atom as a function of atomic density.

plasma in Ref. [27], use was made of a 'confined' atom model [23] and the pseudopotential plasma model [36].

At about the same time, work was carried out (by V E Bespalov, V E Fortov) on the study of the optical properties of shock-compressed plasma. Measurements of the absorption coefficient of nonideal argon plasma as a function of density showed its significant underestimation in comparison with the calculated values at high plasma densities [37] (Fig. 8). Moreover, with an increase in density, the experimental values tended to the theoretical ones caused by only the bound-bound transitions. This effect was interpreted in Ref. [37] as a result of deformation of the electronic energy spectrum of atoms compressed by the action of surrounding particles. In a dense plasma, the interparticle interaction makes the intra-atomic potential a shorter-range one, which leads to a finite number of discrete energy levels and a sequential transition of highly excited states into the continuous spectrum with an increase in the plasma density. This disappearance of some of the excited energy levels excludes the mechanism of photoionization absorption from these states and leads to the experimentally observed decrease in the absorption coefficient. To describe this effect, the confined atom model was again taken advantage of. In this case, in addition to thermodynamic quantities, argon photoionization cross sections were calculated using the calculated wave functions of excited atoms.

The range of parameters was also broadened in the study of the electrical conductivity of nonideal plasma. Improvement in the temporal characteristics of probe measurements of electrical conductivity and in the gas dynamics of the flow in an explosive shock tube made it possible to carry out measurements behind reflected shock waves and to increase the pressure in xenon to $P \sim 7$ GPa and the temperature in dense plasma to $T \sim 100$ kK with up to a threefold degree of ionization [38]. To realize a highly heated nonideal plasma, cumulative devices based on flow compression in converging geometry were also used. The electrophysical properties of such a plasma turned out to be largely unexpected [38], since they indicated that there was no similarity to the Coulomb component of a nonideal plasma: the dimensionless electrical conductivity of a high-temperature plasma (Fig. 9) turns out to be lower than the low-temperature one for the same values of the Coulomb nonideality Γ. An analysis of high-temperature data suggests that this effect is caused by the non-Coulomb character of the scattering of high-energy electrons by heavy ions. Indeed, with an increase in temperature, the amplitude of Coulomb scattering $f_{\rm C} \sim e^2/(k_{\rm B}T)$ decreases and turns out to be comparable to the characteristic sizes of xenon ions, ~ 4 Å, so that high-energy conduction electrons in their scattering can approach sufficiently close to the nucleus, where the interaction potential is no longer purely Coulombic: it is distorted by the inner electron shells. In this neighborhood of the nucleus, the potential turns out to be stronger than the external ionic potential, which leads to an increase in the scattering cross section and, consequently, to the relative decrease in electrical conductivity observed in experiments (Fig. 9b).

The experiments carried out provided only indirect information about free carriers in nonideal plasma. Meanwhile, the problem of determining the electron density was quite acute: which electrons can be considered bound, and which free? An idea therefore arose of using laser radiation to diagnose nonideal plasmas. It was at that time that lasers were coming into wide use in experimental technology. It was proposed to use the effect of total reflection of electromagnetic radiation with a wavelength λ from a medium with an electron density exceeding the critical one $n_{\rm e}^{\rm cr} \geqslant \pi c^2 m/(\lambda^2 e^2)$, which was well known in radar and solid-state physics. The density of free carriers in a dense plasma is quite high, so the region of wavelengths of interest to us lies in the optical range ($n_{\rm e}^{\rm cr} = 10^{21}$ cm^{-3} corresponds to $\lambda = 1.06$ μm). Yu B Zaporozhets built an experimental facility for laser diagnostics of dense xenon plasma produced by an explosive generator of rectangular pulses, and obtained the first data on the reflective properties of xenon at pressures up to $P \sim 17$ GPa and electron densities $n_{\rm e} \sim 10^{22}$ cm^{-3} [39 , 40].

The results turned out to be quite unexpected (Fig. 10): observed was a smooth density-dependent increase in the reflection coefficient, up to $R \sim 50\%$, which is characteristic of metals, but the expected step at the critical density was not found. It was only possible to estimate the frequency of electron collisions, which turned out to be of the order of the doubled laser frequency, $\sim 3 \times 10^{15}$ s^{-1}.

At this time, our cooperation began with Igor Tkachenko, who was then working at Odessa University (now Igor is a professor at the University of Valencia (Spain)). He suggested using reflection data to determine the permittivity of a nonideal plasma [41]. A little later, cooperation with German scientists from the University of Rostock began (G Repke, R Redmer, H Reinholz). In close collaboration with them, new experiments were carried out at different wavelengths and at different angles of incidence of laser radiation [42–44]. The effect of the width of the shock front and the kinetics of the establishing of ionization equilibrium in the front were taken into account, which led to a reasonable description of the entire set of experiments. This fruitful cooperation continues to this day.

Note that the desired direct measurement of the electron density in a nonideal plasma was carried out somewhat later, after the introduction of an electrodynamic facility, which made it possible to carry out experiments with strong magnetic fields. In particular, investigated in N S Shilkin's

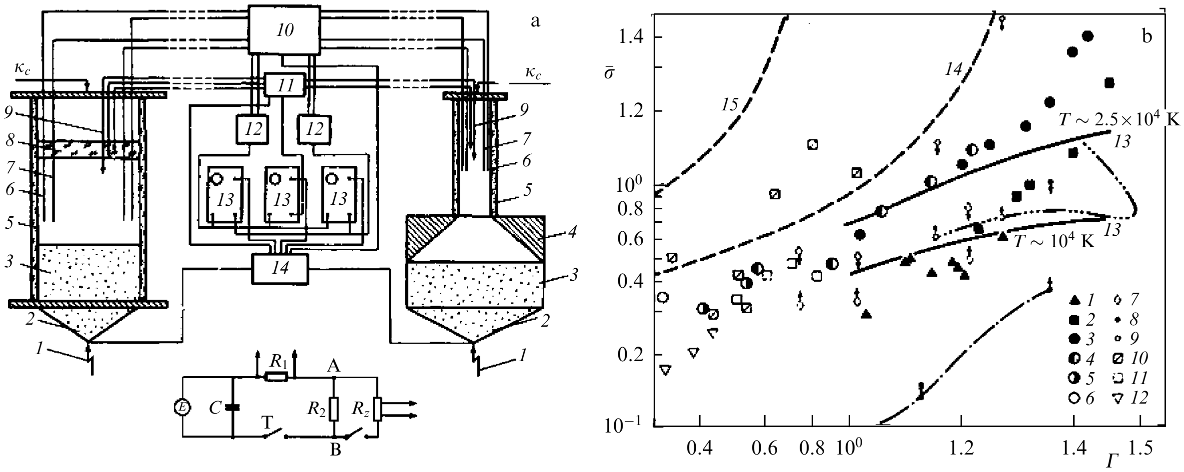

Figure 9. (a) Setup for measuring electrical conductivity σ on linear (left side of the figure) and cumulative (right side of the figure) generators [38]: *1* — detonator, *2* — explosive lens, *3* — HE charge, *4* — compression chamber , *5* — shock tube channel, 6 and *7* — current and potential electrodes, *8* — barrier, *9* — electrodes for measuring shock velocity, *10* — unit for generating an electrical conductivity measuring pulse, *11* — block for generating a shock velocity measuring pulse, *12* — differential amplifiers, *13* — recording oscilloscopes, *14* — delay unit. Shown in the lower part of the figure is a schematic electrical diagram of measurements: E — voltage source, C — charging capacitor, R_1, R_2 — reference resistors, R_z — plasma resistance, T — closing switch, A, B — plasma closure circuit. (b) Dimensionless electrical conductivity in relation to the nonideality parameter [38]: *1–12* — experimental data (see references in Ref. [38]), *13–15* — calculation results (see references in Ref. [38]).

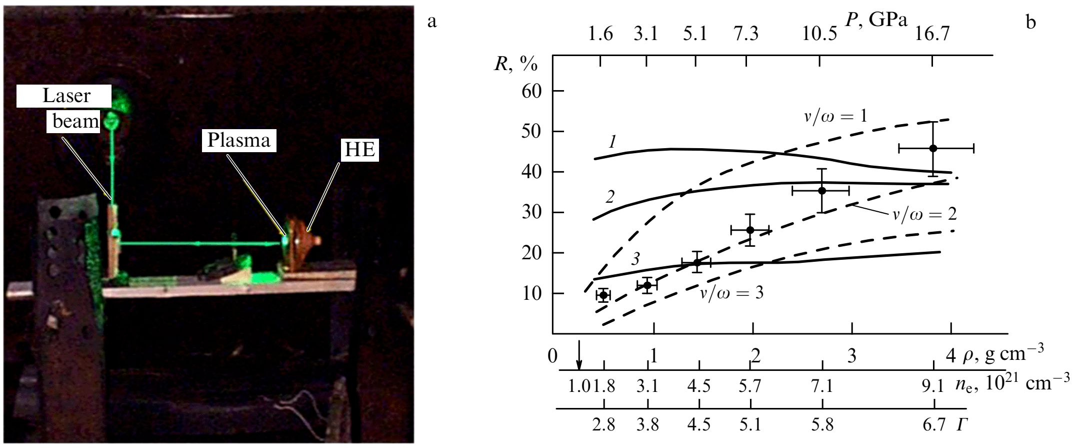

Figure 10. (a) Assembly before experiment. (b) Density dependence of reflection coefficient R of xenon plasma [39]. Calculation results [39]: *1* — using the Drude theory, *2* — using integral relations, *3* — with the inclusion of electron scattering by thermal plasma oscillations; ν is the electron collision frequency and ω is the laser radiation frequency.

work were the Hall effect in a nonideal plasma and the dependence of the electrical resistance on the magnitude of the magnetic field [45].

The implementation of many energy and space projects is associated with nonideal plasma. In one of them — the development of the physical principles of operation of a gas-phase nuclear reactor — V E took part when he was a student and graduate student. Another extremely interesting area is controlled fusion. In order for the synthesis reaction, or fusion, to proceed, a very high temperature and extremely high pressures are needed. Such 'combustion', though initiated by a nuclear charge, was first realized more than 60 years ago during the explosion of the first H-bomb. However, such an explosion is an uncontrollable process, suitable only for destruction. To use it for creative purposes, one must learn to control it. V E began to develop schemes for the implementation of pulsed inertial confined fusion based on the compression of deuterium in conical targets using impactor accelerated by HEs to a high velocity [46]. The first steps were taken on a standard generator of rectangular pulses, accelerating metal impactors to speeds of ~ 5.5 km s^{-1} (Fig. 11). This work was supported by Academician A M Prokhorov, who came to Chernogolovka more than once to get acquainted with the 'live' results, and his employee from the P N Lebedev Physical Institute (LPI), I K Krasyuk, spent day and night at our institute.

The joint work of our entire laboratory and the employees of the Lebedev Physical Institute led to interesting results: a neutron yield of about 10^6 neutrons per pulse was recorded, which indicated the realization of a thermonuclear plasma under the experimental conditions at pressure $P \sim 5-10$ TPa, temperature $T \sim 0.3-0.5$ keV, and a compression ratio of $\sim 10^3$. Of course, this is not enough to ignite the reaction, in connection with which further efforts were aimed at increasing the velocity of the impactors. Layered (gradient) systems were developed, allowing the acceleration of 0.1-mm thick molybdenum foils to velocities of ~ 12.8 km s^{-1} [47], and conical explosive generators, in which shock wave velocities

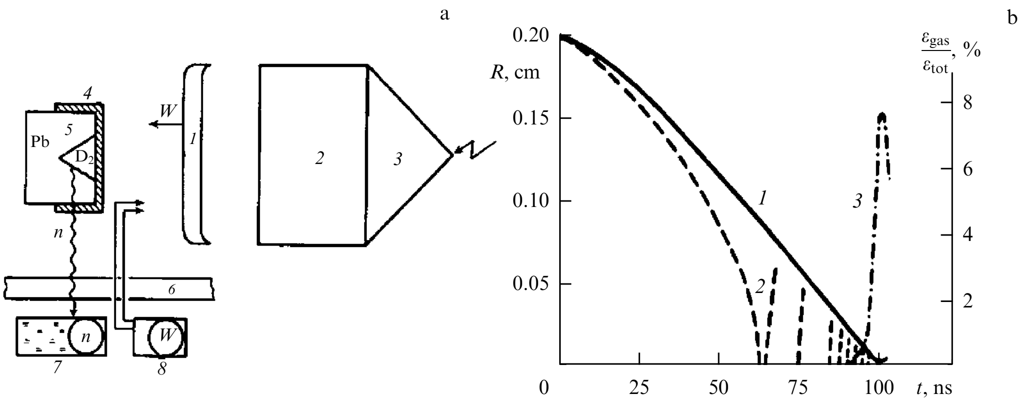

Figure 11. (a) Diagram of the neutron production facility: *1* — striker, *2* — HE charge, *3* — detonation lens, *4* — target cover, *5* — target, *6* — steel shield, *7* — neutron detection unit, *8* — unit for measuring the projectile flight speed. (b) Results of numerical simulation of target compression dynamics: *1* — motion of the inner boundary of the liner, *2* — shock waves, *3* — proportion of energy transferred to deuterium plasma [46].

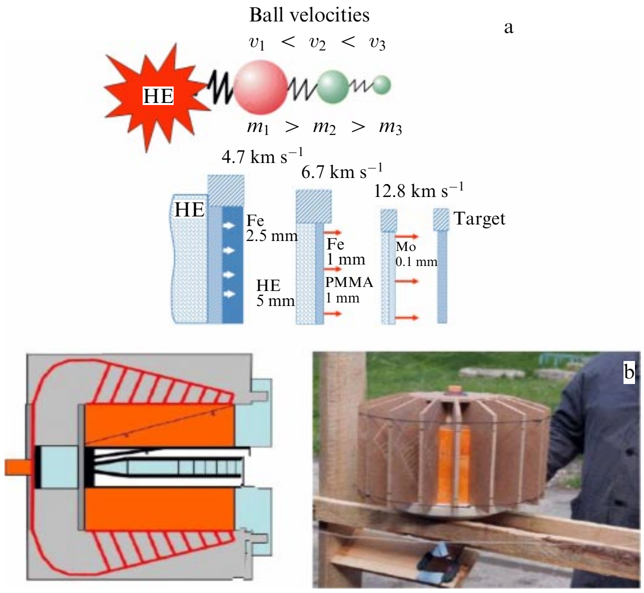

Figure 12. (a) Schematic of gradient cumulation [47] (PMMA — polymethyl methacrylate). (b) 'Mach' cumulative generator [49]. (From V E Fortov's presentation of 2012.)

of ~ 17 km s^{-1} were reached in copper and pressures $P \sim 1.4$ TPa [48] were obtained (Fig. 12).

True, such an increase in parameters was reached at the expense of a decrease in the lifetime of the plasma bunch and its significantly lower mass. However, this was several years later, when impact devices were not used in experiments with thermonuclear plasma, since the calculations carried out on the basis of the first experiments suggested that the velocities of the impactors in this formulation should be several times higher to ignite a thermonuclear reaction. Nevertheless, these devices turned out to be extremely interesting for studying the equation of state of matter in the megabar pressure range. Significant progress in the implementation of simple conical designs of terapascal pressures has been achieved only in the last decade [49].

5. Electrodynamic facility

How can the velocity of condensed projectiles be significantly increased? All methods of impactor acceleration using the chemical energy of condensed HEs have significant limitations associated with the finite speed of sound of the compressed and heated thrusting gas. Here, the use of electromagnetic ponderomotive forces looks promising, in which restrictions of this kind, at first glance, are not visible. In the late 1970s, there was a very popular idea of using a so-called railgun [50] to achieve speeds of the order of 100 km s^{-1}. The railgun is two parallel metal buses, between which a plastic striker closing an electric circuit moves, accelerated by a magnetically pressed discharge with a ~ 1 MA pulsed current. To produce powerful current pulses in this device, it looked attractive to use the chemical energy of condensed explosives, which could significantly reduce its dimensions. The fact is that the density of chemical energy in a condensed HE is several megajoules per kg, which is several orders of magnitude higher than the energy density stored in capacitors. Various designs of explosive magnetic generators (EMGs) developed by that time in Sarov and Los Alamos were rather compact devices that made it possible to obtain record high values of current (~ 300 MA), energy (~ 300 MJ), and magnetic fields (~ 28 MG) [51, 52].

At that time, V E Fortov, when discussing experiments with neutrons, got acquainted with L P Feoktistov,[7] and they came up with the idea [53] of making a powerful source of thermonuclear neutrons based on compression, with the use of a cylindrical liner, of a plasma preheated to temperatures of ~ 0.6 keV in a longitudinal magnetic field. To accelerate the liner, they proposed the use of a chemical condensed HE, and to preheat the plasma, the use of a collision of deuterium flows accelerated by plasma accelerators to speeds of ~ 300 km s^{-1}.

To implement such work, it was necessary to make a special explosive facility equipped with low-voltage and high-voltage capacitor banks of a megajoule energy storage level. Director of DICP F I Dubovitskii supported these ideas, a place was allocated at the test site in Pavilion A-3 of the DICP of the Russian Academy of Sciences, and a start was made on the procurement of the necessary equipment and the construction of the electrodynamic facility, the scientific leader-

[7] L P Feoktistov (1928–2002): Soviet and Russian nuclear physicist, one of the developers of nuclear and thermonuclear weapons in the USSR, academician of the Russian Academy of Sciences (2000), Hero of Socialist Labor (1971), laureate of the Lenin Prize (1958) and State Prize of the USSR (1978).

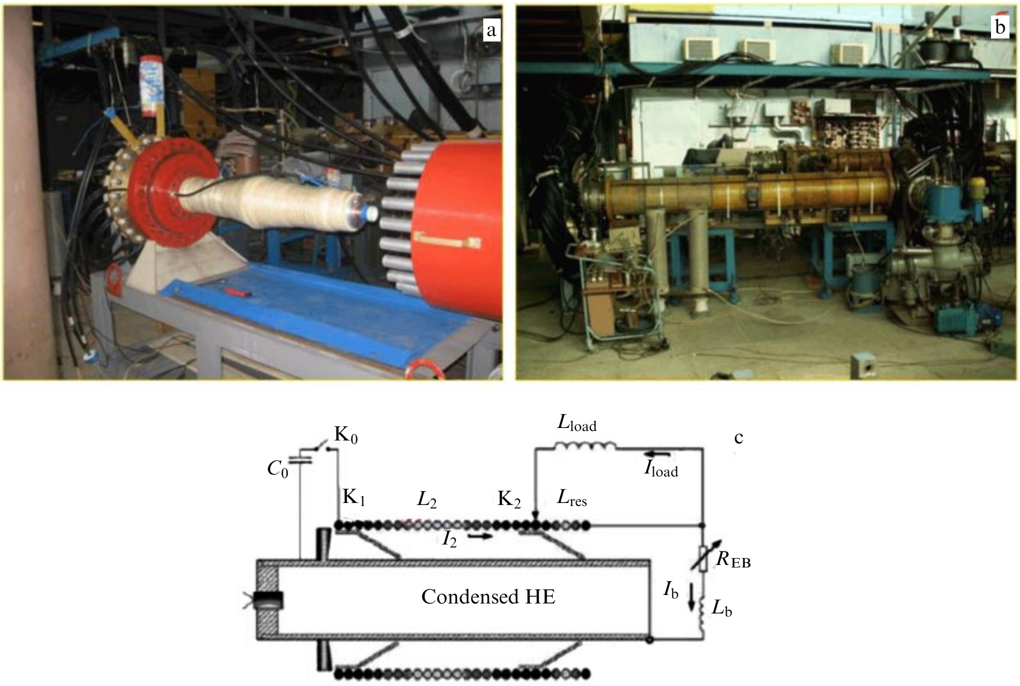

Figure 13. (a) Explosive magnetic generator for feeding plasma accelerators. (b) TRINITY plasma accelerator. (c) Electrical diagram of the operation of the EMG with switch-closures K_0, K_1, K_2 and the explosive breaker R_{EB}, L_2 — initial inductance of the EMG, L_{res} — residual inductance of the EMG, L_{load} — load inductance, L_b — ballast inductance, I_i — currents in the corresponding circuits [54].

ship of which was entrusted to V Mintsev. I must honestly say, although the work with high explosives at our institute was set at a high level, we did not have specialists in high-voltage technology. I had to travel to different institutions, select the necessary equipment, and consult on various issues. By 1986, the facility was put in operation and preliminary experiments were carried out.

In 1986, N N Semenov passed away, and F I Dubovitskii gradually moved away from the management of the institute. There was no personality of N N Semenov's caliber capable of holding together a large institute, although there were many prominent scientists in the field of chemical physics. The directors were constantly changing: for a short time even an 'outsider' from the Institute of General and Inorganic Chemistry (IGIC) of the USSR Academy of Sciences was appointed. V E Fortov's laboratory moved from sector to sector (from macrokinetics and gas dynamics of extreme chemical-technological processes to the physics of combustion and explosion, and vice versa). In 1986, Vladimir Evgen'evich was elected head of the laboratory at IHT and moved there at the invitation of Academician A E Sheindlin for a permanent job. He took with him a number of tasks related to high-current electronics, in particular, to railgun topics. To his credit, I must say that he did not forget about Chernogolovka: he remained the head of the laboratory on a voluntary basis. However, we did not even feel his absence, since his every appearance in Chernogolovka was accompanied by stormy discussions of scientific problems and the formulation of new problems. After that, 'Holy' Friday appeared — the day when Vladimir Fortov was sure to be in the laboratory, unless, of course, he was on long business trips. This tradition always persisted, even when V E held responsible government positions, until the very last days.

Despite all the upheavals at the institute, work on the electrodynamic setup began to develop further, although the emphasis shifted. As already mentioned, they began intensively dealing with the railgun topic at the IHT, where at that moment all the necessary equipment and work experience were already available. We returned to work with neutron sources only 15 years later thanks to the activity of the director of the Joint Stock Company State Research Center of the Russian Federation Troitsk Institute for Innovative and Fusion Research (TRINITI JSC), V E Cherkovets. By 2010, special explosive magnetic generators were developed for feeding plasma accelerators [54] (Fig. 13).

But new interesting tasks would appear. In particular, how and with what efficiency is it possible to convert the chemical energy of the condensed HE into the energy of an electromagnetic wave? In 1985, A B Prishchepenko came to us with his compact devices developed at the Central Research Institute of Chemistry and Mechanics (CRICM). A series of experiments were carried out at the test site, with diagnostics specially developed for these experiments, and quite powerful pulses of electromagnetic radiation were recorded both in the megahertz and in the ultra-high-frequency (microwave) wavelength ranges. However, the explosive devices were extremely unstable in operation. The authors concealed the principle of their operation; it was impossible to carry out experiments on the physics of the process. Therefore, the joint continuation of the work looked pointless. In addition, our bosses did not find a common language either.

At that time, the idea was conceived to use high-current relativistic electronics in such experiments. We recognized that EMGs allow converting the chemical energy of condensed HEs into the energy of an electromagnetic field with an efficiency of up to 40%, while relativistic microwave emitters have an efficiency of converting electrical energy into the energy of an electron beam and electromagnetic radiation up to 50%. However, this raises a number of nontrivial problems

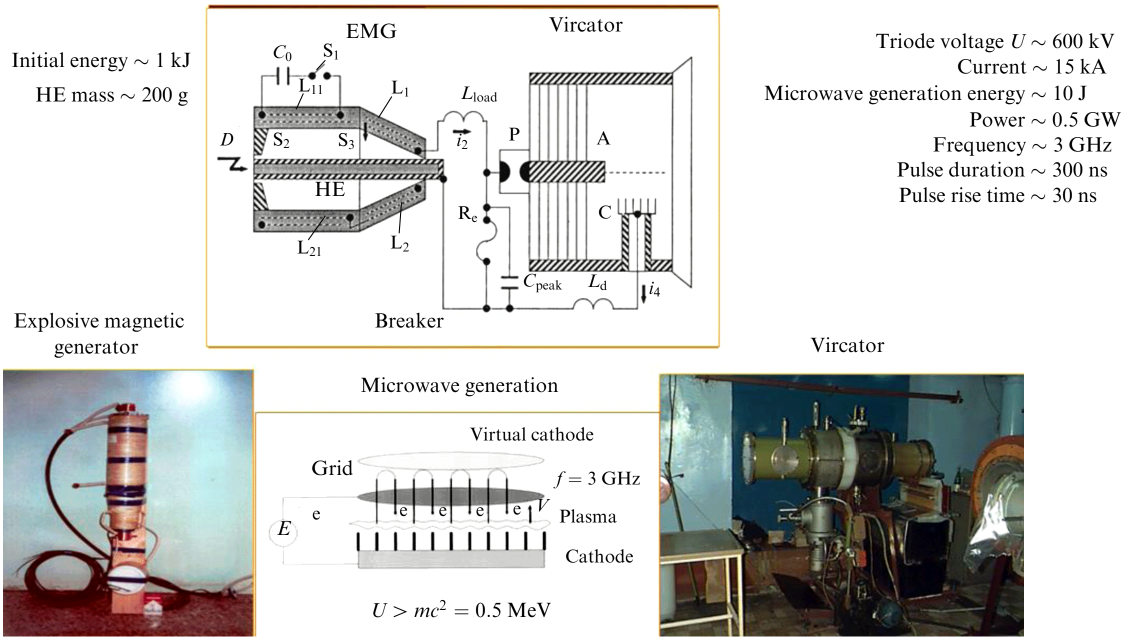

Figure 14. Layout of explosion energy conversion to electromagnetic radiation [60]. (Slide from V E Fortov's presentation, 1995.)

caused by the discrepancy between the scale of the characteristic kinetic energies. The fact is that the typical level of energy release during detonation of condensed HE corresponds to the energy of valence electrons and is of the order of 1 eV, while the effective conversion of the energy of the electron beam into electromagnetic radiation is carried out in the relativistic range of ~ 0.5 MeV. A high efficiency of explosive-magnetic generators is realized only when they work at low-inductive loads, while relativistic sources usually operate at a megavolt voltage level and have a high electrical impedance, at the level of several ten ohms. It was necessary to come up with schemes to match them.

We worked together with V P Isakov and his students from Krasnoyarsk State University to develop a special short-pulse high-voltage source based on EMG with flux trapping. Two types of compact (condensed HE mass: 200–600 g) high-voltage EMGs with magnetic flux trapping were developed: a cylindrical generator with an axial initiation of an HE charge [55] and a small-sized conical generator with a sliding contact point [56, 57]. A N Didenko [8] and his group from the Research Institute of Nuclear Physics (RINP) of Tomsk Polytechnic University (TPU) under the leadership of A G Zherlitsin proposed using a triode with a virtual cathode (vircator) as a source of microwave radiation [58]. This device was distinguished by its comparative simplicity, V E calling it simply 'a pot with electrodes'. To coordinate the operation of the devices, exploding wires were used, worked out by E I Azarkevich from the Research Institute of High Voltages (RIHV) at TPU.

The use of high-voltage EMGs with magnetic flux trapping made it possible to develop a transformerless system (Fig. 14) [59, 60] to generate an electron beam and microwave pulses. Use is made of the HE energy and a 'booster' spiral EMG with flux trapping, which plays the role of an energy source, a 'fast' high-voltage EMG with flux trapping, exploding wires, gas-filled peaking discharger P, sharpening capacitor C_{sh}, and a vircator. The external coil of the booster EMG L_{11} is energized from a small capacity $C_0 = 10^{-4}$ F with a voltage of 3 kV, which amplifies the electrical energy in the load — the external solenoid of the high-voltage EMG L_1 — to 5 kJ. When the liner of the high-voltage generator expands, the magnetic flux is 'trapped' by internal solenoid L_2, causing a current in the circuit of electric-explosion current breaker R_e. The overvoltage arising when the current is opened leads to a breakdown of spark gap P, and a high-voltage pulse is applied to anode A of the vircator, causing explosive emission from cathode C, the formation of an electron beam, and the generation of microwave radiation. Obtained in the course of experiments with the vircator were pulses of voltage U up to 600 kV and current up to 16 kA, which corresponds to the power of a relativistic electron beam of 10 GW. The power of the radiation radiated into the atmosphere was higher than 100 MW.

A model of the operation of the circuit elements was proposed, and its reasonable agreement with the experimental results was shown. Thus, the experiments carried out demonstrated the possibility of generating high-power microwave radiation using the energy of explosives. This research was further pursued in the laboratory of E V Nesterov at the IHT.

6. Collaboration with German scientists

International cooperation has developed rapidly since the 1980s. V E Fortov actively participated in the work of various international conferences; delegations of scientists from different countries visited Chernogolovka to become acquainted with the work in the field of extreme states of

[8] A N Didenko (1932–2017): Soviet and Russian physicist, specialist in the physics of charged particle beams, Corresponding member of the Russian Academy of Sciences (1991); Corresponding Member of the USSR Academy of Sciences (1984). He was awarded the Order of the Red Banner of Labor. Laureate of the Prize of the Council of Ministers of the USSR (1991) and the Prize of the Government of the Russian Federation (1999).

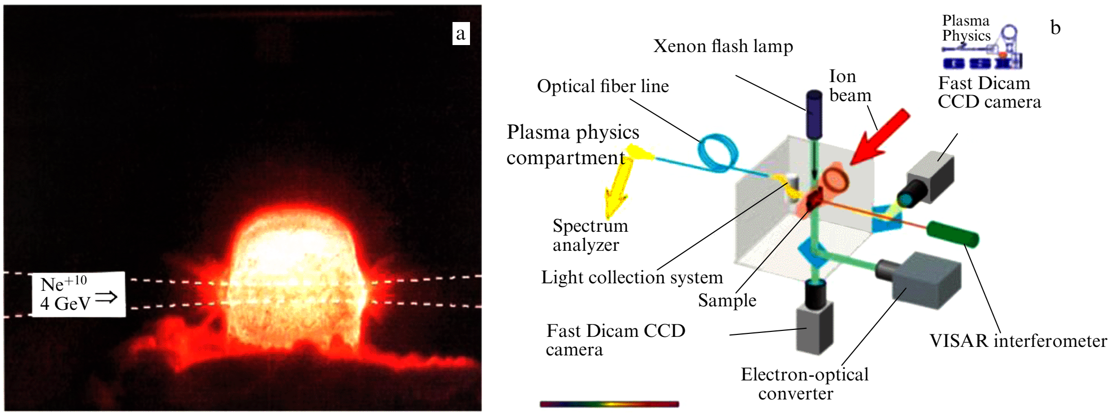

Figure 15. (Color online.) (a) Photo of beam impact on a xenon crystal. (b) Schematic of the HIHEX experiment (CCD — charge-coupled device, VISAR — Velocity Interferometer System for Any Reflector) [64].

matter. I would like to emphasize the particularly close interaction with German scientists. In Germany, a powerful group of theorists worked in the field of nonideal plasma physics at the universities of Berlin, Rostock, and Greifswald under the leadership of Professors W Ebeling, W Kraeft, D Kremp, and G Roepke. The experiments were carried out at the Central Institute of Electronic Physics of the German Democratic Republic under the leadership of H Hess. Conferences on the physics of nonideal plasma were held regularly. Joint work began immediately. In 1990, the book *Thermophysical Properties of Hot Dense Plasma* by V Ebeling, A Forster, V E Fortov, V K Gryaznov, and A Polishchuk was published [61]. A number of papers by V E Fortov and his Russian colleagues in collaboration with scientists from Rostock, G Roepke, R Redmer, and H Reinholz, appeared [42–44]. Chernogolovka was a closed city, and among the first scientists who visited it in the late 1980s were W Ebeling, R Redmer, and L Hitzchke. This cooperation continues fruitfully to this day.

Another area of joint scientific work with German scientists was carried out with the GSI Helmholtz Centre for Heavy Ion Research (GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt-GSI) in the Plasma Physics Laboratory headed by Professor Dieter Hoffmann. Colleagues at the Institute of Experimental and Theoretical Physics (ITEP) (Moscow) under the leadership of B Yu Sharkov (academician of RAS since 2016) and A A Golubev also actively took part in all the joint experiments. The heavy ion accelerator complex at GSI made it possible to obtain focused ion beams with an energy of 200–300 MeV per nucleon, an intensity of up to $\sim 5 \times 10^9$ (the number of particles per pulse for uranium ions), and a pulse duration of up to 100 ns on the target due to the temporal compression of the beam by a high-frequency field [62].

V E Fortov was the first to notice that such a driver looks very interesting from the point of view of generating dense nonideal plasma. Indeed, simple estimates show that the high intensity and significant ion path length in the target material (several millimeters) make it possible to reach a level of specific energy density in the substance up to 1 kJ g^{-1}, which is sufficient to heat a solid to a temperature $> 10^3$ K. Two basic conceptions were proposed for studying the fundamental properties of states of matter with a high energy density obtained using high-intensity ion beams [62, 63]: (1) HIHEX (Heavy Ion Heating and EXpansion), according to which a cylindrical or plane target is quasi-isochorically heated by an ion beam, and then the sample expands isentropically and passes through interesting regions of the phase diagram, including the two-phase region; (2) LAPLAS (LAboratory PLanetary Sciences), in accordance with which the quasi-isentropic compression of a cylindrical target to megabar pressures is carried out by a substance heated by an annular ion beam.

A schematic of the HIHEX experiment and a photograph of the effect of a beam on a xenon crystal are shown in Fig. 15. In the course of these experiments [62, 64], pressures up to 3 GPa and temperatures up to 15 kK were attained, and measurements were made of the thermophysical properties and hydrodynamic response of targets made of various materials (Pb, W, Ta, Al, UO_2).

Cooperation with German scientists was bilateral. Staff members of the Plasma Physics Laboratory came to Chernogolovka to execute joint experiments to study explosion-generated plasmas. Among the most interesting results should be noted the study of the behavior of the spectral lines of xenon and impurity lines of aluminum in xenon plasma [65]. In these experiments, it was possible to trace the broadening, shift, and disappearance of lines in dependence on the plasma density, which made it possible to construct models of the mechanisms of these processes under conditions of strong Coulomb interaction [66].

Methods for studying strongly coupled dense media, which were intensively developed by V E, invited completely new and unusual approaches. In the mid-1990s, the idea was conceived of using powerful relativistic ion beams for the diagnostics of nonideal plasma: such beams have a high penetrating power in matter and the determination of the change in the beam intensity would make it possible to directly determine an important plasma parameter — stopping power, especially since a very interesting effect could be expected due to the strong Coulomb interparticle interaction: an increase in the ion path in the plasma — its 'transparentization'.

The task turned out to be quite difficult. Indeed, how can the extremely 'dirty' explosive technology, which produces high pressures, shock waves, and all-pervading dust, be combined with high-purity high-vacuum accelerating technology? All these issues were quickly resolved with the well-coordinated work of the close-knit teams of Russian institutes IPCP RAS, ITEP, and JIHT RAS and German colleagues

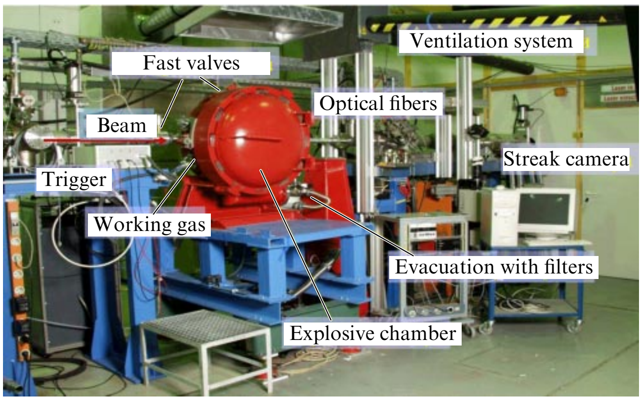

Figure 16. Explosive chamber in the GSI accelerator [69].

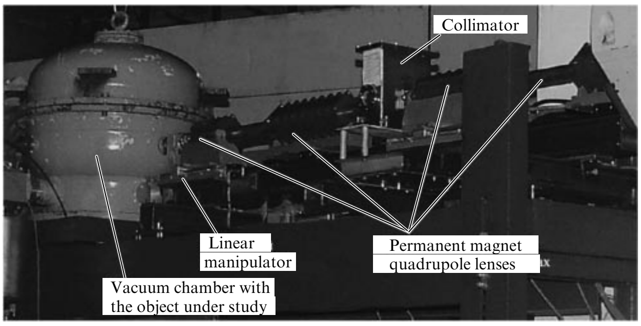

Figure 17. Proton microscope at the TWS-ITEP accelerator complex [70].

from GSI in Darmstadt. The facility was first tested in November 1997, and the first experiments with proton beams were carried out in Moscow at ITEP [67, 68]. The experiments were then continued in Darmstadt with heavy ion beams [69]. Figure 16 shows a photograph of a 150-g TNT explosion chamber built into the beam line at GSI. The extensive experimental material obtained in the course of these experiments made it possible to significantly advance in understanding the processes occurring in nonideal plasma, and served as the basis for constructing theoretical models.

The third line of work, developed in cooperation with GSI, IPCP RAS, and ITEP, was proton radiography [70]. The existing radiographic facilities at proton accelerators in the USA [71] and Russia [70, 72] have clearly demonstrated the advantages of the proton radiography method over traditional X-ray diagnostic techniques in the study of dense objects in dynamic experiments. A proton-radiographic facility using magnetic optics (PUMA proton microscope) was made at the TWS-ITEP accelerator complex (ITEP terawatt storage ring), which makes it possible to measure the density distribution of matter inside static and dynamic objects using a proton beam with an energy of 800 MeV [70]. An explosion chamber with a capacity of 150 g of TNT equivalent was included in the facility specifically for experiments with explosive materials. An external view of the PUMA proton microscope is shown in Fig. 17. Unfortunately, this installation was destroyed in 2012 as a result of a fire. However, it was possible to carry out experiments to record a chemical peak in TNT [73] and measure the density of a shock-compressed nonideal plasma of argon and xenon [74].

A more powerful proton microscope, PRIOR (*Pr*oton m*i*cr*o*scope for FAI*R*), with an energy of 3.5–4.5 GeV was developed and tested in dynamic experiments on exploding wires at GSI [75]. V E Fortov always spoke about the need to include an explosive chamber in this setup in order to obtain important information about the density of the shock-compressed substance and its spatial distribution. He placed emphasis on the development of compact explosive generators specially designed for experiments with a proton microscope. We hope that such experiments will become possible with the commissioning of the FAIR (Facility for Antiproton and Ion Research) project in 2025.

In the early 2000s, preparations began at GSI (Darmstadt) for the establishment of a scientific center based on the antiproton and heavy ion multipurpose accelerator — the FAIR project. The physical program of the new international scientific center covers not only the physics of the extreme states of matter [76, 77], but also studies of the phase transition of nuclear matter into quark-gluon plasma at a high density of nuclear matter, studies of hadronic physics using antiproton annihilation, as well as a number of innovative applications. V E Fortov made a significant contribution to the work of the Supervisory Board of FAIR, being a representative from the Russian Federation and a proponent of the interests of Russian physicists.

7. Extreme states of matter on Earth and in the cosmos

The above describes the onset and development of V E Fortov's scientific research in Chernogolovka. I would like to emphasize that work at the Institute of Problems of Chemical Physics, even after Vladimir Evgen'evich moved to IHT, did not stop and was carried on throughout his life, becoming one of the general narratives of his life. He headed the laboratory, and then the Department of Extreme States of Matter on a voluntary basis, was a member of the Academic Council, and held seminars every Friday, even when he was chair of the State Committee for Science and Technology, Minister of Science and Technology of the Russian Federation, Deputy Prime Minister, and President of the Russian Academy of Sciences. Apparently, it is impossible to describe the whole range of problems that were solved by this Scientist, truly with a capital letter. But his books, papers, and work have remained.

The last conversation of the author of these lines, V B Mintsev, with V E took place by phone in early November 2020. V E was already in the hospital. He was worried about the plenary talk at the All-Russian Conference on Low-Temperature Plasma Physics in Kazan. It was already clear that he himself would not be able to make the report, and so V E instructed me to make the presentation. It was already difficult for him to speak, and he briefly noted what the most important issues were that needed to be covered in the report. They were pressure-induced ionization of hydrogen and inert gases in the megabar pressure range, plasma phase transition in deuterium, attainment of record high pressures of $\sim$ 20 TPa in hydrogen and helium, and the quantum viscosity limit in strongly coupled media.

Indeed, experiments carried out in the late 1990s to study the electrophysical properties of shock-compressed plasma testified to the appearance of a high level of electrical conductivity (corresponding to the metallic one) in hydrogen and inert gases at high densities in the region of megabar pressures [78]. This process of plasma 'metallization' was explained in the framework of pressure-induced ionization. And the determination of the compressibility of hydrogen in

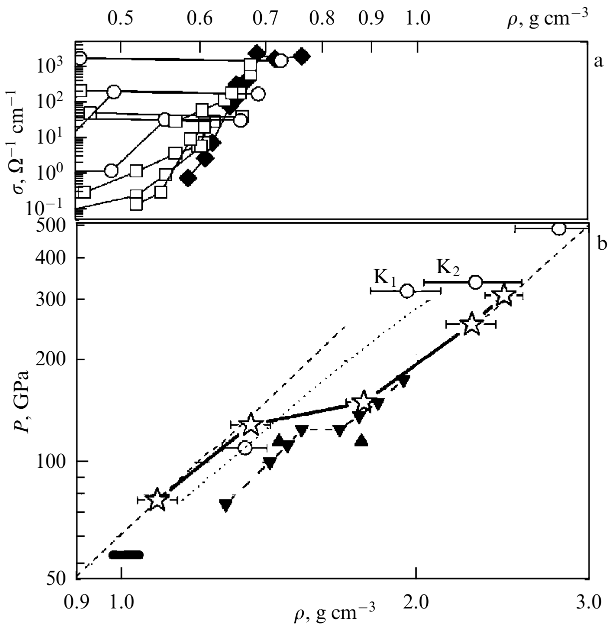

Figure 18. Electrical conductivity (a) and pressure (b) in the quasi-isentropic compression of deuterium as functions of density [79].

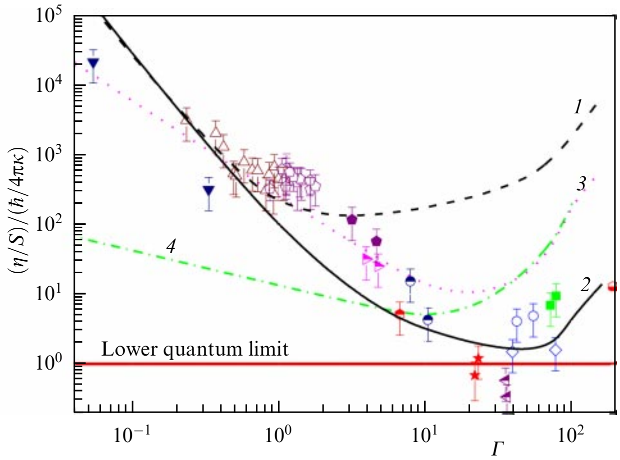

Figure 19. (Color online.) Ratio of shear viscosity to specific entropy in relation to the nonideality parameter [84].

joint experiments with the Russian Federal Nuclear Center–All–Russian Research Institute of Experimental Physics (RFNC–VNIIEF) made it possible for the first time to speak about the discovery of a special phase transition of the 1st-order at pressures of ~ 150 GPa — a plasma phase transition [79, 80] (Fig. 18). The possible existence of precisely such a specific plasma phase transition was predicted by G E Norman and A N Starostin [81] in 1968 (for more details see the paper by G E Norman and I M Saitov [82] in this issue). V E Fortov and his co-workers were taking an active interest in the data processing of the latest RFNC–VNIIEF experiments to achieve record high pressures of ~ 20 TPa in deuterium and helium plasmas and to derive new equations of state in this exotic range of parameters [83].

In recent years, V E Fortov was concerned with the physics of astronomical objects and quark-gluon plasma, where the effects of strong interactions are especially pronounced. In particular, an analysis of the limiting expression for the ratio of shear viscosity to specific entropy, which was derived within the framework of modern string theory, showed that a nonideal plasma with a strong Coulomb interaction is an example of such a medium (Fig. 19), and in this sense it can be called a perfect liquid [84].

8. Conclusions

The legacy that V E Fortov left us is almost 30 books: monographs and textbooks. He implemented another unique project — the 26-volume *Encyclopedia of Low-Temperature Plasma*, in which leading Russian specialists in the field were involved. V E Fortov actively participated in the work of the journal *Uspekhi Fizicheskikh Nauk* (*Physics–Uspekhi*), where he published 30 articles listed in the appendix (see [1*–30*]).

Special issues of the journals *High Temperature* **595** (6) (2021) and *Contributions to Plasma Physics* **61** (11) (2021) will be dedicated to the memory of V E Fortov. In these journals, additional information can be found on both V E's contribution to the development of the physics of extreme states of matter and his recent original work on the physics of nonideal plasma generated by dynamic methods [85–89]

V E Fortov was always full of scientific ideas. Unfortunately, not all the ideas were implemented. But he left behind a large school of followers, many of whom are young people. We hope they will continue to penetrate this extremely interesting area of science — the extreme states of matter.

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9. Appendix. V E Fortov's papers in the *Physics–Uspekhi* journal

1*. Al'tshuler L V, Il'kaev R I, Fortov V E "Use of powerful shock and detonation waves to study extreme states of matter" *Phys. Usp.* **64** 1167 (2021); "Ispol'zovanie moshchnykh udarnykh i detonatsionnykh voln dlya izucheniya ekstremal'nykh sostoyanii veshchestva" *Usp. Fiz. Nauk* **191** 1231 (2021)
2*. Eremin A V, Fortov V E "Detonation wave of condensation" *Phys. Usp.* **64** 1073 (2021); "Detonatsionnaya volna kondensatsii" *Usp. Fiz. Nauk* **191** 1131 (2021)
3*. Shvartsburg A B, Pecherkin V Ya, Vasilyak L M, Vetchinin S P, Fortov V E "Dielectric resonant magnetic dipoles: paradoxes, prospects, the first experiments" *Phys. Usp.* **61** 698 – 706 (2018); "Dielektricheskie rezonansnye magnitnye dipoli: paradoksy, perspektivy, pervye eksperimenty" *Usp. Fiz. Nauk* **188** 780–789 (2018)
4*. Kanel G I, Zaretsky E V, Razorenov S V, Ashitkov S I, Fortov V E "Unusual plasticity and strength of metals at ultra-short load durations" *Phys. Usp.* **60** 490 – 508 (2017); "Neobychnye plastichnost' i prochnost' metallov pri ul'trakorotkikh dlitel'nostyakh nagruzki" *Usp. Fiz. Nauk* **187** 525–545 (2017)
5*. Pikuz S A (Jr.), Faenov A Ya, Skobelev U Yu, Fortov V E "Production of exotic states of matter with the use of X-rays generated by focusing a petawatt laser pulse onto a solid target" *Phys. Usp.* **57** 702 – 707 (2014); "Sozdanie ekszoticheskikh sostoyanii veshchestva s pomoshch'yu rentgenovskogo izlucheniya, generiruemogo pri fokusirovke petavattnogo lazernogo impul'sa na tverdotel'nye misheni" *Usp. Fiz. Nauk* **184** 759–765 (2014)
6*. Fortov V E, Lomonosov I V "Ya B Zeldovich and equation of state problems for matter under extreme conditions" *Phys. Usp.* **57** 219 – 233 (2014); "Ya B Zel'dovich i problemy uravnenii sostoyaniya veshchestva v ekstremal'nykh usloviyakh" *Usp. Fiz. Nauk* **184** 231–245 (2014)
7*. Ivanov M F, Kiverin A D, Klumov B A, Fortov V E "From combustion and detonation to nitrogen oxides" *Phys. Usp.* **57** 234 –

249 (2014); "Ot goreniya i detonatsii k okislam azota" *Usp. Fiz. Nauk* **184** 247–264 (2014)

8*. Fortov V E, Sharkov B Yu, Stöcker H "European Facility for Antiproton and Ion Research (FAIR): the new international center for fundamental physics and its research program" *Phys. Usp.* **55** 582 – 602 (2012); "Nauchnaya programma v novom mezhdunarodnom centre fundamental'noi fiziki — Evropeiskom centre antiprotonnykh i ionnykh issledovanii FAIR" *Usp. Fiz. Nauk* **182** 621–644 (2012)

9*. Skobelev I Yu, Faenov A Ya, Pikuz T A, Fortov V E "Spectra of hollow ions in an ultradense laser plasma" *Phys. Usp.* **55** 47 – 71 (2012); "Spectry polykh ionov v sverkhplotnoi lazernoi plazme" *Usp. Fiz. Nauk* **182** 49–75 (2012)

10*. Khalatnikov I M, Fortov E V, Makarov A A, Fridman A M, Martynenko Yu V "Commemoration of the centenary of the birth of Academician L A Artsimovich (Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 18 February 2009; Joint session of the Research Council of the Russian Research Center "Kurchatov Institute", the Presidium of the Russian Academy of Sciences, and the Rosatom State Corporation, 18 March 2009)" *Phys. Usp.* **52** 1247 – 1272 (2009); "K 100-letiyu so dnya rozhdeniya akademika L A Artsimovicha. (Nauchnaya sessiya Otdeleniya fizicheskikh nauk, 18 fevralya 2009 g. Sovmestnoe zasedanie Uchenogo soveta Rossiiskogo nauchnogo tsentra "Kurchatovskii institut", Prezidiuma Rossiiskoi akademii nauk i Goskorporatsii "Rosatom", 18 marta 2009 g)" *Usp. Fiz. Nauk* **179** 1335–1361 (2009)

11*. Fortov V E, Makarov A A "Avenues for the innovative development of energetics in the world and in Russia" *Phys. Usp.* **52** 1249 – 1265 (2009); "Napravleniya innovatsionnogo razvitiya energetiki mira i Rossii" *Usp. Fiz. Nauk* **179** 1337–1353 (2009)

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14*. Fortov V E, Hoffmann D H H, Sharkov B Yu "Intense ion beams for generating extreme states of matter" *Phys. Usp.* **51** 109 – 131 (2008); "Intensivnye ionnye puchki dlya generatsii ekstremal'nykh sostoyanii veshchestva" *Usp. Fiz. Nauk* **178** 113–138 (2008)

15*. Kanel G I, Fortov V E, Razorenov S V "Shock waves in condensed-state physics" *Phys. Usp.* **50** 771 – 791 (2007); "Udarnye volny v fizike kondensirovannogo sostoyaniya" *Usp. Fiz. Nauk* **177** 809–830 (2007)

16*. Ginzburg V L, Fortov V E, Smirnov B M, Rudenko O V, Kulipanov G N, Denisov S P, Okun L B, Rubakov V A, Menskii M B "Spetsial scientific session of the Editorial Board of the journal "Uspekhi Fizicheskikh Nauk" honoring Vitalii Lazarevich Ginzburg on his 90th birthday (3 October 2006)" *Phys. Usp.* **50** 331 – 332 (2007); "Spetsial'noe zasedanie redaktsionnoi kollegii zhurnala *Uspekhi fizicheskikh nauk*, priurochennoe k 90-letiyu so dnya rozhdeniya Vitaliya Lazarevicha Ginzburga (3 oktyabrya 2006 g)" *Usp. Fiz. Nauk* **177** 345–346 (2007)

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