Compressibility of nonideal plasma of deuterium and helium under extreme pressures up to 20000 GPa

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Abstract: The authors present experimental data on compressibility of strongly nonideal plasma of deuterium and helium, which undergone quasi-isentropic compression up to densities $\rho \approx 14$ g/cm^3 in pressure region up to 20000 GPa (200 Mbar) in devices of the cylindrical and spherical geometries.

Keywords: quasi-isentropic compressibility, gaseous, nonideal plasma, X-ray sources, gasdynamic calculations, cylindrical and spherical shock wave generators.

1. Introduction.

This work presents capabilities of experimental physics of high energy densities to reproduce the extreme states of substance, which are typical for the Universe, in the laboratory environments. For 2007-2018, using the method of quasi-isentropic compression, RFNC-VNIIEF experts investigated compressibility of deuterium and helium plasma in the pressure range up to ~ 12 TPa [1-10]. In the new unique experiment, the compression of gaseous deuterium up to the density of 14 g/cm^3 by the pressure of ~ 200 million atmospheres was measured.

2. Experimental setup.

To investigate compressibility of nonideal plasma of gases under pressures of the megabar and gigabar ranges, the dynamic method was used for generation of high pressures due to energy of powerful shock waves. Devices of the cylindrical and spherical geometries were developed in RFNC-VNIIEF for providing pressures of the mentioned range. In these devices, gas compression was performed by a system of shock waves which were circulating in the gas volume and by converging to the center steel shells. This process was named quasi-isentropic, since after arrival of the first shock wave, the further gas compression occurs actually without strong heating of the gas. Finally, when pressure grows inside the investigated substance, the shell stops (the "stop" time), and then it is scattered. The goal of our experiment was recording of the radius vs time path of the experimental device shell and determination of its size at the "stop" time when the maximum compression of the investigated substance was achieved.

Fig. 1 presents scheme of the test with use of spherical devices at the unique three-beam X-ray radiography facility of RFNC-VNIIEF. Shadow image of boundaries of the shells, which were compressing the investigated gas, was recorded by simultaneous use of decelerating radiation from three powerful betatrons (1) with the limiting electron energy of ≈ 60 MeV. The betatrons were mounted in a protective concrete bunker (2). They were operating in the regime of consequent generation of three pulses of X-ray radiation (Fig. 1(a)).

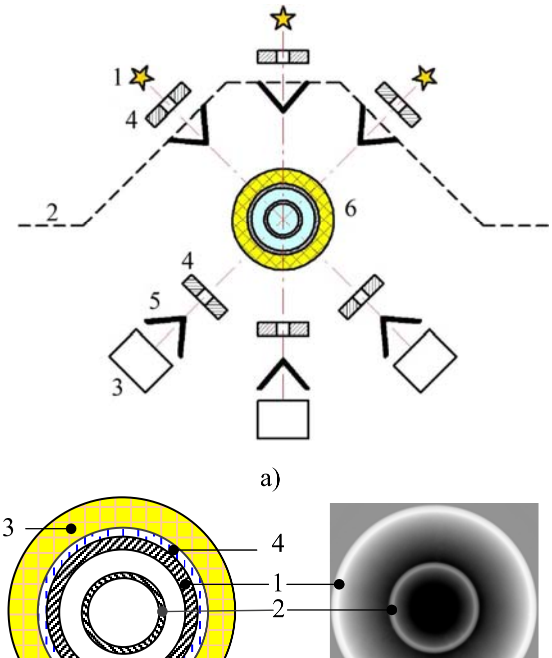

Fig. 1. a) Experimental setup: 1 – X-ray sources (betatrons); 2 – protective covering; 3 – detectors; 4 – collimators (Pb); 5 – cones (Al); 6 – experimental device; b) Two-cascade spherical experimental device: on the left – construction design, on the right – X-ray image of the device in initial state; 1 – external shell (Fe1), 2 – internal shell (Fe2), 3 – HE, 4 – plexiglass.

Duration of each radiation pulse was ~150-180 ns in this regime. In the test, an individual optical-electronic detection system (3) was used. It was activated synchronously with the betatron pulses.

In this system, monocrystals of sodium iodide and lutecium silicate were employed as transducers of X-ray radiation to be visible. To eliminate influence of scattered radiation on high-sensitive detectors (3), the recording field sizes were limited with lead collimators (4) in each of three projections. Aluminum cones (5) were used for protection of betatrons (1) and optical-electronic recorders of X-ray radiation (3).

The basis of the experimental device (Fig. 1(b)) was a spherical chamber, which was filled with gas. The chamber consisted of two shells 1 and 2. Each shell was manufactured from high-strength steel by soldering of two hemispheres. A system based on thermodesorption sources was used to fill the experimental devices with nonradioactive hydrogen isotopes. A thermocompression source of helium was used in the experiments with helium. To compress the gas, the authors used high explosive (HE) (3) based on HMX with weight of 85 kg of the TNT equivalent.

With the supposition of compressed substance mass conservation, its density can be obtained by the formula:

$$\rho = \rho_o \cdot (R_o / R_{min})^n \qquad (1)$$

where ρ_o is the initial density of gas, R_o and R_{min} are the internal radius of the shell in the initial state and at the shell "stop" time, respectively; $n = 2$ or 3 for the cylindrical or spherical geometry, respectively. Pressure in plasma was determined by gasdynamic calculations with taking account for real thermodynamic and strength properties of all elements of the experimental devices and their equations of state. Calculation of characteristics of the experimental devices was performed with use of the one-dimensional gasdynamic code intended for numerical simulation of nonsteady motions of solid medium, which had been verified with experimental data obtained in Russia and in other countries. To evaluate the basic thermodynamic parameters of compressed plasma of deuterium and helium, the authors used values of pressure and temperature in plasma at time of its maximum compression. The values were obtained by averaging the calculated values of P(R) and T(R) in mass.

3. Experimental data.

Experimental R(t) data on compressibility of deuterium plasma under effect of energy of powerful HE with weight of 85 kg of the TNT equivalent are presented in **Fig. 2** together with results of the gasdynamic calculation. It is clearly seen in the graph that the calculation well describes dynamics of shell boundaries motion for both cascades, control points of motion of shock wave (SW) in the plexiglass shell, as well as values of boundaries of shells of the experimental device measured by the X-ray radiography method.

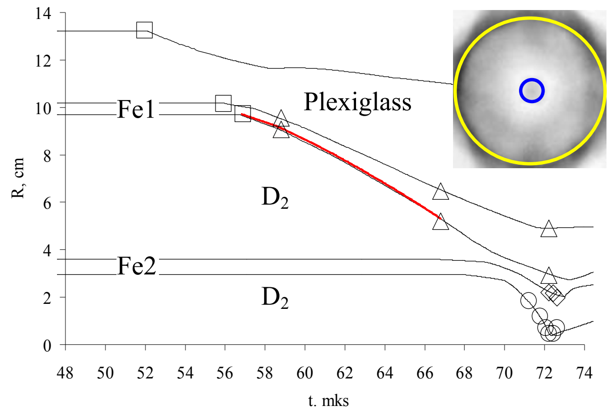

Fig. 2. Comparison of calculated R(t)-diagrams and experimental data. Results of X-ray radiography of the boundaries: Δ – external shell (Fe1); ◇ and O – internal shell (Fe2); □ – control points of SW motion. ——— – PDV data.

The same figure presents the X-ray image, which was recorded in the experiment at maximum compression. The bold circle designates the area of compressed deuterium plasma. For tracing the boundaries of the spherical shells, the functional method was employed. It is based on use of a priori information on function of photo material darkening density in vicinity of extended boundaries.

It follows from analysis of the obtained data on the performed experiment that at time of the maximum compression the deuterium plasma state is characterized by the parameters: $P = (18500 \pm 600)$ GPa, $\rho = (13.8 \pm 2.1)$ g/cm^3 at compression extent $\delta = \rho/\rho_o = 460 \pm 70$. Error in pressure corresponds to deviation of the pressure profile from the weighted average value.

Fig. 3 presents all experimental and calculated data of RFNC-VNIIEF on quasi-isentropic compression of deuterium plasma in the devices of the cylindrical and spherical geometry from [1-2] as well as result of this work at pressure P = 18500 GPa.

The presented data in the pressure range P ~ 30 - 18500 GPa are persuasively pointing to anomaly in deuterium plasma compression that is followed by density jump on adiabat $(\partial P/\partial \rho)_S = 0$ in the density range $\Delta\rho = 1.46–1.68$ g/cm^3 at temperature $T \approx 3700$ K. Data, which were obtained in [3]**,** are evaluating the value of pressure of this transition $P \approx 154$ GPa. As the graph shows, the obtained results are also pointing to the peculiarity of behavior of compressed deuterium plasma at pressure $P \sim 5500$ GPa that was already mentioned earlier in work [3].

The experimental point, which was obtained in this work, does not contradict the general path of the dependence P(ρ).

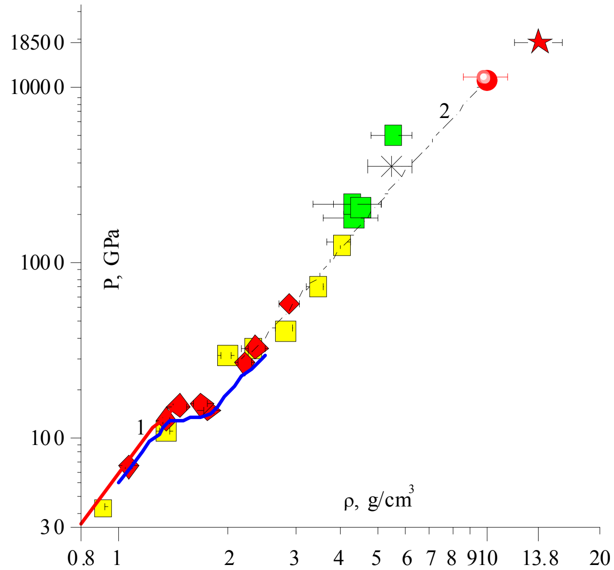

Fig. 3. Quasi-isentropic compressibility of deuterium plasma: ◆ – cylindrical devices [1-2], ■ – spherical devices [2-6], ● – spherical device [7-8], ■ – spherical devices [11], ✳ – [12], ★ – this work, —— – first-principle calculation [13], which predicts phase transition in plasma of compressed deuterium. Isentropes [2]: 1 –S = 23.5 J/g·K, 2 – S = 26 J/g·K.

The authors used the similar experimental setup for investigation of quasi-isentropic compressibility of helium. The obtained P(ρ) data are presented in **Fig. 4**.

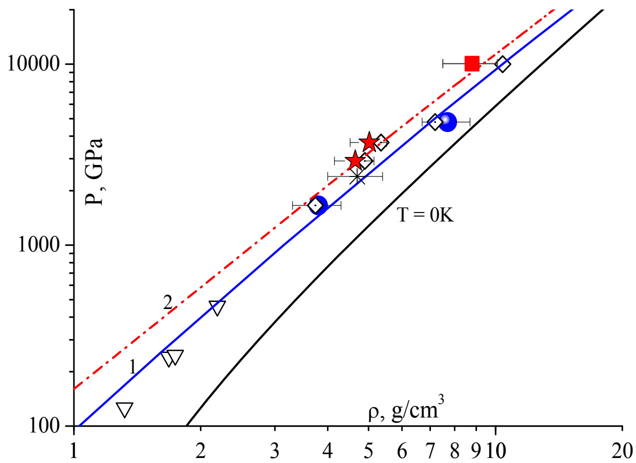

Fig. 4. Quasi-isentropic compressibility of helium plasma. Test: ■ – [9], ★ – [6-7], ● – [2-4], ✳ – [12], ▽ – [14]; ◇ – calculation. Isentropes [7]: 1 – S/R=14.9, 2 – S/R=16.3.

With use of the spherical two-cascade chamber and high explosive having weight M ≈ 85 kg of the TNT equivalent at the initial gas pressure Po = 25 MPa the nonideal plasma of helium was compressed up to density ρ ~ 9 g/cm³ by pressure P ~ 10000 GPa [7].

With use of the spherical two-cascade chamber and high explosive having weight M ≈ 85 kg of the TNT equivalent at the initial gas pressure Po = 25 MPa the nonideal plasma of helium was compressed up to density ρ ~ 9 g/cm³ by pressure P ~ 10000 GPa [7]. In unique experiments with involvement of the two-cascade spherical chamber having separated cavities, the nonideal plasma of helium was ≈ 600 and 900 times compressed (★ in **Fig. 4**) at the ≈ 9:1 ratio of the initial pressure of gas in the external and internal cavities of the two-cascade spherical construction [7].

Thus, in laboratory experiments with quasi-isentropic compression of deuterium and helium plasma, the thermodynamic parameters were achieved which exceeded the expected parameters in centers of such giant planets as Jupiter (pressure P ~ 60 million atmospheres) and Saturn (pressure P ~ 10-20 million atmospheres).

Analysis of the developed methodology gives hope to investigate quasi-isentropic compressibility of nonideal plasma of deuterium and helium in RFNC-VNIIEF up to pressures P ~ 25000 GPa.

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