*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.017 (2004)*

Thermodynamic and Transport Properties of Shock Compressed Plasmas at Megabars

V. Fortov

Institute for High Energy Density, Russian Academy of Sciences, Moscow 127412 Russia

The report presents the experimental results of investigation of physical properties of the coupled nonideal plasmas generated as a result of shock compression of metals, H_2, He, noble gases, S, I, fullerene C_{60} and H_2O in the megabar pressure range. High energy plasma states were generated by single and multiple shock compression and adiabatic expansion of solid, liquid, porous and low-density foam samples. The highly time-resolved diagnostics permit us to measure thermodynamical, electrophysical and radiative properties of high pressure condensed plasmas in the phase diagram broad region – from the compressed condensed solid state up to the low density gas range, including high pressure evaporation curves with near-critical states of metals, strongly coupled plasma and metal-insulator transition regions [1-3]. These data in combination with exploding wire conductivity measurements demonstrate an ionization rate increase up to ten orders of magnitude as a result of compression of nonideal plasmas at $p \sim 10^4$ - 10^7 bars.

A typical experimental assembly for multiple shock compression of condensed hydrogen and inert gases in planar geometry is shown in Fig. 1. Shock waves were generated by an impact of a steel impactor (*2*) 1–3 mm thick and 30–40 mm in diameter accelerated by detonation products of a condensed high explosive (*1*) to velocities of 3–8 km/s with the aid of the gradient-cumulation effect. The absence of melting and evaporation of a shock-worker material, as well as the absence of mechanical fracture of the impactor during dynamic acceleration, was tested in methodological experiments. The transition of a shock wave from a metallic screen (*3*) of thickness 1–1.5 mm to the substance under study (*4*) having an initial thickness of 1 to 5 mm generated, in it, the first shock wave of amplitude pressure P_1 = 0.02−0.8 Mbar; upon being reflected from a transparent sapphire window (*5*) 4–5 mm thick and 20 mm in diameter, this wave excited a repeated-compression shock wave. A further rareflection of shock waves between the screen *3* and the window *5* led to multiple shock compression of the sample to maximum pressures of $P \approx$ 1–2 Mbar, whose level was determined by the velocity of the impinging impactor, its thickness, and the dimensions of the substance being studied.

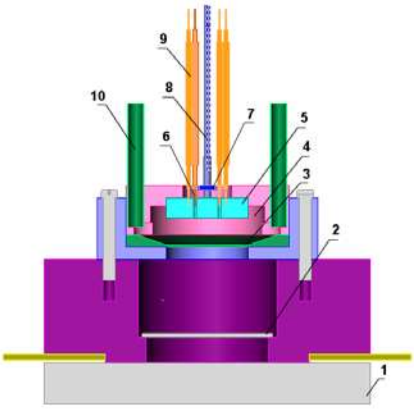

Figure 1. Experimental assembly for multiple shock compression of condensed hydrogen and inert gases in planar geometry.

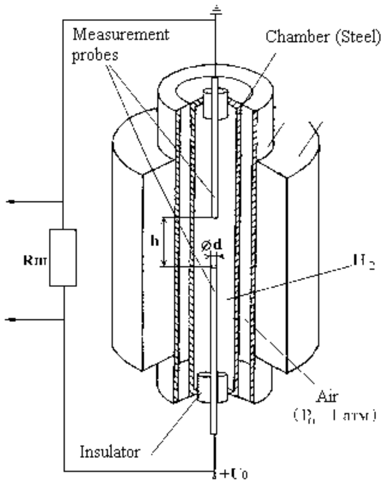

Figure 2. Scheme of cylindrical compression.

The initial states of the explored substances for a further multiple compression were either in the gas region of the phase diagram at pressure and temperature values of P_0 = 5-35 MPa, T_0 = 77.4-300 K, respectively, or in its liquid region at P_0~ 0,1-1 MPa, T_0~ 20,4-160 K. In the last case, liquefaction was performed from high-purity gases supplied to the assembly through pipes (*10*). Initial temperature was measured by thermocouples and platinum resistance thermometers. The process of multiple compression was observed by means of fast optic-electronic converters and five-channel fiber-optic-coupled pyrometer of time resolution 2–5 ns (*8*). Shock-compressed sapphire of the optic window *6* retained transparency up to $P \approx 20$ GPa and made it possible to record from five to six reverberations. In these experiments, the compression and irreversible heating of the substance under study were implemented by series of shock waves arising upon successive reflections from the sapphire window and the steel screen. A hydrodynamic analysis of the process revealed that, following the propagation of the first two waves through the compressed layer, a further compression proceeded in a quasi-isentropic way. This made it possible to advance to the region of higher densities (ρ/ρ_0~10-100) in comparison with single wave compression and to reduce the final temperature.

The second series of measurements was performed by employing shock compression under the conditions of cylindrical geometry (Fig. 2). A cylindrical charge of a high explosive (an alloy formed by trotyl and hexogen in the ratio 40 : 60), its 1 1 2 outer diameter being 30 cm, was initiated over the outer surface at 640 points that generated, at the inner surface of the charge, a highly symmetric detonation wave (the difference in time of arrival was not greater than 100 ns). The arrival of this wave at the inner surface caused the centripetal motion of the steel impactor at an initial velocity of W ~ 5 km/s. The deceleration of this cylindrical impactor against the metallic surface of the chamber filled with the gas under study at an initial pressure of up to 70 MPa generated a converging shock wave. Successive reflections of the shock wave from the center of symmetry and from the inner surface of the chamber gave rise to multiple shock compression, which, as in the case of planar geometry, proved to be close to isentropic compression. At each instant of time, the profiles of thermodynamic parameters of multiple compression were determined on the basis one- or two-dimensional gas-dynamic calculations.

Shock compression of H_2, Ar, He, Kr, Ne, and Xe in initially gaseous and cryogenic liquid state allows us to measure the electrical conductivity, Hall effect parameters, equation of state, stopping power of intense particle beams and emission spectra of strongly nonideal plasma.

Experiments on multiple shock compression of hydrogen and inert gases make it possible to obtain physical information in a new region of phase diagram. For hydrogen pressures are up to 15 Mbar, temperatures of 3000 to 7000 K and densities one order of magnitude higher than those of solid state. This region is of interest since strong interaction both between atoms (molecules) ($\Gamma_a=r_a n_a^{-1/3} \sim 1$ - that is, molecular or the atomic size r_a is comparable with the interparticle spacing $n_a^{-1/3}$) and Coulomb particles (the mean interaction energy of charged particles E_C, is much greater than the mean kinetic energy of thermal motion, E_T ($\Gamma_D = E_C/E_T \sim 10$).). The situation is additionally complicated electrons become degenerated, ($n_e \lambda_e^3 \sim 200$, λ_e is the thermal de Broglie wavelength).

From Fig.3-4 one can see that the most prominent feature of the electrical conductivity of strongly nonideal plasma is sharp increase of the electrical conductivity at final stages of compression (by three to five orders of magnitude) in a narrow range of densities ($\rho \approx 0.3$–1 g/cm^3 for hydrogen, and $\rho \approx$ 8–10 g/cm^3 for xenon) at megabar pressures, reaching values of about 10^2–10^3 Ω^{-1} cm^{-1}, which are peculiar to alkali metals.

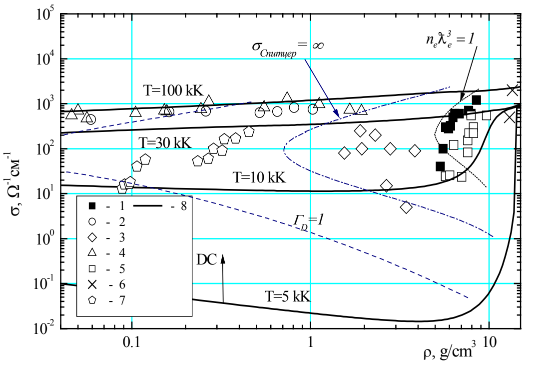

Figure 3. Electrical conductivity of xenon as a function of density.

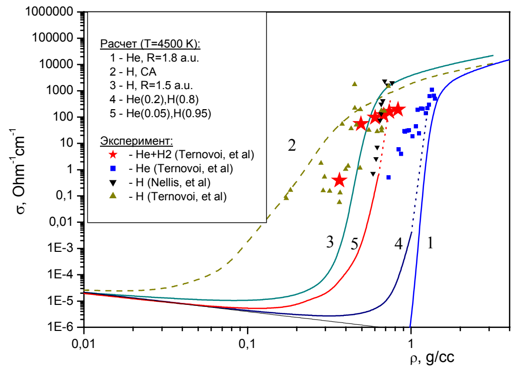

Figure 4. Electrical conductivity of hydrogen, helium and H2- He mixture as a function of density.

Thermal and pressure ionization of strongly coupled matter is the most prominent effects under the experimental conditions. It was shown that plasma compression strongly deforms the ionization potentials, emission spectra and scattering cross-sections of the neutrals and ions in the strongly coupled plasmas. Comparison of the data obtained with theoretical models (percolation, Mott transition, Zeeman and Lorenz approach etc.) is presented. The multiple shock compression of solid Li and Na shows "dielectrization" of these elements at megabar pressure range. Theoretical analysis of the pressure ionization and dielectrization for some elements at ultramegabars are presented and compared with the experiments. The computer simulations of nonsteady hydrodynamics of strongly nonideal plasmas at high energy densities are presented.

This work was supported by the Russian Foundation for Basic Research (project nos. 00-15-96738, 00-02-17550), by the Ministry for Industry and Science of the Russia (contract no. 40.009.1.11192, project no.1938.2003.02), and by the Presidium of RAS (Program for Scientific Research into Thermophysics and Mechanics of Intense Energy Action).

REFERENCES

1. *Encyclopedia of Low-Temperature Plasma*, Ed. by V. E. Fortov , Nauka, Moscow 2000.
2. V. E. Fortov and I. T. Yakubov, *Nonideal Plasma* Énergoatomizdat, Moscow 1994.
3. Fortov V.E., Ternovoi V.Ya.., M.V.Zhernokletov et al., JETP 97, 259 2003.