# Lecture no.3

# Experimental Generation Methods of Nonideal Plasma

## Electrical Methods of Nonideal Plasma Generation

Introduction. There are two principally different techniques, namely:

- the heating in resistance furnaces of ampoules containing the investigated material;
- the Joule heating of the investigated material by an electric current.

Plasma heating in furnaces. The stationary methods of plasma generation are based on heating an ampoule containing the material under investigation (measuring cell) in electric furnaces of various designs. In the Figure 1 the schematic diagram of such facility for investigating of alkali metals at high temperatures and pressures is shown (Alekseev 1968). Argon from cylinder (1) was fed via a system of valves to chamber (3) for cleaning. Cleaned argon was delivered to a nitrogen thermocompressor (4) with the pressure up to 600 bar, and from the thermocompressor to measuring chamber (5) accommodating a heater and a measuring cell. The pressure was monitored by gauges (2). The temperature was determined using a standard thermocouple.

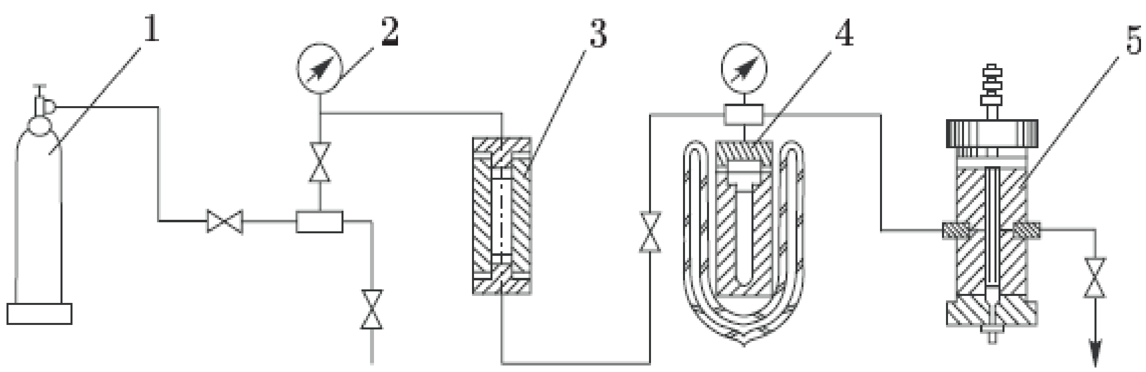


*Figure 1. The schematic diagram of experimental facility for the generation and investigation of nonideal plasma of metals. 1 - cylinder with argon; 2 - pressure gauges; 3 - argon cleaning system; 4 - thermocompressor; 5 - high–pressure chamber.*

The most convenient object for investigations of the nonideality effect is cesium which has a low ionization potential ($I = 3{,}89\, eV$), low critical pressure (about $110\, bar$), and a critical temperature that is quite accessible to static experiments (about $2000\, K$). In the such experiments plasma has the following value of the nonideality parameter $\gamma \le 1$.

The isobaric Joule heating in a capillary. This method was developed by Kulik et al. (1984) to investigate the properties of a nonideal plasma of cesium, sodium, potassium and lithium. A schematic diagram of such experimental setup is shown in Fig. 2.

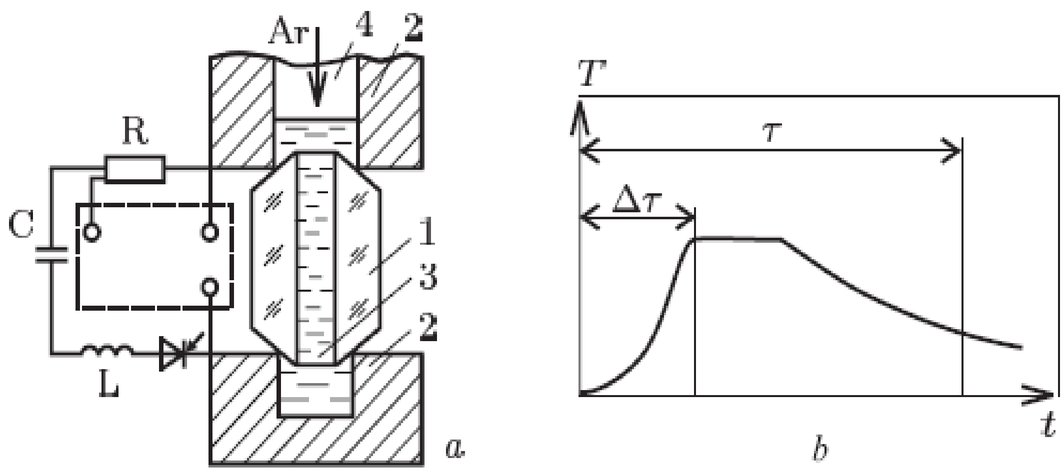


*Figure 2. Schematic diagram of setup for isobaric heating in a transparent capillary. (a): 1 - capillary; 2 - electrodes; 3 - liquid cesium; 4 - argon purge. (b) The behavior of the time dependence of plasma temperature.*

In this apparatus a transparent quartz (or glass) capillary $0{,}7\, mm$ in diameter and $20\, mm$ long is filled with liquid cesium (or other metals) under constant pressure of argon. The cesium in the capillary is heated by a current pulse shaped by an electric circuit consisting of a capacitor, inductor and a control thyristor (see, Fig.2). In the experiment, the current–voltage characteristic $F(i)$ is measured (from the oscillogram). Then, the isobars of electrical conductivity $\sigma(T)$ and thermal conductivity $\kappa(T)$ are calculated on the basis of the dependence $F(i)$ by the following relations:

$$\frac{1}{r}\frac{d}{dr}\left(r\kappa\frac{dT}{dr}\right)+\sigma F^{2}=0; \quad i=2\pi F\int_{0}^{R}\sigma r dr \quad , \qquad (1)$$

where the first equation is the equation of thermal balance and the second one is the Ohm's law; $r$ is the distance from the capillary axis and $R$ is its radius. It should be added some boundary conditions for equation (1) such as $dT/dr=0$ at $r=0$ and $T=T_S$ at $r=R$, here $T_S$ is the temperature of the outside surface of the plasma measured by pyrometer. The typical plasma parameters in such experiments are follows: the maximum pressure is $0{,}1\,GPa$ and the temperature range is $(4\div 20)\cdot 10^{3}K$.

Exploding wire method. The schematic diagram of the exploding wire method is shown in Figure 3 (Dikhter and Zeigarnik, 1981). A cesium (or lithium) wire 6 is placed in a high–pressure chamber 5. A electrical current with a density of $(1\div 5)\cdot 10^{6}A\cdot cm^{-2}$ is passed through the wire and metallic plasma is generated.

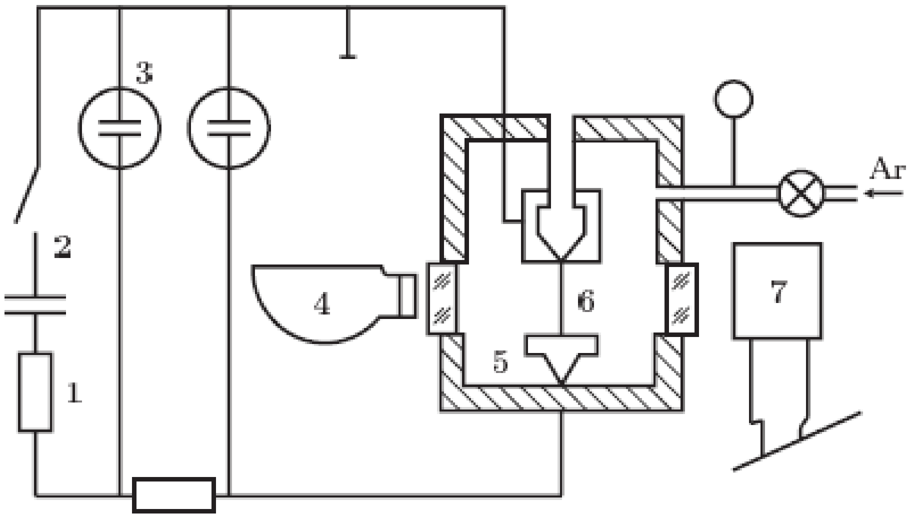


*Figure 3. Schematic diagram of the experimental setup for exploding wire method. 1 - ballast resistor; 2 - capacitor bank; 3 - oscillograph; 4 - high–speed photorecorder; 5 - high–pressure chamber; 6 - heated wire; 7 - spectrograph.*

Such plasma contained by a high–pressure inert gas is heated and expands at constant pressure. In the experiment the pressure in the chamber, the oscillography of current in the circuit and the voltage drop across the plasma column are measured. Also the plasma column expansion process with time is registered by photorecording. Finally, one can use the measured values to calculate the enthalpy, density, and electrical conductivity. The typical plasma parameters in the experiment with an exploding wire are follows: the maximum pressure is $0,5\,GPa$ and the temperature range is $(5 \div 9) \cdot 10^3\,K$.

High–pressure electric discharges. Due to the high density of material and high level of temperature, the charged particle concentration in a plasma of high–pressure electric arcs and discharges is equal to $10^{18} \div 10^{21}\,cm^{-3}$ at pressures $\geq 1\,MPa$. It should be noted that in such plasma, the nonideality parameter may reach substantial values. Pulsed discharges in gases are generated upon discharging a battery of capacitors through an inter-electrode gap. One of the possible designs for a discharge tube is shown in Figure 4 (Radtke, Guenter, 1976).

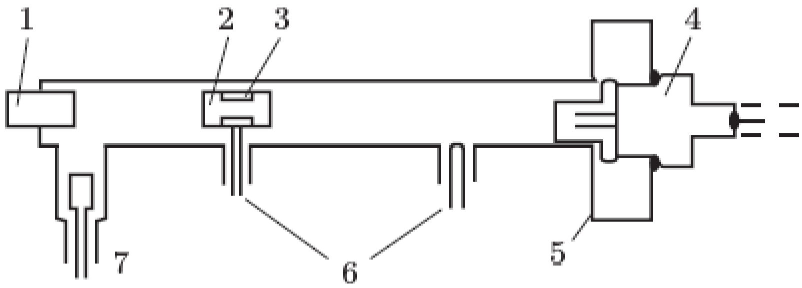


*Figure 4. Schematic diagram of high pressure discharge tube. 1 - quartz window; 2 - auxiliary electrode; 3 - steel ring; 4 - pressure sensor; 5 - cathode; 6 - tungsten probes; 7 - anode.*

It consists of a quartz tube with four electric leads: anode, cathode (with a pressure sensor), and two measuring probes. Inside the tube, a movable auxiliary electrode for ignition is mounted. The tube has a length of $10\,cm$ and a diameter of $1\,cm$. It is filled with an inert gas at an initial pressure of up to $0,1\,MPa$. The typical plasma parameters are as follows: $p = 0,1\,GPa$; $T = 18 \cdot 10^3\,K$; $n_e = 10^{18} \div 10^{19}\,cm^{-3}$; $\Gamma = (1 \div 2,3)$.

Conclusion. In the first method (plasma heating in furnaces) the homogeneous volumes of plasma is obtained but the plasma temperature is restricted of $3000\,K$ due to the thermal resistance of structural materials. The methods of the Joule heating include high–pressure gas discharges, the explosion of conductors, discharges in liquids, and some other techniques. By these methods the plasma can be generated at considerably higher temperatures of up to $10^5\ K$ but there are some difficulties concerning with the homogeneity of plasma volumes and by various plasma instabilities.

## Dynamic Methods of Nonideal Plasma Generation

Here we consider the principally different dynamic methods of nonideal plasma generation. Notice that by these methods the highest plasma parameters can be obtained. These methods are based on the accumulation of energy in the investigated material, or on the viscous dissipation in the front of shock waves which propagate throughout the material to cause its compression, acceleration, and irreversible heating, or as a result of adiabatic variation of pressure in the material.

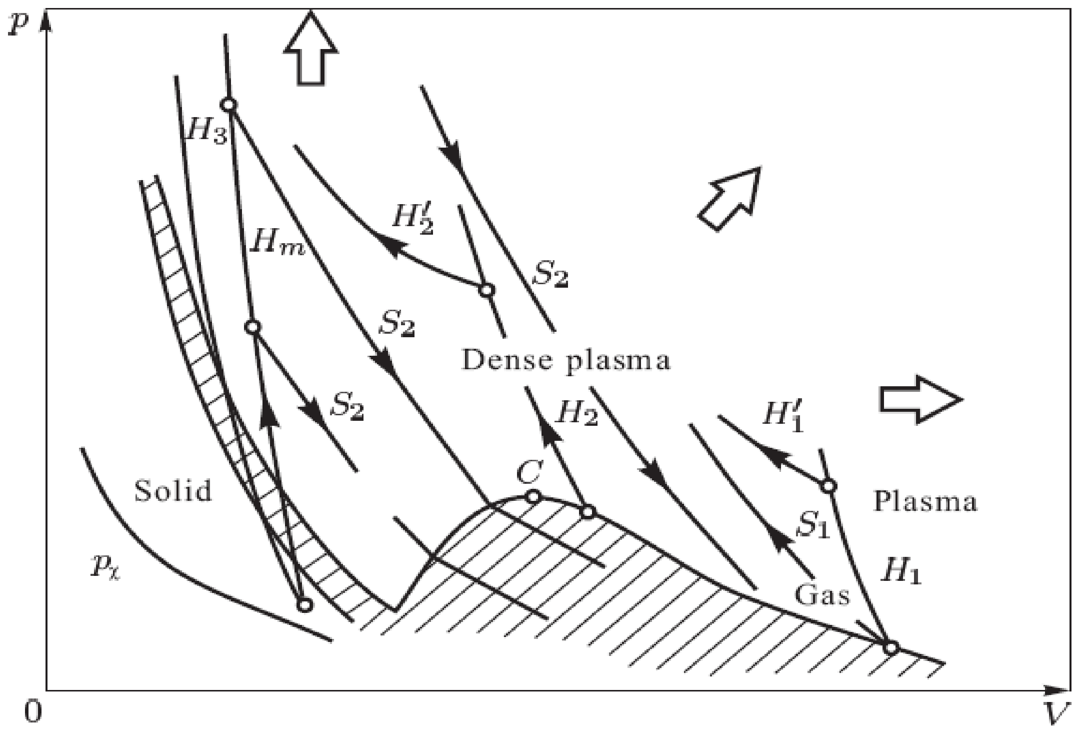


*Figure 5. Schematic presentation of the principles of dynamic generation of plasma. $p_x$ is the boundary of maximum compressions of the material, i.e., the "cold" (T = 0 K) compression curve. The shaded areas show two–phase regions of melting and evaporation. $C$ is the critical point. Circles indicate the initial states of the medium. $H_1$ and $H_2$ are the curves of cesium and inert gas compression by incident and reflected ($H_1'$ and $H_2'$) shock waves. $H_3$ and $H_m$ are the curves of shock-wave compression of solid and porous metals. $S_1$ is the curve of adiabatic compression of cesium. $S_2$ is the unload adiabats of shock–compressed metals.*

The technique of dynamic generation of plasma consists the following methods:

- the adiabatic compression of gases (curve $S_1$);
- the shock–wave compression of gases (curves $H_1$ and $H_2$);
- the shock–wave compression of solid matter (curves $H_3$ and $H_m$);
- the adiabatic expansion of shock–compressed matter ($S_2$).

The main advantages of these methods are

- the high purity and homogeneity of the investigated volume;
- the absence of electric and magnetic fields (hampering the diagnostics and causing the development of various instabilities in the plasma);
- the possibility of obtaining extremely high parameters of plasma;
- on the basis of the general laws of conservation of mass, momentum, and energy we can obtain the thermodynamic characteristics of plasma by the registration of the kinematic parameters of the shock waves(i.e., by the measurement of times and distances).

The adiabatic and shock-wave compression of gases. As an example we consider the dynamic compression of the cesium plasma because cesium has the lowest ionization potential $3{,}89\,eV$ and we have high charge concentration $n_e$ at moderate temperatures and a substantial value of the nonideality parameter. Therefore, cesium is the most popular element in nonideal plasma experiments.

Figure 6 shows schematic diagram of experimental setup on the basis of the pneumatic, diaphragm shock tube for dynamic compression of cesium vapors (V.Fortov e.a., 1976). The experimental apparatus with a length of $4\,m$ and an inside diameter of $4{,}5\,cm$ was heated to $700\,C$. An ionizing shock wave emerged upon expansion to saturated cesium vapor of helium, argon or their mixtures precompressed to about $0{,}1\,GPa$.

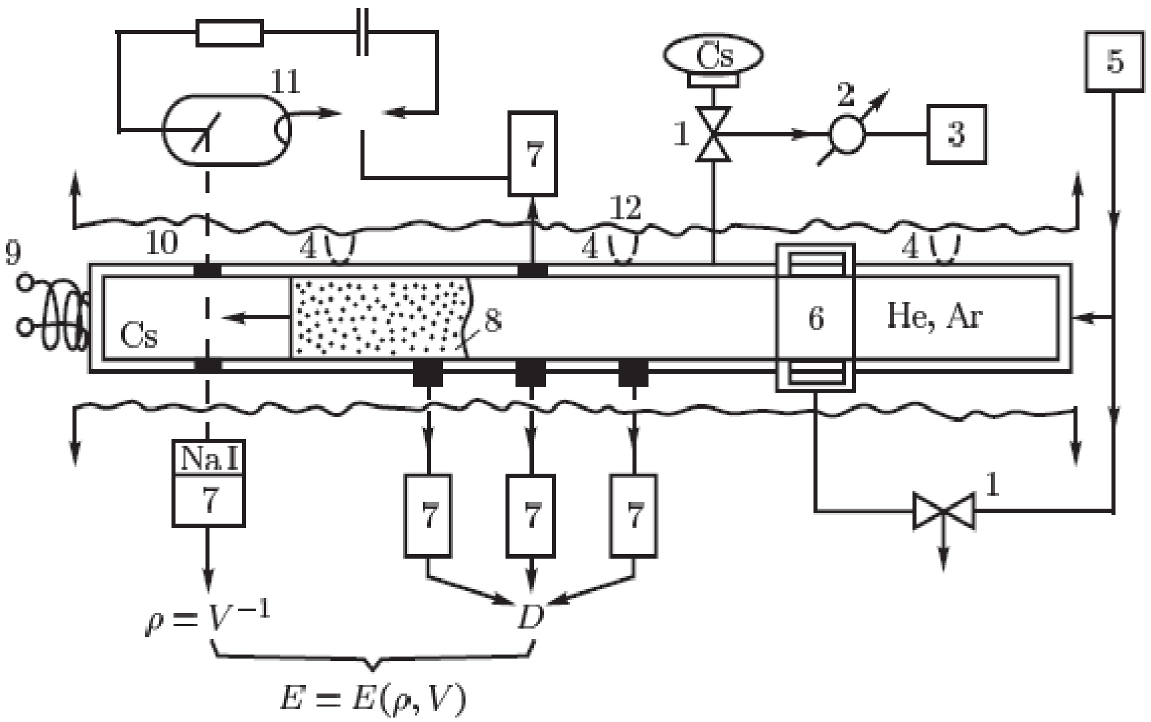


*Figure 6. The schematic diagram of a heated cesium shock tube. 1 - air–operated valves; 2 - system for measuring the initial cesium pressure; 3 - liquid cesium vessel; 4 - thermocouples; 5 - propelling gas; 6 - diaphragm unit; 7 - photomultipliers; 8 - shock– compressed plasma; 9 - electrical conductivity measuring coil; 10 - beryllium windows; 11 - X–ray tube; 12 - electric heater.*

For determination of physical characteristics of plasma the corresponding diagnostic methods should be developed. The dynamic diagnostic methods are based on the using of the relationship between the thermodynamic properties of the investigated medium and the experimentally observed hydrodynamic phenomena. (Zel'dovich and Raizer 1966). It is known that the laws of conservation of mass, momentum, and energy are satisfied in the front of the shock wave upon propagation of a stationary shock–wave through the material:

$$\begin{cases} \upsilon/\upsilon_0 = (D-u)/D; \\ p = p_0 + Du/\upsilon_0; \\ E - E_0 = (1/2)(p+p_0)(\upsilon_0 - \upsilon) \end{cases}, \qquad (2)$$

where the subscripts "0" denote the parameters of material before the front of the shock wave; $D$ is the shock velocity; $u$ is the mass velocity in the front of the shock wave; $E$, $p$, $\upsilon$ are the specific internal energy, the pressure and the specific volume, respectively. It is seen that the hydrodynamic and thermodynamic characteristics of the material can be derived from the recording of any two out of five parameters characterizing the shock wave $E, p, \upsilon, D, u$. Usually the shock velocity $D$ is measured most readily and accurately using the well known techniques. The choice of the second measured parameter depends on the actual experimental conditions.

The typical plasma parameters are as follows: $p = (0{,}1 \div 20) GPa$; $T = (0{,}1 \div 2) \cdot 10^5 K$; $n_e = 5 \cdot 10^{15} \div 5 \cdot 10^{22} cm^{-3}$; $\Gamma = (0{,}2 \div 3{,}2)$.

The adiabatic expansion of shock–compressed matter. In such experiments the isentropic expansion curves for shock–compressed matter (curve $S_2$, see Fig.5) are described by the Riemann integrals:

$$\begin{cases} \upsilon = \upsilon_H + \int\limits_p^{p_H} \left( \dfrac{du}{dp} \right)^2 dp \, ; \\ E = E_H - \int\limits_p^{p_H} p \left( \dfrac{du}{dp} \right)^2 dp \end{cases} \qquad (3)$$

These quantities are calculated along the measured isentrope $p_S = p_S(u)$. By recording under different initial conditions and shock–wave intensities, one can determine the caloric equation of state $E = E(p, \upsilon)$ in the region of the $p - \upsilon$ diagram. The experimental results for cooper demonstrate that the adiabatic expansion from the states on the shock adiabat with $p \sim 1410\, GPa$, $T \sim 5 \cdot 10^4 K$, $\upsilon \sim 0{,}052\, cm^3 g^{-1}$ leads to a weakly nonideal plasma with the following parameters $p \sim 0{,}73\, GPa$; $T \sim 9200 K$; $\upsilon \sim 1{,}3\, cm^3 g^{-1}$ and $\Gamma \sim 0{,}1$.