*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-5.031 (2006)*

Electrical conductivity of strongly coupled tungsten plasma: measurements interpretation using different equations of state

S.I. Tkachenko, P.R. Levashov, K.V. Khishchenko

Institute for High Energy Densities, Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia

Strongly coupled plasma is used commonly in fundamental research and high technology applications [1]. For a prediction of plasma dynamics it is necessary to know its thermophysical properties depending on temperature T and density ρ. There are a scant set of experimental data on plasma properties in the range of $T \sim 1$–5 eV and $\rho \sim 1$ g/cm^3 so far. A reliable theoretical model of plasma transport coefficients in this range of parameters does not exist also. Therefore an investigation of equation of state (EOS) and transport properties of plasmas in the mentioned range of parameters is very interesting.

Optical opacity of plasma impoverishes significantly diagnostic techniques of experiments. In this case a volumetric homogeneity of a studying sample is a principal requirement for specific quantities determination.

A new method for measurements of the electrical conductivity of plasma based on explosion of metal foils under high-power current pulse was proposed recently [2]. In the present paper we study the influence of EOS model on the interpretation of data from experiment [2] for tungsten.

The measurements [2] were carried out in a plane geometry. A tungsten foil stripe with the length $l_z = 10$ mm, width $h = 1.5$ mm and thickness $2a = 20$ μm was placed between two glass plates with the thickness $a_1 = 5$ mm. Side slits were shielded with thin mica stripes. In the experiment under consideration the skin layer thickness δ is significantly larger than the foil thickness. Cartesian coordinate system is introduced as follows: *x*-axis is perpendicular to the foil plate, *y*-axis is directed along the smaller side of the foil, and *z*-axis — along the bigger side. In 1D process the foil expands along the *x*-axis, the magnetic induction B is directed along the *y*-axis, and the heating current I as well as the electric field intensity E are directed along the *z*-axis.

The foil was heated by the current pulse; the time dependencies of the current through the sample $I(t)$ and voltage drop $U(t)$ were registered. Then it was calculated the resistive part of the voltage drop $U_R(t)$, electrical resistance $R(t) = U_R(t)I^{-1}(t)$ and Joule heating rate $Q_t(t) = U_R(t)I(t)$. Other values required for conductivity calculation can be obtained by means of numerical simulation. Assuming that the current density j is distributed uniformly over the cross-section of the foil and depends only on time, i.e. $j(t) = I(t)S^{-1}(t)$, where $S(t) = 2a(t)h$,

from the Maxwell equation $j(t) = \mu^{-1}\partial B/\partial x$ (SI system of units is used, μ is the magnetic permeability) one can calculate $B(t,x) = \mu I(t)xS^{-1}(t)$. So it is possible to determine the x–t-dependencies of foil parameters as a numerical solution of only a set of hydrodynamic equations with the Ampere force $jB = \mu I^2(t)xS^{-2}(t)$ and energy input $jE = Q_t(t)V^{-1}(t)$, where $V(t) = S(t)l_z$ is the foil volume.

The results of calculation by such a technique not allowing for magnetic field diffusion were presented in [2].

Assuming that spatial perturbations of the sample form are small and electron and ion temperatures are the same, as well as neglecting the thermal conductivity effect, the set of 1D magnetohydrodynamic (MHD) equations in Lagrangian description for the foil heating can be represented as follows:

$$\mathrm{d}m/\mathrm{d}t = 0, \tag{1}$$

$$\rho\,\mathrm{d}\upsilon/\mathrm{d}t = -\partial P/\partial x - (2\mu)^{-1}\partial B^2/\partial x, \tag{2}$$

$$\rho\,\mathrm{d}\varepsilon/\mathrm{d}t = -P\partial\upsilon/\partial x + j^2/\sigma_w, \tag{3}$$

$$\mathrm{d}(\mu B)/\mathrm{d}t = \partial(\sigma_w^{-1}\partial B/\partial x)/\partial x, \tag{4}$$

where m is the mass, υ is the particle velocity, P is the pressure, ε is the specific internal energy, σ_w is the electrical conductivity. The initial conditions for the set of equations (1)–(4) are written as follows: $\rho(x,0) = \rho_0$, $\upsilon(x,0) = 0$, $P(x,0) = P_0$, $B(x,0) = 0$. The conditions on the symmetry plane $x = 0$ and on the surface $x = a(t)$ of the foil, as well as on the outer boundary of the glass plate $x = a_1$ are as follows: $\upsilon(0,t) = 0$, $\upsilon(a,t) = \mathrm{d}a/\mathrm{d}t$, $\upsilon(a_1,t) = 0$, $B(0,t) = 0$, $B(a,t) = \mu I(t)/2h$, $\partial P/\partial x|_{x=0} = 0$, $P(a-0,t) = P(a+0,t)$, $P(a_1,t) = P_0$. Here ρ_0 and P_0 correspond to normal conditions.

We used three different EOS models for tungsten [3–5]. Semiempirical multi-phase EOS [3] in a form of functions $P = P(\rho,T)$ and $\varepsilon = \varepsilon(\rho,T)$ (EOS1) takes into account the effects of melting, evaporation and ionization. This EOS agrees with the collection of experimental data on isothermal and shock compression as well as on adiabatic and isobaric expansion of the metal, see details in [3]. Caloric EOS [4] in a functional form $P = P(\rho,\varepsilon)$ (EOS2) neglects phase transitions; however it describes available shock-wave data within a good accuracy. The soft-sphere EOS [5] as functions $P = P(\rho,T)$ and $\varepsilon = \varepsilon(\rho,T)$ with coefficients from [6] (EOS3) allows for evaporation and has been calibrated using isobaric expansion experiments but does not take into account melting and gives understated density at normal temperature and pressure. To describe the properties of glass we used caloric EOS $P = P(\rho,\varepsilon)$ [7].

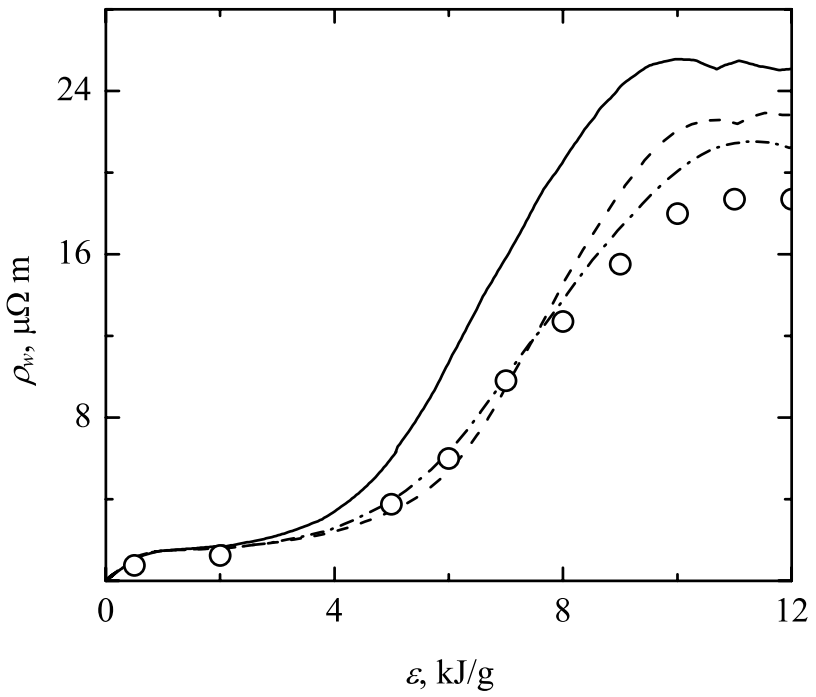

Figure 1: Resistivity of tungsten versus specific internal energy in the foil during heating from calculations based on measurements [2]: circles are from simulations [2], lines correspond to the present modeling with EOS1 (solid line), EOS2 (dashed line) and EOS3 (dash-dotted line)

The electrical conductivity of tungsten was determined by the relation

$$\sigma_w = I(t) l_z [U_R(t) S(t)]^{-1} \tag{5}$$

using the experimental dependencies $I(t)$ and $U_R(t)$ [2] except for the stage of heating up to $T = 10$ kK. In case of EOS1 at $T < 10$ kK we used the semiempirical formulae [8–10] for the conductivity $\sigma_w = \sigma_w(\rho, T)$ taking into account melting effect instead of experimental functions because of noise on the measured time dependence of voltage at the initial stage. In cases of EOS2 and EOS3 during the initial stage we used time dependence of voltage $U_R(t)$ obtained in numerical modeling with EOS1 to determine the electrical conductivity according to (5).

We carried out a number of simulations of the experiment using 1D MHD model as described above. Modeling shows that pressure, density and temperature are distributed almost homogeneously across the foil except for the moment of melting which is clearly distinguishable by pressure oscillations. After melting thermodynamic states of the foil though sometimes very close to the binodal are always in liquid or supercritical plasma state.

The EOS model used in [2] for the interpretation of experimental data is based upon the soft-sphere EOS [5] and takes into account ionization effects according to the mean ion model [11]. As one can see in Fig. 1, distinctions in the methodology of simulation and description of ther-

modynamic properties of tungsten lead to systematically higher values of electrical resistivity $\rho_w = \sigma_w^{-1}$ in our interpretation than in [2]. Maximum excess is $\Delta\rho_w/\rho_w \sim 0.6$ for simulation with EOS1.

Thus even in the case of the foil heating regime [2], where certain efforts have been taken for achievement of homogeneous distribution of thermophysical parameters to simplify interpretation, there are still open problems to treat experimental data. We believe that further investigations of thermodynamic and transport properties of tungsten plasma will be helpful for the creation of adequate wide-range EOS and electrical conductivity models.

The authors are grateful to V.N. Korobenko, A.D. Rakhel and A.I. Savvatimskiy for valuable comments. This work was done under financial support of the Russian Foundation for Basic Research, grants No. 04-02-17292, 05-02-16845 and 05-02-17533.

References

[1] V. Fortov, I. Iakubov and A. Khrapak, Physics of Strongly Coupled Plasma (New York: Oxford University Press, 2006)

[2] V.N. Korobenko, A.D. Rakhel, A.I. Savvatimskiy and V.E. Fortov, Plasma Phys. Rep. **28**, 1008 (2002)

[3] K.V. Khishchenko, in: Physics of Extreme States of Matter — 2005, ed. V.E. Fortov et al. (Chernogolovka: IPCP RAS, 2005), p. 170

[4] K.V. Khishchenko, Tech. Phys. Lett. **30**, 829 (2004)

[5] D.A. Young, A soft-sphere model for liquid metals, Lawrence Livermore Laboratory Report UCRL-52352 (1977)

[6] H. Hess, A. Kloss, A. Rakhel and H. Schneidenbach, Int. J. Thermophys. **20**, 1279 (1999)

[7] K.V. Khishchenko, I.V. Lomonosov and V.E. Fortov, in: Shock Compression of Condensed Matter — 1995, ed. S.C. Schmidt and W.C. Tao (New York: AIP Press, 1996), p. 125

[8] H. Knoepfel, Pulsed High Magnetic Fields (Amsterdam: North Holland, 1970)

[9] S.I. Tkachenko, K.V. Khishchenko, V.S. Vorob'ev, P.R. Levashov, I.V. Lomonosov and V.E. Fortov, High Temp. **39**, 728 (2001)

[10] S.I. Tkachenko, K.V. Khishchenko and P.R. Levashov, Int. J. Thermophys. **26**, 1167 (2005)

[11] M.M. Basko, High Temp. **23**, 388 (1985)