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Electrical Conductivity of Strongly Coupled Zinc Plasmas - First Results

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Abstract

Measurements are reported of the electrical conductivity of strongly coupled zinc plasmas in the temperature range 7 - 15 kK, in a density range from about nearly solid state down to 4 g cm^{-3}. The plasmas were created by rapid vaporization of metal zinc wires surrounded by glass capillaries. The capillaries guarantee longer confinement times. The measurements are compared with some data from Kloss et al. [1], Otter et al. [2] and theoretical calculations by Likalter [3] and Ziman [4].

1 Introduction

In a previous paper [5], measurements of the electrical conductivity of nonideal carbon plasmas having densities of the order 10^{22} cm^{-3} and temperatures between 8 and 25 kK were presented. Now the same facilities where used with zinc wires.

The electrical conductivity of nonideal plasmas is a fundamental quantity and its measurement, therefore, of high interest to verify or to stimulate new theories. Especially the electrical conductivity of such plasmas near the critical point is actually of great interest. According to Mott [6] the conductivity of mercury near the critical point decreases rapidly and attains values below the minimum metallic conductivity ($\approx 200\ \Omega^{-1}\text{cm}^{-1}$). That means mercury reaches the metal-nonmetal transition inside the liquid phase at densities higher than the critical density. According to Likalter [3] and Hess and Schneidenbach [7] zinc should show a similar behaviour at higher than critical density. Kloss et al. [1] performed some measurements with zinc.

The present investigation extends these data to higher densities. In the overlapping density range the results agree very well with those of Kloss et al. [1].

To produce nonideal plasmas with near-solid-state densities and temperatures lower than 25 kK the technique of rapid vaporization of wires by a pulsed current (exploding wire) is commonly used. This method is working well only for metal wires, because the high conductivity of metals ensures a fast and homogeneous energy input.

Nonideal plasmas are characterized by the coupling parameter $\mathit{\Gamma}$. It is defined as the ratio of the mean potential energy to mean kinetic energy:

$$\mathit{\Gamma} = \frac{Z^2 e^2}{4\pi\epsilon_0 k T d_i}, \qquad d_i = \sqrt[3]{3/4\pi n_i}. \tag{1}$$

It is determined by the ion temperature T and the ion density n_i. Relating to the following measurements, $Z = 1$.

2 Experimental set-up

The wire is surrounded by a glass capillary to achieve a longer confinement time of the exploding plasma. The arrangement of the two electrodes holding the wire is shown in Fig. 1. Two capacitors connected in parallel, totalling 3.86 μF are charged to at least 14 kV to ensure vaporization of the wire. The energy of the capacitors is more than twice the energy of evaporation. They are discharged by closing a low-inductive pressurized spark gap switch. A total inductance of only 154 nH makes sure that the current can rise rapidly. A Rogowski coil surrounds one electrode to measure the time derivative of the current. The voltage is measured with two coaxially designed resistive voltage dividers Fig. 1. The emitted light is observed with two different spectrometers and an OMA system. A Planck curve is fitted to the spectrum to determine the temperature of the optically thick LTE plasma. The time depending radius of the plasma is recorded by an ICCD camera and a streak camera.

The purity of the wire is greater than 99.97 %. The length is $l_D = (24.5 \pm 0.5)$ mm. The radius is $r_D = (0.19 \pm 0.005)$ mm. The inner radius of the capillary is $r_{ci} = (0.2 \pm 0.005)$ mm.

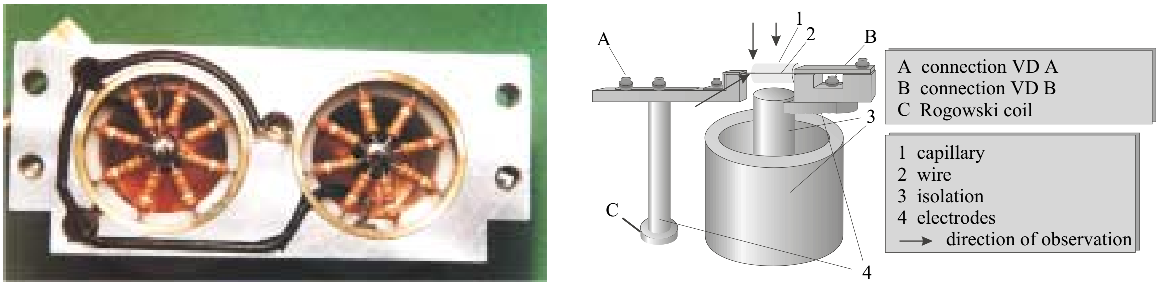

Fig. 1: Inner part of the voltage dividers and the arrangement of the electrodes

2.1 Conductivity measurements

The voltage measured with the two voltage dividers consists of a resistive and an inductive component $U = IR + d/dt(LI)$. At the beginning of the discharge, the inductive component becomes important. Later the resistive component dominates. Since the change in inductance due to phase transitions is negligibly small, solving for the plasma conductivity σ yields

$$\sigma = \frac{l}{RA} = \frac{I}{U - L_D \dot{I}} \frac{l}{\pi r^2}. \tag{2}$$

The derivation of the current is measured with the Rogowski coil. After the calibration and determination of the integration constant one obtains the current by integrating the Rogowski signal.

Small disturbances of density propagate with the local sound speed c_s and therefore the expansion will be homogeneous in the case when $c_s \cdot t \leq d$ (d: diameter of the plasma, t: characteristic time). While the capillary is surrounding the plasma, the unequation will fulfil very well. Also the skin depth is larger than the radius of the plasma. Therefore the plasma can be considered to be homogeneous.

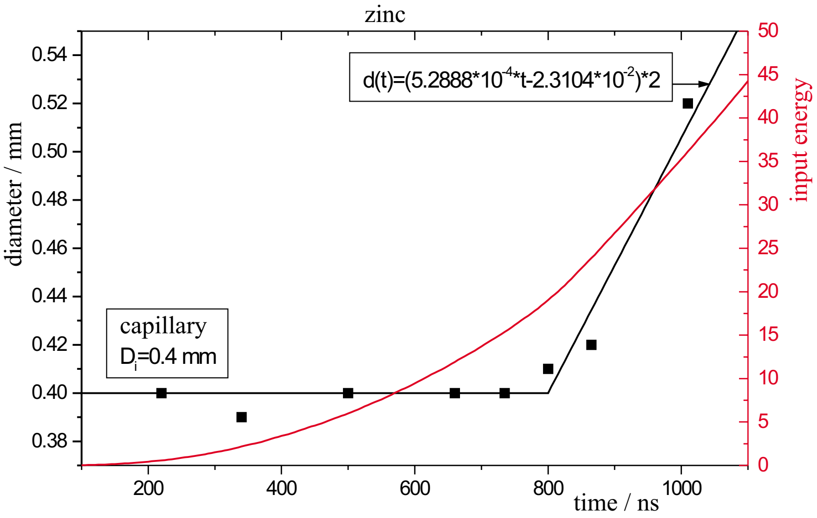

Fig. 2: Diameter and input energy of the zinc plasma

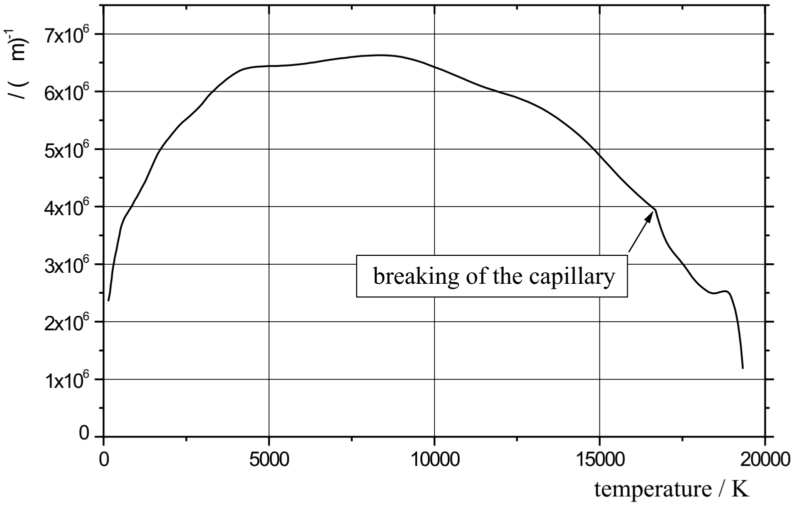

Fig. 3: Conductivity in relation to the temperature

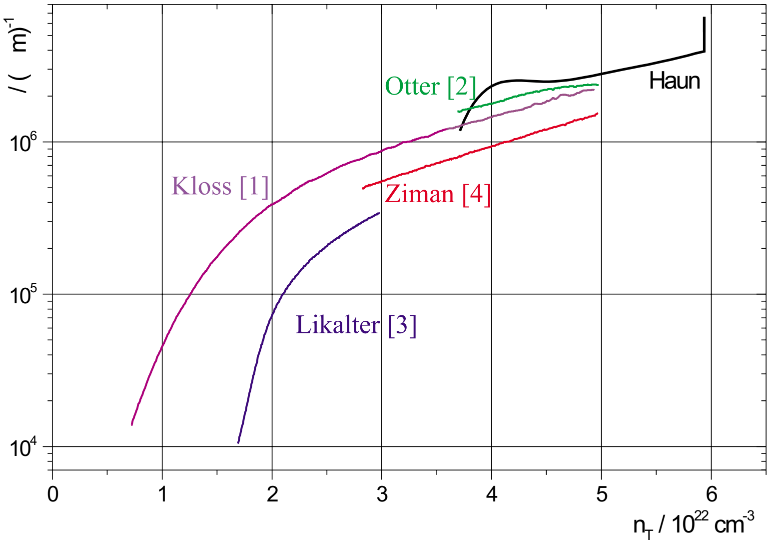

Fig. 4: Comparison of some measured and calculated conductivities of zinc

3 Results

In Fig. 5, the behaviour of the current through and the ohmic voltage across the plasma are shown. The curves are averaged data from over 40 shots. The maximum current is about 40 kA and the maximum voltage is up to 6 kV.

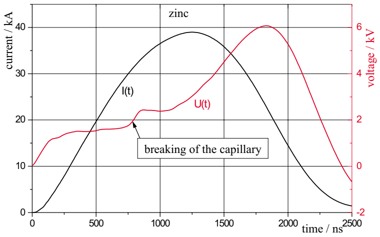

Fig. 5: Measured current and voltage during time

800 ns after the beginning of the discharge the capillary is breaking. The plasma is homogeneous while the capillary is surrounding the plasma. After breaking, sausage and kink instabilities can be seen in the ICCD pictures. Therefore the resulting conductivity makes only sense up to the breaking point of the capillary. The moment of breaking can be seen on some ICCD pictures and in the voltage signal.

Figure 2 shows the diameter and the input energy of the plasma. The plotted energy is the effective energy which is transferred into the plasma. The energy for heating up the wire and the two phase transitions (solid-liquid, liquid-gas) on the one hand and the work on the capillary (compression of the glass) on the other hand are subtracted before.

The conductivity in relation to the plasma temperature is shown in Fig. 3. The temperature is calculated from the input energy. In earlier measurements it was shown that these calculations agree rather well with spectroscopic measurements.

The comparison between the present data, some other measurements and calculations of the electrical conductivity of zinc is shown in Fig. 4. The new measurements give results for high (up to nearly solid state) densities and, at the low density end, fit well with the results of Kloss et al. [1] and of Otter et al. [2].

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