

Conductivity Measurements of Nonideal C Plasmas

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Abstract

We report measurements of the conductivity of nonideal C-plasmas. They are produced by evaporating a carbon-wire placed in a capillary within some hundred nanoseconds. Homogeneity of the plasma is obtained by the use of a 'pre-heating-system' which heats the wire before the main discharge. This way the initial resistivity of the wire is decreased, the discharge time is shortened. The reproducibility of the plasma is enhanced, the growth of instabilities is reduced. The conductivity is measured during 1 ms of the discharge. The particle density is of the order of 10^{22} cm^{-3} while the electron temperature is varying between 8000 K and 25000 K, the electron density is about 10^{18} cm^{-3} . The temperature is measured spectroscopically by fitting a Planck curve to the spectrally resolved emission profile. The results are compared with theories from Spitzer, Ziman and the SESAME-data.

1 Introduction

The electrical conductivity of nonideal plasmas is a fundamental quantity and its measurement, therefore, of high interest to verify or to stimulate new theories. Theories of Spitzer [1] and Ziman [2] for ideal plasmas or conducting liquids, respectively, are not able to describe the behaviour of such plasmas. Also newer theories of Lee and More [3], Djuric [4] and the QEOS model [5] do not fit experimental values very well. Only the recent partially ionized plasma model (PIP) of Redmer gives conductivities for hydrogen, dense aluminum and copper plasmas [6], which agree reasonably with measurements on copper and aluminum plasmas carried out at the Bochum facility [7, 8]. DeSilva made some other good measurements with copper and aluminum plasmas in water [9].

To produce nonideal plasmas with near-solid-state densities and temperatures lower than 25000 K 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. In contrast to this, the conductivity of carbon is three orders of magnitude smaller. Carbon is the first metal like element in the periodic system that can be handled in the laboratory without special security equipment. Therefore conductivity measurements were attempted in the past, but because of the low electrical conductivity of carbon it was not possible to produce a homogeneous carbon plasma. In this work we accomplished this with a preheating system.

Nonideal plasmas are characterized by the coupling parameter Γ . It is defined as the ratio of the mean potential energy to mean kinetic energy:

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

It is given by the ion temperature T and the ion density n_i . Relating to the following measurements, Γ is set to $Z = 1$. The coupling parameter in our carbon plasma is in the range of $1 \leq \Gamma \leq 8$.

2 Experimental setup

The wire is surrounded by a glass capillary to achieve a longer confinement time of the exploding plasma. The arrangement in the discharge chamber is shown in Fig. 1. Two capacitors connected in parallel, totaling $3.86 \mu\text{F}$ are charged to at least 14 kV to ensure vaporization of the wire. 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 resistive voltage dividers. The emitted light is observed with two different spectrometers and an Optical Multichannel Analyser (OMA) system. A Planck curve is fitted to the spectrum to determine the temperature of the optically thick Local Thermal Equilibrium (LTE) plasma. The time depending radius of the plasma is recorded by an Intensified Charge Coupled Device (ICCD) camera and a streak camera. The purity of the wire is greater than 98 %. The length is $l_D = (24.5 \pm 0.5) \text{ mm}$. The radius is $r_D = (0.135 \pm 0.005) \text{ mm}$. The inner radius of the capillary is $r_{Ki} = (0.145 \pm 0.005) \text{ mm}$.

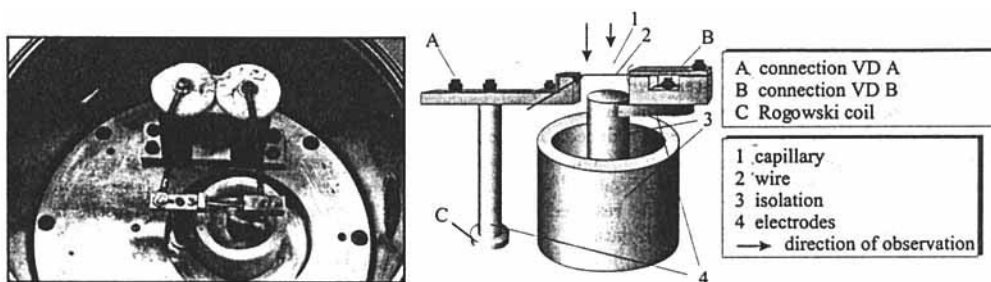


Figure 1: Inner part of the discharge chamber.

2.1 The preheating system

The conductivity of graphite at 0°C ($\sigma_C = 28 \times 10^3 (\Omega\text{m})^{-1}$) is three orders of magnitude smaller than the conductivity of copper. Therefore, the energy input is smaller at the beginning of the discharge. In contrast to metals, the conductivity of carbon increases with increasing temperature. As a result the plasma heats up more at the surface than in the core. The higher current density at the surface at the beginning (skin effect) and the low heat conductivity of air leads a higher temperature at the surface. This causes a higher conductivity there. This self amplifying process is responsible for an inhomogeneous plasma. In some cases the wire is not exploding at all.

We built a preheating system which heats the wire for about 1 second before the main discharge by a DC current (1 A). The wire is glowing red before the main discharge is triggered. With this preheating system it was possible to produce a homogeneous plasma. Further advantages are the reduction of contact problems and a faster and higher energy input at the beginning of the discharge.

2.2 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

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

3 Data analysis and results

It is interesting to compare the behaviour of the current to previous measurements with other materials at the same experiment, see Fig. 2. The current through carbon is not as high as the current through metals.

The radius of the wire is constant for $t < 190$ ns. After a linear expansion the radius of the plasma is decreasing because of the pinch effect.

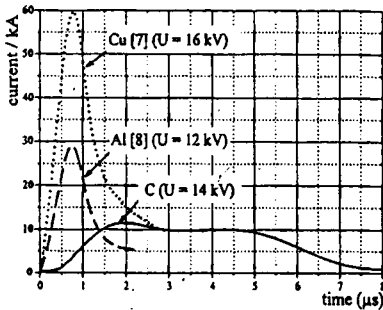


Figure 2: Time traces of current (solid line) in relation to earlier measurements [7], [8].

The conductivity as a function of particle density is shown in Fig. 3. The temperature is different at the same density before and after pinching because of the energy input during the discharge. Hence, expansion and compression are nonadiabatic.

In the analysis, we have assumed that the plasma fills the column uniformly and that we have a homogeneous plasma. The good reproducibility of the discharge, the behaviour of the current and voltage, and the pictures of the ICCD camera are indicators for this. It is also checked that the sound speed in the material is always higher than the expansion rate. Also the product of sound speed c_s and characteristic time t is always smaller than the radius of the plasma r : $c_s \cdot t \ll r$.

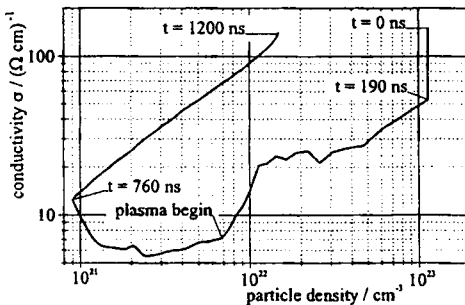


Figure 3: Conductivity as a function of particle density.

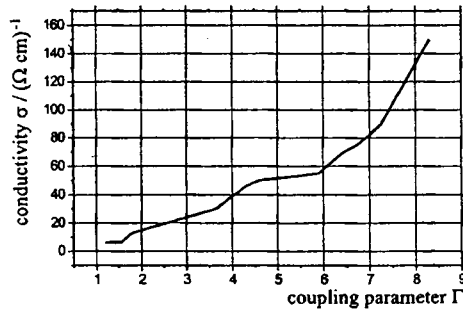


Figure 4: Conductivity as a function of the coupling parameter.

Similar to nonideal copper [7] and aluminum [8] plasmas, the measured conductivity rises with increasing coupling Γ , as shown in Figure 4.

As expected, the theories of Ziman, Spitzer and the SESAME-datas do not fit the conductivities for all temperatures (Figure 5), although at the lowest temperature the Ziman theory agrees well and at the highest temperature the SESAME data.

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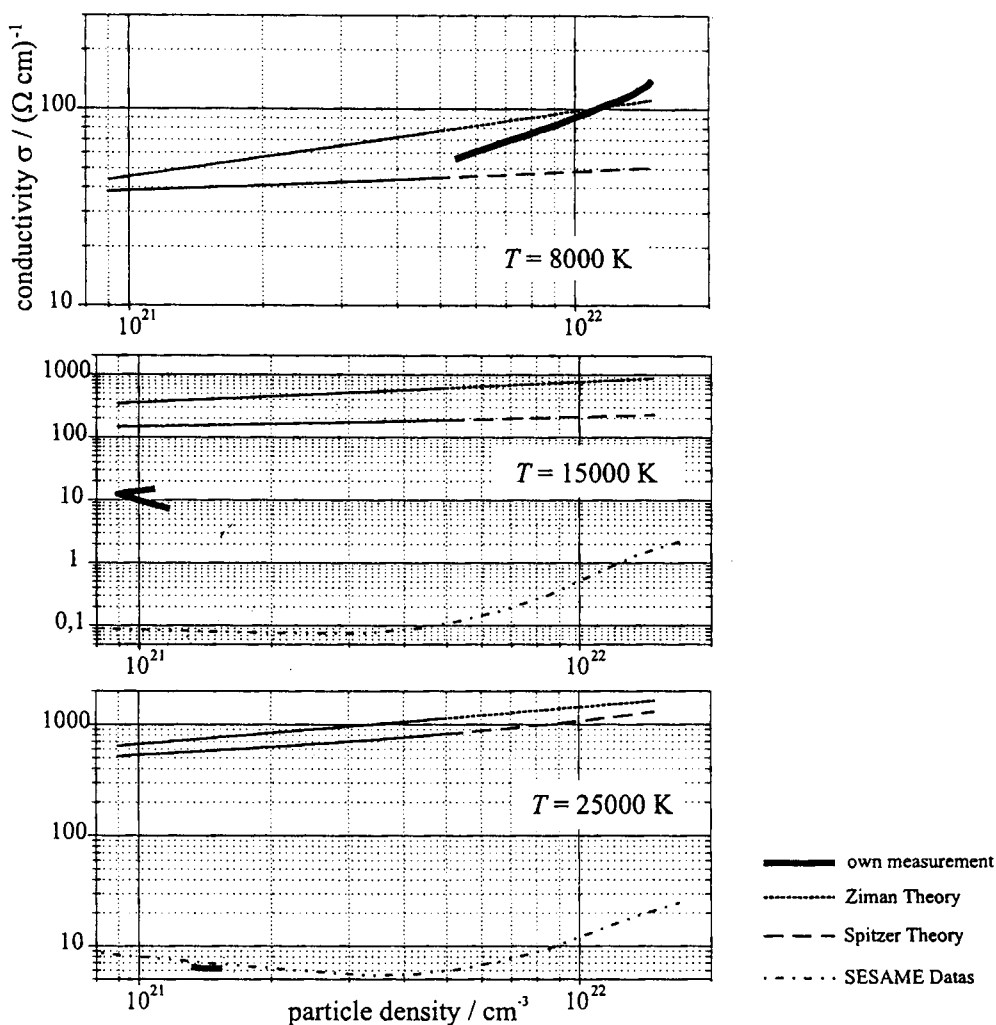


Figure 5: Conductivity as a function of particle density for various temperatures.

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