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2006 J. Phys. A: Math. Gen. 39 4341

(http://iopscience.iop.org/0305-4470/39/17/S05)

Institute of Physics Publishing Journal of Physics A: Mathematical and General

J. Phys. A: Math. Gen. **39** (2006) 4341–4346 doi:10.1088/0305-4470/39/17/S05

Measurements of static electrical conductivity of a dense plasma in a magnetic field

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Received 28 September 2005, in final form 29 January 2006
Published 7 April 2006

Abstract

New experimental setup for generation of a non-ideal plasma, placed in a magnetic field of up to 25 T, is presented. The plasma generation technique is based on gas compression and heating behind the front of a shock wave with the use of an explosively driven linear generator. The magnetic field is produced by a discharge of a capacitor through a solenoid reeled on the generator channel. DC electrical conductivity of the plasma is determined by two and four contact techniques. Possibilities of magnetized dense plasma generation are discussed.

PACS numbers: 52.25.Fi, 52.27.Gr, 52.50.Lp, 52.70.Ds

Introduction

Description of properties of non-ideal plasmas $\Gamma = E_C/E_K \geqslant 1$ is of great interest for physics at high energy densities and some technical applications [1]. The degree of plasma non-ideality is defined by the coupling parameter Γ, which represents the ratio of average potential energy of Coulomb interaction E_C per particle and average thermal energy E_K per particle. In the limit of weakly non-ideal ($\Gamma \ll 1$) low-density plasmas strict theoretical expressions for static electrical conductivity were obtained in [2] for fully ionized plasmas, and in [3] for weakly ionized plasmas. Pioneer experiments on the measurement of dc electrical conductivity of the non-ideal plasma have been conducted about 40 years ago in [4, 5]. It is known [1] that the values of electrical conductivity obtained in [4, 5] appreciably deviated from the Spitzer [2] and Lorentz [3] values. So these experiments have demonstrated that the above approaches [2, 3] cannot be applied to plasmas with strong Coulomb interparticle interaction. Since that time these seminal approaches [2, 3] were generalized by various authors [6–12]. A large number of publications with experimental results on electrical conductivity of strongly coupled Coulomb systems have also been done. See [13–15] for a review of first works. In the presence of a magnetic field the conductivity is a second-rank tensor. Some models [6, 16–18] were extended to the case of plasma in a magnetic field and calculations of conductivity tensor

0305-4470/06/174341+06$30.00

were presented. Recently, we carried out experiments [19] on measurements of low-frequency ($\omega \ll \omega_{\mathrm{pl}} = \sqrt{4\pi n_{\mathrm{e}} e^2/m_{\mathrm{e}}}$) electrical conductivity σ and electronic concentration n_{e} of the non-ideal plasma placed in a magnetic field. The investigated plasma was not magnetized ($\Omega\tau < 1$). $\Omega = eH/m_{\mathrm{e}}c$ is the cyclotron frequency of electrons in a magnetic field H, and τ is the relaxation time of electrons. Now we plan new experiments with the magnetized plasma. Experimental studies of the magnetized non-ideal plasma are of great interest because it allows one to investigate the influence of a magnetic field and effects of nonideality on plasma conductivity and to check existing transport theories for the dense plasma. We report here estimates of parameters needed to magnetize the non-ideal plasma, and details on conducted experiments and the new experimental setup.

Experimental part

In our earlier work [19] we investigated the transport and thermodynamical properties of the non-ideal plasma of noble gases (Ar, Xe and He) placed in a magnetic field. The range of plasma parameters that we studied was $0.01 < \Gamma < 2.8$, $P = 20$–650 MPa and $T = 6000$–$22\,000$ K. In these experiments the plasma was generated by the dynamic method based on gas compression and irreversible heating in the front of high-power shock waves excited by explosively driven linear generators. A magnetic field with the induction of about 5 T was formed inside a solenoid reeled on the generator channel. To ensure free penetration of the magnetic field inside the moving plasma the hydrodynamic flows with small magnetic Reynolds numbers $Re_{\mathrm{m}} \ll 1$ were realized. The four-probe method was used for the determination of dc conductivity. This method is based on the measurement of voltage drop on a segment of conducting medium and the electric current flowing through it at a known factor of the measuring cell. The comparison of measured values of plasma electrical conductivity in a magnetic field and without a magnetic field has demonstrated that plasma was not magnetized. For determination of electronic concentration the four-contact method based on measurement of Hall voltage was applied. At some distance from active charge an obstacle with a measurement cell was placed inside the generator channel. Plasma diagnostics were performed in both incident and obstacle-reflected shock waves. The shock wave front velocity D was measured with the use of three pairs of probes of different lengths. D was calculated from the distances between the probes and the times of arrival of the plasma to the probes. The times of plasma arrivals to different pairs of probes were determined from oscillograms. It was shown in a special series of high-speed filming experiments that the plasma flow is one-dimensional and stationary. In this case the conservation laws at the shock-wave discontinuity are written in a simple algebraic form [20], which allows the thermodynamic parameters of a shock-compressed gas to be calculated from the measured parameters of hydrodynamic flow.

To expand the range of the used magnetic fields new constructions of solenoid and explosive generator were developed. The new explosive generator is schematically shown in figure 1. An electric current I is supplied to the shock-compressed plasma 1 by power electrodes 2 and the potential difference U caused by this current is taken from two potential electrodes 3. Electrodes are mounted on an obstacle 4, which is placed inside generator channel 5 in the centre of solenoid 6. The dc conductivity is calculated by the equation $\sigma = \frac{IK}{Uh}$ where h is the plasma thickness and K is the geometrical factor of the measuring cell, which takes into account the size of the probes and the plasma, and their mutual arrangement. This coefficient is calculated theoretically and refined by electrolytic modelling.

To increase the values of magnetic fields the inner diameter of the generator was diminished to 20 mm. A pulsed magnetic field with induction up to 25 T was generated by a discharge of a capacitor bank ($C = 1.2$ mF, $U_0 = 7$ kV) through the solenoid wound on

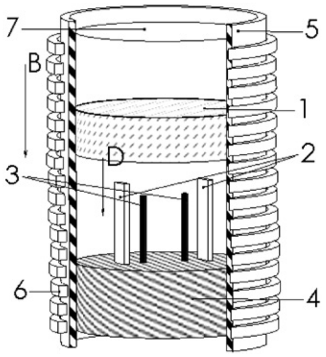

Figure 1. Linear explosive generator. 1—plasma, 2—power electrodes, 3—potential electrodes, 4—obstacle, 5—generator channel, 6—bare loop of a solenoid, 7—products of detonation.

the channel of an explosively driven generator. An inductive gauge mounted on the obstacle measured the magnetic field. The geometric factor of the solenoid $g = B/I$ was determined by measuring the dependence of magnetic induction in the centre of solenoid on the electric current. After that inductive gauge was placed inside the solenoid and was calibrated at the electric current 1–2 kA flowing through the solenoid when the latter was not deformed. The solenoid was wound by a copper wire of 1 × 5 mm, its length being 40 mm and inner diameter 22 mm. Winding of several layers of fibreglass ribbon with epoxy resign strengthened the solenoid. The maximum initial energy in the capacitance bank was $E_0 \approx 30\,\mathrm{kJ}$. This energy allowed producing a magnetic field with induction $B = \sqrt{2\mu_0 E_0/V}$ in the volume V. Taking into account real parameters of our solenoid we had to obtain the magnetic field 25–35 T. To obtain stronger magnetic fields we plan to increase the capacitance of bank and use more strong materials for solenoid winding.

We conducted first test experiments with a shock-compressed plasma of argon to determine the static electrical conductivity without a magnetic field. The initial pressure of gas $P_0 \approx 1$ bar and the temperature $T_0 \approx 300\,\mathrm{K}$. Behind the front of incident shock wave we measured the conductivity $\sigma \approx 20\,(\Omega\,\mathrm{cm})^{-1}$ for the speed of shock wave front $D \approx 3600\,\mathrm{m\,s^{-1}}$. This means that in the case of experiments with a magnetic field $Re_\mathrm{m} = \mu_0 u l \sigma \ll 1$ and the magnetic field will freely penetrate into the moving plasma. $\mu_0 = 4\pi \times 10^{-7}(\mathrm{H\,m^{-1}})$ is the permeability of free space, u is the mass speed of particles of the flow (that is less than D) and l is the characteristic scale length.

Calculations

In the experiments with magnetic fields we plan to measure dc electrical conductivity of the plasma in the direction perpendicular to the magnetic field and in the direction along the magnetic field. In the latter case the magnetic field will be produced with a Helmholtz coil, which will be set perpendicular to a generator (the magnetic field is parallel to the shock front). Here we present estimations of plasma parameters and values of the magnetic field needed to magnetize ($\Omega\tau \geqslant 1$) plasma. Under magnetization we mean only reduction of conductivity in a direction perpendicular to the magnetic field. The thermodynamic parameters and the composition of shock-compressed plasmas were calculated in frames of chemical model of the plasma using the procedure described in [21]. Corrections to thermodynamic functions due to effects of Coulomb interactions were calculated in frames of Debye approximation

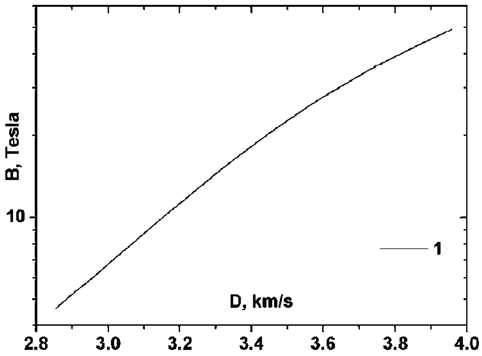

Figure 2. 1—magnetic induction needed to magnetize the plasma of Ar.

in a grand canonical ensemble. Static conductivity σ_{tr} perpendicular to the direction of the magnetic field was calculated by the expression

$$\sigma_{\mathrm{tr}} = \frac{4e^2(k_{\mathrm{B}}T)^{-5/2}}{3\sqrt{\pi}m_{\mathrm{e}}}\frac{2}{\lambda_{\mathrm{e}}^3}\int_0^\infty \frac{\varepsilon^{3/2}\tau(\varepsilon)\,\mathrm{e}^{-\frac{\varepsilon}{k_{\mathrm{B}}T}}\,\mathrm{d}\varepsilon}{1+(\Omega\tau)^2}.$$

This expression is usually derived from the moments of the classical Boltzman equation in the case of non-degenerate electron gas. $e, m_{\mathrm{e}}, \varepsilon$ are the charge, mass and kinetic energy of electrons respectively, k_{B} is Boltzman's constant and $\lambda_{\mathrm{e}} = \sqrt{\frac{2\pi\hbar^2}{m_{\mathrm{e}}k_{\mathrm{B}}T}}$ is the thermal de Broglie wavelength. The inverse electronic relaxation time is the frequency of collisions of electrons, which is the sum of frequencies of electron scatterings by atoms and ions:

$$\tau(\varepsilon)^{-1} = \nu(\varepsilon) = \nu_{\mathrm{ea}} + \sum_j \nu_{\mathrm{e}j}/\gamma_j = \sqrt{\frac{2\varepsilon}{m_{\mathrm{e}}}}\left[n_{\mathrm{a}}Q_{\mathrm{ea}}(\varepsilon) + \sum_{j=1}^{\infty} n_j Q_{\mathrm{e}j}(\varepsilon)/\gamma_j\right].$$

$Q_{\mathrm{e}j}$, Q_{ea} are the energy-dependent cross sections of electron scattering by ions and atoms respectively, n_{a} is the concentration of atoms and n_j is the concentration of ions with charge j. Energy-dependent cross sections Q_{ea} of electron–atom collisions were taken from [22]. γ_j is the factor taking into account electron–electron collisions and depending on the ionization multiplicity j [2].

The $Q_{\mathrm{e}j}$ cross sections were calculated as $Q_{\mathrm{e}j} = \frac{Z_j^2\pi e^4}{\varepsilon^2}\Lambda_j$ ($Z_j \equiv j$ is the ionic charge). $\Lambda_j = \frac{1}{2}\ln\left[1+\left(\frac{2\varepsilon r_{\mathrm{D}}}{e^2}\right)^2\right]$ is the Coulomb logarithm and $r_{\mathrm{D}} = \sqrt{\frac{k_{\mathrm{B}}T}{8\pi n_{\mathrm{e}}e^2}}$ is Debye radii.

Figures 2 and 3 represent calculations of electrical conductivity of the shock-compressed plasma (initial state of gas is $P_0 = 1$ bar, $T_0 = 300$ K) in incident shock wave without the magnetic field and calculations of values of magnetic induction needed to magnetize ($\Omega\tau \geqslant 1$) such a plasma. D is the velocity of shock wave front. The condition $\Omega\tau = 1$ means that the conductivity in the magnetic field will be decreased by a factor of 2. So our estimates showed that by using the above-described explosive generator it is possible to magnetize the weakly non-ideal ($\Gamma \leqslant 0.3$) plasma of argon in magnetic fields of 20–40 T. Behind the front reflected from an obstacle, wave states with $0.5 < \Gamma < 1$ could be reached. To magnetize such plasma magnetic fields 100–300 T are needed.

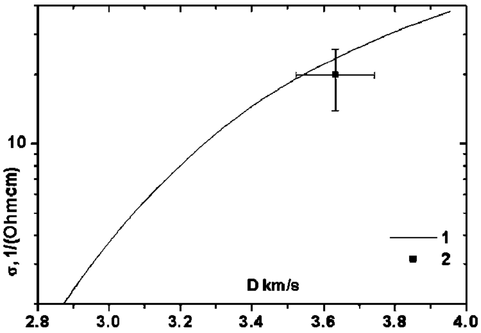

Figure 3. 1—calculated electrical conductivity of the non-magnetized plasma of Ar, 2—experimental results.

Conclusions

In this paper, we present a new construction of the explosive generator for investigation of static electrical conductivity of the shock-compressed non-ideal plasma of argon in magnetic fields up to 25 T. We have also carried out calculations of parameters of the plasma and values of the magnetic field that needed to magnetize the dense plasma of argon.

Acknowledgments

The authors are grateful to Dr V K Gryaznov for his help in thermodynamical calculations. This work is done under the financial support of the Russian Foundation for Basic Research, grant 04-02-17242 and RFBR-DFG 03-02-04012. The authors also thank the Russian Science Support Foundation, CRDF and Russian Ministry of Science and Education (grant Y2-P-11-17).

References

[1] Fortov V E and Yakubov I T 1989 *Physics of Nonideal Plasmas* (New York: Hemisphere)
[2] Spitzer L Jr and Harm R 1953 *Phys. Rev.* **89** 977
[3] Lorentz H A 1909 *The Theory of Electrons* (New York: Stechert) p 266
[4] Kikoin I K, Senchenkov A P, Gelman E B, Korsynski M M and Naurzakov S P 1965 *Zh. Exp.Teor. Fiz.* **49** 124
[5] Franck E U and Hensel F 1966 *Phys. Rev.* **147** 109
[6] Lee Y T and More R M 1983 *Phys. Fluids* **27** 1273
[7] Rinker G 1985 *Phys. Rev.* B **31** 4207
[8] Ichimaru S and Tanaka S 1985 *Phys. Rev.* A **32** 1790
[9] Ropke G and Redmer R 1989 *Phys. Rev.* A **39** 907
[10] Mihajlov A A, Ermolaev A M, Djuric Z and Ignjatovic L 1993 *J. Phys. D: Appl. Phys.* **26** 1041
[11] Tkachenko I M and Fernandez de Cordoba P 1998 *Phys. Rev.* E **57** 2222
[12] Stygar W A, Gerdin G A and Fehl D L 2002 *Phys. Rev.* E **66** 046417
[13] Wihelm H E 1982 *Plasma Phys.* **24** 1091
[14] Ivanov Yu V, Mintsev V B, Fortov V E and Dremin A N 1976 *Sov. Phys.—JETP* **44** 112
[15] Mintsev V B, Fortov V E and Gryaznov V K 1980 *Zh. Eksp. Teor. Fiz.* **79** 116
[16] Daybelge U 1969 *Phys. Rev.* **187** 296
[17] Adamyan V M, Djuric Z, Ermolaev A M, Mihailov A A and Tkachenko I M 1994 *J. Phys. D: Appl. Phys.* **27** 111

[18] Zaika E V, Mulenko I A and Khomkin A L 2000 *High Temp*. **38** 821

[19] Shilkin N S, Dudin S V, Gryaznov V K, Mintsev V B and Fortov V E 2003 *JETP* **97** 922

[20] Zel'dovich Ya B and Raizer Yu P 1966, 1967 *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (New York: Academic)

[21] Gryaznov V K, Iosilevskii I L and Fortov V E 1973 *Prikl. Mekh. Tekh. Fiz.* **3** 70

[22] Frost L S and Phelps A V 1964 *Phys. Rev.* A **136** 1538