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ELECTRICAL RESISTIVITY OF STRONGLY COUPLED PLASMAS IN INTENSE FIELDS*

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It is now possible to measure the electrical resistivity, or alternatively the electron collision frequency, in strongly coupled plasmas through the use of very fast laser pulses. In such experiments, the effect of the intense laser field needs to be included in the calculation of material transport coefficients. We derive a form for the electrical resistivity which includes the effects of strong correlations, as well as an external electric field. Our results are compared with other theories and a recent set of experiments.

1. INTRODUCTION

The advent of intense, subpicosecond laser pulses has opened a new window in the study of very high density plasmas¹. When such a pulse is focused on a solid, much of the laser energy absorbed by the ionizing electrons is rapidly conducted away by cold matter below an absorption skin depth. The result is a cold very dense plasma. The theoretical interpretation of these experiments relies mainly on the electron-ion collision frequency, which governs laser light absorption through inverse bremsstrahlung, and on the electron thermal conductivity, which controls plasma cooling. Given these conditions and the plasma environment, the form of the collision frequency must be appropriate to strongly coupled plasmas in the presence of a strong electromagnetic pump source. Below we take into account both major effects by calculating the electrical resistivity or conductivity, in strongly coupled plasma including the presence of a strong electric field.

2. GENERAL THEORY

The electron collision frequency, ν , electrical conductivity, σ , and electrical resistivity, ρ , share the following relations:

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$$\sigma = \omega_{pe}^2 / (4\pi\nu) \quad \text{and} \quad \rho = 4\pi\nu / \omega_{pe}^2 \quad \text{or} \quad \rho = 1/\sigma,$$

where ω_{pe} is the electron plasma frequency. Forms for the plasma dc² and ac³ resistivity in the case of weak coupling are well known. The bases for these formulations are inappropriate in the presence of a strongly coupled plasma⁴⁻⁷. Attempts to find an appropriate form for these transport coefficients in strong coupling must consider strong electron-ion and ion-ion correlations, electron degeneracy, quantum effects, and completeness of the solution (since most of the final forms are Chapman-Enskog polynomial expansion types). For this calculation, we concentrate on classical statistics in order to elucidate a more complete solution (and include an external electric field). Quantum effects are contained entirely in an effective electron-ion potential and degeneracy is ignored altogether.

We start by writing the kinetic equation for the phase space particle-particle distribution functions, $C_{ab}(r_a, r_b, p_a, p_b, t)$, in the disconnected approximation^{8,9}, which contains a memory function form of the collision operator; $a, b = i, e$ for point ions and electrons. "Lower order" (analytic) solutions of C_{ab} must be used in the collision operator to obtain a solution¹⁰.

The next step is to "solve" the kinetic equation by expanding in terms of an infinite set of orthogonal momentum polynomials. We assume separability of momentum and configuration spaces, i.e., classical statistics. The transport coefficients are easily recognized by separating the hydrodynamic momentum powers from the remainder of the set. The number of terms retained beyond the hydrodynamical subspace dictates the completeness of the solution. Most of the correction is included by using two additional polynomials¹¹ corresponding to the so-called two Sonine polynomial approximation. For dc resistivity, the details of this process can be seen in Ref 12.

For ac resistivity, the time dependence of the analytic C_{ab} 's must be retained. The simplest correlation propagator is the free streaming form¹⁰; we use this for ion motion. But for electron transport, we take the free streaming correlation modified by the presence of an external electric field. For the two Sonine case where the electric field, E , is strong the result is

$$\rho_2(\omega) = \rho_1(\omega) - \Theta(\omega),$$

where ρ_1 is the one Sonine result, given by

$$\rho_1(\omega) = \frac{n}{\omega_{pe}^2 \sqrt{2\pi kT}} \int_{-1}^1 \mu^2 d\mu \int_0^\infty d||^3 c_D^{gi}(l) V^{ei}(l) \Delta(l) \Omega(l, \omega)$$

where

$$\Delta(l) = S^{ee}(l) S^{ii}(l) - S^{ei}(l) S^{ie}(l)$$

and

$$\Omega(l, \omega) = \exp \left\{ \frac{-m}{2kTl^2} \left(\omega + \frac{eEl}{m\omega} \mu \right)^2 \right\}$$

The term, $\Theta(\omega)$, represents corrections to the one Sonine case and contains formulae similar to these. Above, S^{ab} and c_D^{ei} are static correlation functions and V^{ei} is the bare electron-ion potential. In weak coupling, ρ_2 / ρ_1 is a known ratio.

RESULTS

We gear our results to recently published values of the electrical resistivity of solid density aluminum¹³. The plasmas were created by 400 fsec laser pulses. Values of the temperature were derived and presented as a function of the laser intensity. A reproduction of the data appears in Fig. 1.

Our static correlation functions were found in the hypernetted chain (HNC) approximation using a pseudopotential developed by an activity expansion of the partition function¹⁴. Results for the aluminum resistivity are presented in Fig. 1, along with results from another, completely different method¹⁵. Lee and More¹⁵ (L&M) evaluated ρ by obtaining parameters from the scattering cross section found by a partial wave solution to the Schrödinger equation with the Thomas-Fermi potential. Connections were made to low temperatures. Other calculations, Ichimaru and Tanaka¹⁶ and Boercker, Rogers, and DeWitt¹⁷, both using Coulomb potentials (not pseudopotentials) and a high temperature limit of the Fermi-Dirac distribution, produce much smaller values of ρ . [The latter results are equivalent to the one Sonine approximation and those values in the figure have been reduced by the appropriate ratio.^{16,17}]

We note that there is little distinction between our results and L&M over the range we have calculated, although the curves do not fit the data very well. The closeness is somewhat remarkable since our approach is very different to that of L&M. For the cases here, the degeneracy parameter is greater than one for all but the lowest temperatures, so our calculation should not suffer greatly from nonclassical effects. We have not calculated a pseudopotential for temperatures less than 10 eV. For comparison, we have approximated the correlations by their Debye forms and the potential by a screened Thomas-Fermi-like form, which allows an analytic solution.

For most of the data here, there is approximately a 10-20% increase in the value of ρ due to assumed intensities of electric fields. We predict that higher laser field intensities can increase the resistivity by as much as 50%. Here the presence of the non-zero laser frequency is more important. We note that, when the aluminum is maintained at solid density, none of the calculations predict a ρ as large as the data around 40 eV ($\approx 200 \mu\Omega\text{-cm}$).

FIGURE 1

Electrical resistivity data from Milchberg¹³ compared with theories of Lee and More¹⁵ and this work with HNC and Debye correlations, as well as Spitzer².

REFERENCES

- 1) M. M. Murnane, H. C. Kapteyn, and R. W. Falcone, Phys. Rev. Lett. 62 (1989) 155.
- 2) L. Spitzer, Jr., Physics of Fully Ionized Gases (Interscience, New York, 1962).
- 3) J. M. Dawson and C. Oberman, Phys. Fluids 5 (1962) 517.
- 4) J. P. Hansen and I. R. McDonald, Phys. Rev. A23 (1981) 2041.
- 5) M. Baus, J. P. Hansen, and L. Sjögron, Phys. Lett. 82A (1981) 180.
- 6) F. J. Rogers, H. E. DeWitt and D. B. Boercker, Phys. Lett. 82A (1981) 331.
- 7) R. Cauble and D. B. Boercker, Phys. Rev. A28 (1983) 944.

- 8) G. F. Mazenko, Phys. Rev. A9 (1974) 360; G. F. Mazenko and S. Yip, in Statistical Mechanics, Part B, ed. B. J. Berne (Plenum, New York, 1974).
- 9) J. Wallenborn and M. Baus, Phys. Rev. A18 (1978) 1737.
- 10) R. Cauble and W. Rozmus, Phys. Fluids 28 (1985) 3387.
- 11) R. H. Williams and H. E. DeWitt, Phys. Fluids 12 (1969) 2326.
- 12) R. Cauble and W. Rozmus, J. Plas. Phys. 37 (1987) 405.
- 13) H. M. Milchberg, R. R. Freeman, S. C. Davey, and R. M. More, Phys. Rev. Lett. 61 (1988) 2364.
- 14) F. J. Rogers, Phys. Rev. A29 (1984) 868.
- 15) Y. T. Lee and R. M. More, Phys. Fluids 27 (1984) 1273.
- 16) S. Ichimaru and S. Tanaka, Phys. Rev. A32 (1985) 1790.
- 17) D. B. Boercker, F. J. Rogers, and H. E. DeWitt, Phys. Rev. A25 (1982) 1623.

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