Electrical Conductivity of a Dense Plasma

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The ac electrical conductivity of a dense plasma is studied by use of reflectivity measurements on the rear surface of a laser-irradiated planar target. The results show general agreement with theory in which a minimum collision mean free path is assumed, yielding correspondingly a minimum conductivity. However, the results also suggest that the minimum mean free path is greater than the interatomic radius.

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The study of plasma transport properties such as electrical conductivity is of fundamental importance to the understanding of collision processes in a plasma. The Spitzer[1] and Braginski[2] formulas for electron conductivities are rigorously valid for fully ionized, nondegenerate plasmas. The electrical conductivity of a partially ionized, moderately coupled plasma has been computed by Rogers, DeWitt, and Boercker,[3] taking into account quantum diffraction effects and scattering from the electronic shells of the ions and from neutrals. Their numerical results for argon and xenon plasmas agree with the experimental result[4] much better than the Spitzer theory. The work of Sommerfeld and Frank on degenerate electron conduction was reported by Mott and Jones.[5] The theory was extended by Ziman[6] and was used to explain electron conductivity in liquid metals. The Ziman model also forms the basis of the tabular conductivity data in the SESAME Library.[7] More recently an electron conductivity model for dense plasma was described by Lee and More,[8] in which transport coefficients were obtained from solutions of the Boltzmann equation in the relaxation time approximation. On the other hand, the dc electrical conductivity of a nonideal but nondegenerate plasma was measured by Ivanov, Mintsev, Fortov, and Dremin.[4] However, measurements on the electrical conductivity of a strongly coupled and degenerate plasma have not been reported.

In this Letter, we present a novel experimental study of the ac electrical conductivity of a dense plasma. This is based on the measurement of the reflectivity of the shock-compressed free surface of a solid when the shock wave emerges. The electrical conductivity of the cold, dense plasma in the shock-unloading surface exhibits a strong effect on its reflectivity. The results showed generally better agreement with the model of Lee and More.[8] However, the minimum collision mean free path assumed in the original model appears to be too small.

In this experiment, planar aluminum targets (typically 15×15 mm^2 with the thickness ranging from 25 to 50 μm) were irradiated with a 0.53-μm, 2-ns (FWHM) laser pulse from a Nd-glass laser. The rear surface of the target foil was carefully polished to near optical quality with a residual surface roughness of ≤ 0.2 μm. The laser beam was focused with $f/10$ optics onto the target front side at an incident angle of 10° off target normal. The intensity distribution at focus is nearly Gaussian with 90% of the incident laser energy contained in a spot of 80-μm diameter and 60% energy in a spot of 40-μm diameter. The irradiance averaged over the focal region containing 60% laser energy (Φ_{60}) was therefore higher than that averaged over the 90%-energy area (Φ_{90}) by a factor of about 2.7. For the measurements reported here, the absorbed irradiance was $\Phi_{60} < 10^{14}$ W/cm^2. Time-resolved (30-ps resolution) measurements showed spatial intensity modulation (4-μm resolution) of $< 30\%$.

The shock wave generated by laser-driven ablation in the aluminum target has been extensively characterized in earlier experiments.[9–11] Measurements of target rear-surface luminescence showed that the incident laser pulse produced a shock wave which remained quasisteady and planar in a region of 40-μm diameter even for 50-μm thick aluminum targets. This shock region was smaller than the 80-μm laser focal spot and resulted from edge rarefaction effects which became significant when the target thickness was of the order of the focal-spot diameter.[12]

To measure the reflectivity of the shock-compressed, dense aluminum plasma, the target rear surface was illuminated at normal incidence by a dye-laser probe beam. This was obtained by optical pumping of rhodamine 6G using 0.53-μm laser light from the Nd-glass laser. The resulting 2-ns (FWHM), 0.57-μm probe pulse was thus synchronized with the 0.53-μm

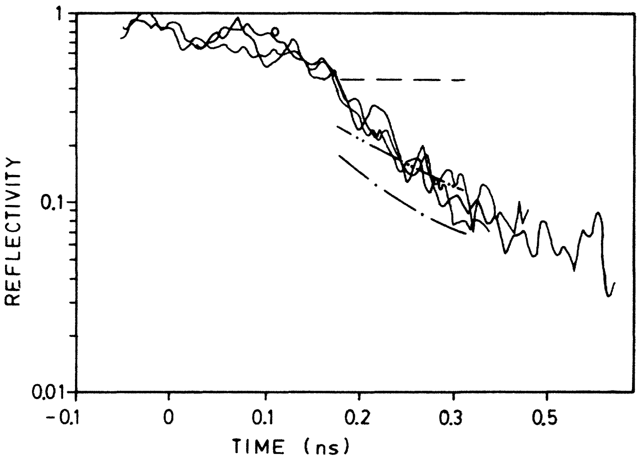

FIG. 1. Measured reflectivity of the rear surface of a 25-μm aluminum target for a shock speed of 1.7×10^6 cm/s (solid lines). Time zero corresponds to the peak of laser pulse. Calculated reflectivity R_F of the shocked free surface using SESAME conductivity data (open circle). Calculated reflectivity of the unloading plasma using SESAME conductivity data (dashed line), Lee and More's model (dot-dashed line), and Lee and More's model with $\lambda_{mfp}(\min)=2r_0$ (dot-dot-dashed line).

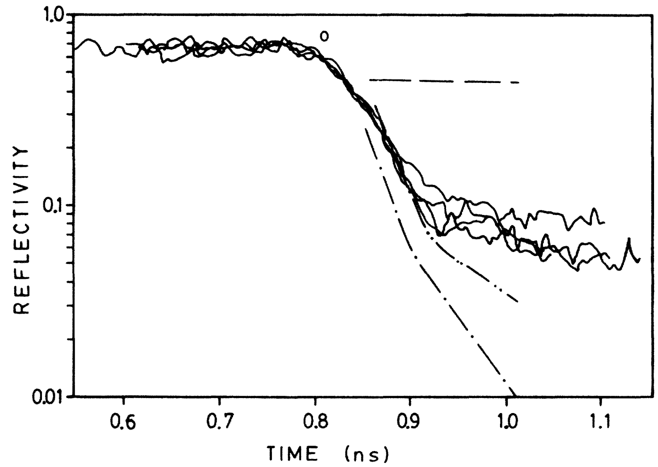

FIG. 2. Measured reflectivity of the rear surface of a 50-μm aluminum target for a shock speed of 2.2×10^6 cm/s (solid lines). Time zero corresponds to the peak of laser pulse. Calculated reflectivity R_F of the shocked free surface using SESAME conductivity data (open circle). Calculated reflectivity of the unloading plasma using SESAME conductivity data [dashed line (Ref. 14)], Lee and More's model (dot-dashed line), and Lee and More's model with $\lambda_{mfp}(\min)=2r_0$ (dot-dot-dashed line).

main beam. The target rear surface was imaged through the focusing lens of the probe beam onto the entrance slit of a Hamatsu C1370 streak camera. This yielded reflectivity measurements with a spatial resolution of 3 μm and a temporal resolution of 10 ps. Absolute reflectivity calibration was obtained *in situ* by use of a first-surface mirror positioned at the plane of the target rear surface. Details of the diagnostic have been described elsewhere.[13] It has also provided further evidence on the planarity of the shock front.

Figures 1–3 show the measured reflectivities as a function of time for the shock-compressed target plasma. Each trace represents a single measurement. Typically, the time of shock breakout at the target rear side varied within 200 ps from shot to shot. The traces in the figures were superposed relative to the instant of shock breakout. The reflectivity measurements showed good reproduciblilty. To avoid edge effects, we limited the analysis of the reflectivity measurements to a central region of < 40 μm in the shock front. The data presented here represent measurements over a central region of 10 μm. (It should also be noted that similar results were obtained for reflectivities measured over a 3-μm region at the center of the shock front.)

Before discussing the interpretation of the data, the principle of the reflectivity measurement as a means of studying the ac conductivity of a dense plasma can be described as follows. When a shock wave reaches the solid-vacuum interface (target rear surface), the Fresnel reflectivity R_F of the shock surface will vary according to its electrical conductivity. At the same instant, a rarefaction wave is launched into the solid, releasing the dense plasma into the vacuum. The reflectivity then changes rapidly with time, depending on

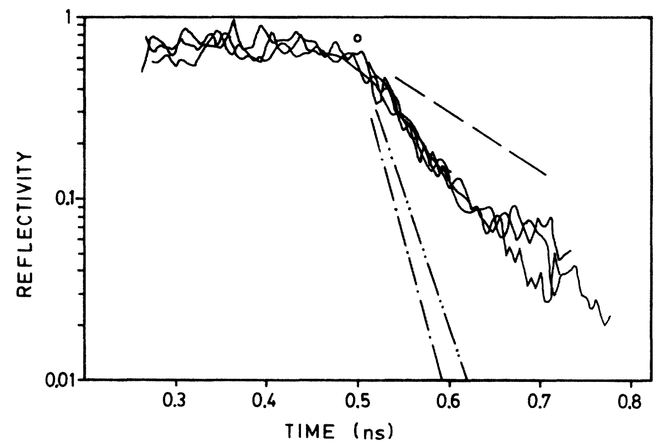

FIG. 3. Measured reflectivity of the rear surface of a 50-μm aluminum target for a shock speed of 2.5×10^6 cm/s (solid lines). Time zero corresponds to the peak of laser pulse. Calculated reflectivity R_F of the shocked free surface using SESAME conductivity data (open circle). Calculated reflectivity of the unloading plasma using SESAME conductivity data (dashed lined), Lee and More's model (dot-dashed line), and Lee and More's model with $\lambda_{mfp}(\min)=2r_0$ (dot-dot-dashed line).

the electrical conductivity of the plasma region where absorption and reflection occur. This process has been treated in detail with use of a one-dimensional hydrodynamic code.[15] At $t=0$, we consider the arrival of the shock wave at the target rear surface which becomes a step discontinuity in density, temperature, and pressure. The hydrodynamic and thermodynamic parameters of the shocked state are determined from the principal Hugoniot of aluminum from a SESAME equation of state.[16] The reflectivity of the shocked surface is given by the Fresnel formula[17]

$$R_F = \frac{4\pi\sigma/\omega + 1 - 2(2\pi\sigma/\omega)^{1/2}}{4\pi\sigma/\omega + 1 + 2(2\pi\sigma/\omega)^{1/2}}, \quad (1)$$

where ω is the frequency of the incident radiation and σ is the electrical conductivity. Equation (1) is generally valid when the gradient scale length of the reflective index n is much less than the wavelength λ of the radiation. As the unloaded plasma expands, the gradient scale length increases, and for $[(1/n)(dn/dx)]^{-1} > \lambda/2\pi$, the reflectivity of radiation propagating into the plasma profile is given by[16]

$$R \cong \left| \tanh \left| \int_{-\infty}^{\infty} \frac{1}{2n} \frac{dn}{dx} \times \exp\left(-\frac{2i\omega}{c} \int_{-\infty}^{x} n(y)\, dy \right) dx \right| \right|^2 . \quad (2)$$

The local refractive index is

$$n^2(\omega,x,t) = 1 - \frac{\omega_p^2(x,t)}{\omega^2} \left(\frac{1}{1 + i\nu_{ei}(x,t)/\omega} \right), \quad (3)$$

where ω_p is the plasma frequency and ν_{ei} the electron-ion collision frequency. Results of the simulations[15] show that the reflectivity of the unloading plasma is a sensitive measure of its electrical conductivity.

Two conductivity models were used in the simulations. They were the tabular data from from SESAME Library[7] and the calculation of Lee and More.[8] The resulting reflectivities are also indicated in Figs. 1–3. Evidently, the idealized Fresnel reflectivity of a shocked surface was not observed. Previous calculations[13] showed that even for shock speeds up to 3×10^6 cm/s, the reflectivity only reduced by $\sim 20\%$ compared with the approximately 92% reflectivity of a perfect aluminum surface at normal conditions. This was within the range of accuracy of the measurement. The low reflectivity ($R \sim 0.7$) observed before the shock breakout was caused by residual scattering from an imperfect surface. The possibility of measuring R_F was further impeded by the finite temporal resolution of the measurement due to camera resolution (~ 10 ps), residual foil roughness (~ 10 ps), finite skin depth (~ 5 ps), as well as finite shock rise time.

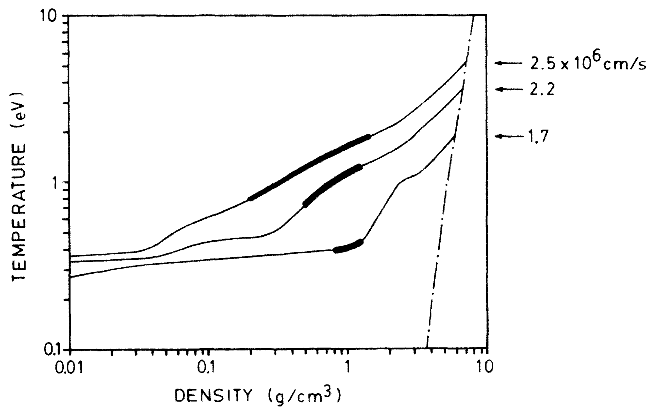

FIG. 4. Density-temperature regimes of the plasma probed in the reflectivity measurements.

The experimental result, however, yields the reflectivity of the unloading dense plasma. Interestingly, the data lie between predictions using the two different conductivity models. The SESAME conductivity appears to be much too high, whereas Lee and More's conductivity is too low. This discrepancy can be traced to the inability of existing theories to treat the collision process exactly when the electron mean free path λ_{mfp} becomes of the order of the interatomic distance r_0. The density-temperature regimes of the plasma probed by the reflectivity measurements are given by the release isentropes shown in Fig. 4. The plasma regions of interest are marked by the bold lines. The upper-density limits correspond to the critical density for the probe radiation, whereas the lower-density limits correspond to plasmas which give rise to a reflectivity $\geqslant 1\%$. Thus we are probing a dense-plasma region characterized by densities of approximately 1 g/cm^3 and temperature approximately 1 eV, a regime where λ_{mfp} approaches r_0.

In the original model of Lee and More,[8] the minimum value that the electron mean free path can take is restricted to r_0. This yields correspondingly a minimum conductivity. The adoption of a minimum conductivity followed the arguments developed for amorphous semiconductor by Mott,[18] but the choice of the limiting λ_{mfp} was a heuristic one. That such a conductivity model generally gives better results than SESAME data is encouraging. It is also interesting to note that if the minimum conductivity is chosen to correspond to $\lambda_{mfp}(\text{minimum}) = 2r_0$, much better agreement is obtained between the calculated and measured reflectivities at lower shock velocities (Figs. 1 and 2). Yet, a significant disagreement between experiment and both theoretical models remains evident at high shock velocity (Fig. 3). Such a discrepancy is currently not understood, although it too suggests a much greater value for the minimum conductivity than that obtained by allowing the collisional mean free path to approach the interatomic distance.

In conclusion, we have presented a novel diagnostic for studying the ac electrical conductivity of a dense plasma. The results show general agreement with a current theoretical model. More importantly, they also indicate that a larger value for the minimum collision mean free path needs to be used than previously assumed.

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