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Anomalous reflectivity from nonideal plasma

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Abstract
An approach is developed for computation of the reflectivity from nonideal plasma for probe laser frequencies ω near the plasma frequency ω_p. Different factors are taken into account which could violate the conventional Drude dependence of the reflectivity on the ω/ω_p ratio. Possible nonequilibrium of experimental nonideal plasma appears to be the main factor.

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1. Introduction

The reflectivity from the nonideal xenon plasma created by the shock wave front was measured in two series of experiments with different laser wavelengths $\lambda = 1.06\ \mu$m and 0.694 μm [1, 2]. The values of the reflectivity R along with the values of nonideality parameter $\Gamma = e^2(4\pi n_\mathrm{e}/3)^{1/3}/(4\pi\epsilon_0 k_\mathrm{B}T)$ and degeneracy parameter $\Theta = k_\mathrm{B}T/\varepsilon_F = 2m_\mathrm{e}k_\mathrm{B}T(3\pi^2 n_\mathrm{e})^{-2/3}/\hbar^2$ are presented in table 1, n_e is the electron number density and T is temperature. The plasma is not degenerate in the whole parameter range studied. It is singly ionized, the degree of the first ionization ranges from 0.5 to 0.75.

The results showed that the reflectivity from nonideal plasma at the shock wave front did not agree with a simple Drude model for any reasonable value of collisional frequency. These unexpected results were extensively discussed in [1–6] and the explanation has not yet been found. The reflectivity from the shock wave front in hydrogen was measured in [7]. Unfortunately, there are no references to the electron number densities either in [7] or in the theoretical studies [8, 9]. Thus the data [7] cannot be used in the discussion of the reflectivity of xenon.

The approach presented in this paper is based on molecular dynamics (MD) simulations [10, 11] and the account of possible nonequilibrium effects. The concept of nonequilibrium nonideal plasma began to be developed from the mid-1980s [12].

Table 1. Reflectivity and plasma parameters in the experiments with two different wavelengths [1, 2].

n_e (10^{21} cm^{-3})	T (10^3 K)	Γ	Θ	R
	$\lambda = 1.06\ \mu$m			
1.8	30.1	1.09	4.8	0.096
3.2	29.6	1.34	3.2	0.12
4.5	30.3	1.47	2.6	0.18
5.7	29.8	1.61	2.2	0.26
7.2	29.3	1.77	1.8	0.36
9.1	28.8	1.95	1.5	0.47
	$\lambda = 0.694\ \mu$m			
3.8	33	1.27	3.2	0.11
6.6	32	1.58	2.1	0.18
8.8	29	1.92	1.6	0.43

2. Theoretical approach

In the case of a step-like gradient of the shock wave front, the reflectivity is given by Fresnel's formula

$$R(\omega) = \left| \frac{\sqrt{\epsilon(\omega)} - 1}{\sqrt{\epsilon(\omega)} + 1} \right|^2 \tag{1}$$

where $\epsilon(\omega)$ is the dielectric function in the limit $k \to 0$ (k is the wave number). In this limit the transverse and longitudinal dielectric functions are the same. In our case the laser wavelength is much greater than any characteristic length of plasma. Thus, $k = 0$ is assumed. The simple estimation of $\epsilon(\omega)$ may be performed using the Drude formula

$$\epsilon_{\mathrm{dr}}(\omega) = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega(\omega + \mathrm{i}\nu_{\mathrm{c}})} \tag{2}$$

where ν_c is the collision frequency and ω_p is the plasma frequency. But in this case the required values of ν_c turn out to be greater than the plasma frequency [1]. These high values of collision frequency have never been observed for equilibrium plasma either in laboratory (see references in [4]) or in computer experiments [10, 13].

The effective scattering frequency was introduced in [14],

$$\nu_{\mathrm{eff}} = \nu_{\mathrm{c}} + \xi\omega_{\mathrm{p}} \tag{3}$$

where the second term describes the additional scattering of electrons by plasma waves, and $\xi = \langle E^2 \rangle / nk_{\mathrm{B}}T$ is the ratio of the collective electric field energy to the particle thermal energy [15]. In the equilibrium plasma $\xi \approx 0.1\Gamma^{3/2}$ [16].

The validity of expression (3) can be checked by comparison with the MD simulation [17]. It is seen in figure 1 that the results [17] range from Debye plasmas where the collisional frequency dominates to strongly nonideal plasmas where collective scattering prevails. The results of another theoretical approach for collision frequency are given in [18] for $\Gamma < 1$. They agree with curve 1 in figure 1.

Accounting for the scattering by equilibrium plasma waves (3) in (2) cannot explain the experimental data for the reflectivity. A more refined approach is based on MD simulations and linear response theory. If the plasma Hamiltonian includes a nonscreened Coulomb potential, the response function is $\epsilon(\omega)^{-1}$ [19],

$$\epsilon^{-1}(\omega) = 1 - \frac{\mathrm{i}}{\epsilon_0\omega}\chi(\omega) \tag{4}$$

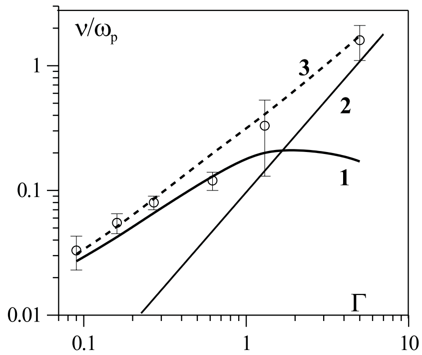

Figure 1. Collision frequency. MD simulations [17]: circles, and theory [16]: 1—ν_c/ω_p, 2—$\xi = 0.1\Gamma^{3/2}$ and 3—$\nu_{eff}/\omega_p = \nu_c/\omega_p + \xi$.

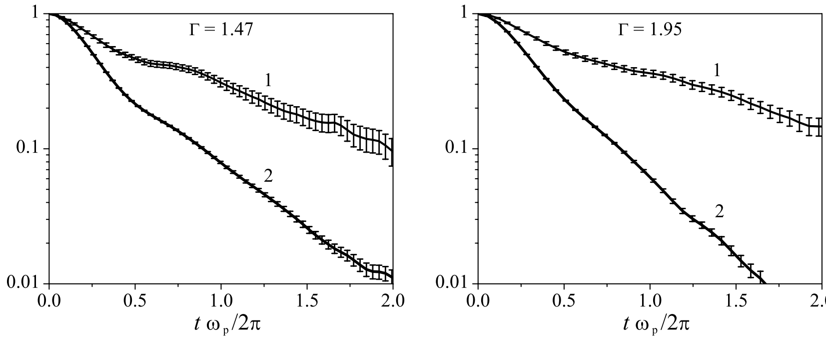

Figure 2. The results of the equilibrium MD simulations for the normalized autocorrelation functions for two values of the nonideality parameter Γ: 1—current and 2—velocity.

where $\chi(\omega)$ is the electric susceptibility,

$$\chi^{\mathrm{MD}}(\omega) = \epsilon_0 \omega_p^2 \int_0^{\infty} \frac{\langle \mathbf{J}(t)\mathbf{J}(0)\rangle}{\langle \mathbf{J}^2(0)\rangle} \, \mathrm{e}^{\mathrm{i}\omega t} \, \mathrm{d}t \tag{5}$$

and $\langle \mathbf{J}(t)\mathbf{J}(0)\rangle$ is a current autocorrelation function in the limit $k \to 0$.

We consider a two-component fully ionized system of $2N$ single-charged particles (electrons and ions). The interactions between particles are described by an effective pair potential ('pseudo-potential') such as the corrected Kelbg potential [20]. Pairwise quantum effects are taken into account by modifying the short range potential for both e–i and e–e interactions. The possibility of the formation of low energy bound states is excluded. The details of the plasma model and numerical integration scheme are presented in [10, 11].

3. Results and discussion

The velocity and current autocorrelation functions are calculated by MD simulations for equilibrium plasmas (figure 2). The results obtained for the reflectivity at a step-like density profile from equations (1), (4) and (5) are given in figure 3. The figure also shows the theoretical estimations [21]. It is seen that neither the MD simulations nor the theoretical models for the equilibrium plasma explain the experimental data. This discrepancy could be a result of different reasons (or their cumulative effect) which are not taken into account in the theory

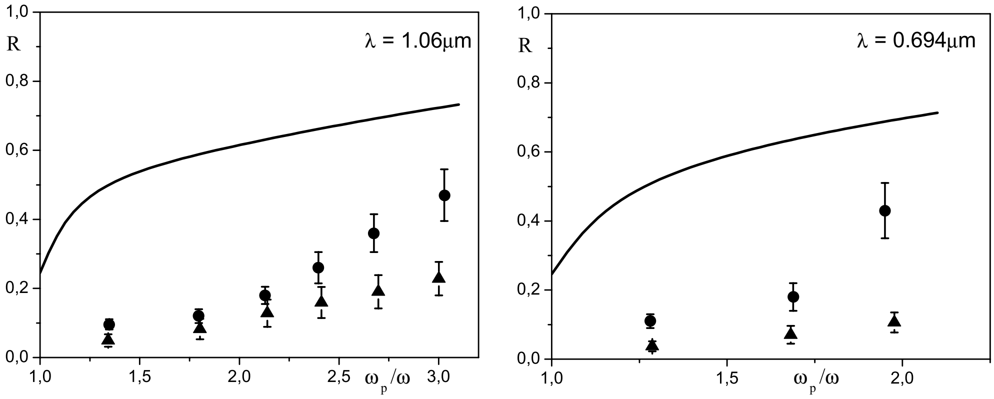

Figure 3. The reflectivity from the shock-compressed plasma. The experimental results (circles) are compared with the equilibrium molecular dynamic data (triangles) and theoretical estimations [21] (solid curve) for equilibrium plasma.

and the simulation. Now let us focus on the possibility that the plasma is in a nonequilibrium state.

Note that there are some indications of oscillations even in the equilibrium autocorrelation functions (figure 2). The excitations of the more pronounced oscillations of kinetic energy are observed in MD simulations of strongly nonequilibrium plasma [22]. The superthermal excitation of plasma waves results in an increase of ξ in (3). This phenomenon was observed in the experiment [23] where ν was of the order of $\omega_{\rm p}$. The latter was the feature of high turbulence in an ideal plasma. It was shown in [12] that the development of beam instability was possible at the conditions studied in [23]. This resulted in the excitation of plasma oscillations to superthermal level. It means that the value of ξ becomes greater than the equilibrium one.

In order to investigate the influence of the nonequilibrium excitation of plasma waves, the inverse problem is solved for the simple schematic model for the current autocorrelation function proposed in [4],

$$\frac{\langle \mathbf{J}(t)\mathbf{J}(0)\rangle}{\langle \mathbf{J}^2(0)\rangle} = \mathrm{e}^{-\nu t} + \xi\,\mathrm{e}^{-\gamma t}\sin\omega_{\rm p}t. \tag{6}$$

Here $\gamma = \nu_{\rm c}/3\sqrt{2\pi}$ is the decrement of plasma waves in the limit $k \to 0$ [24]. The value of $\nu_{\rm c}$ is inferred from the exponential fit of the velocity autocorrelation function (figure 2). The value of ν is taken in such a way that, for $\xi = 0$, the reflectivity calculated from (6) is equal to that inferred from the equilibrium MD simulation (figure 3). The non-zero values of ξ in (6) allow one to fit the experimental reflectivity. These values of ξ are presented in figure 4.

Thus, it appears that the larger the nonideality parameter the higher the level of nonequilibrium up to which the plasma can be excited. It is consistent with the diminishing of the equilibrium collision frequency with the increase of Γ for large Γ in figure 1.

The existence of a nonequilibrium plasma state is supported by a similar fitting procedure for electrical conductivity [4], electron–ion equilibration time [25] x-ray diffraction [26] and equation of state [27].

Among other factors which could affect the results of the reflectivity, the possible gradient of the electron density on the plasma front should be considered [6]. The front width was estimated in [1] to be equal to $d \approx 0.1\lambda$. Although the front width is quite small, it can affect the reflectivity at some special conditions. In order to investigate the reflection from the front

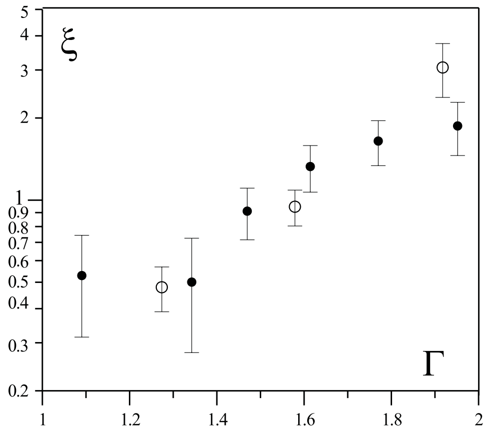

Figure 4. The level of nonequilibrium excitation required to explain the experimental data for the reflectivity: $\lambda = 1.06$ μm (solid circles) and $\lambda = 0.694$ μm (open circles).

with arbitrary profile, the Helmholtz equation for an electromagnetic field should be solved. Let us consider a planar wave propagating along the z-axis. Neglecting nonlocal effects for the conductivity, we write the following equation for the electric field amplitude

$$\frac{\mathrm{d}^2 E(z)}{\mathrm{d}z^2} + \frac{\omega^2}{c^2}\epsilon(z)E(z) = 0. \tag{7}$$

The function $\epsilon(z)$ is calculated from equation (2) for the density and temperature profiles $n(z), T(z)$ given by one of the theoretical models. The results are presented in [28]. The calculations show that the influence of the smooth front profile should be considered but it alone does not explain the reflectivity measured. The thickness of the plasma front, however, could influence the reflectivity for short wavelengths.

4. Conclusion

The theoretical interpretation is given for the experimental results [1, 2] for the reflectivity from xenon nonideal plasma. This interpretation lies within the framework of the concept that nonideal plasmas are generated in experiments mostly in a nonequilibrium state. The results point to an increase in the degree of nonequilibrium with increasing Γ for $\Gamma > 1$. Diverse experimental data [4, 25–27] support the assumption of nonequilibrium excitation of nonideal plasma as well.

The collision frequency and scattering of electrons by plasma waves which are used in the model studied are found to be consistent with MD simulations [17].

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