Polarized reflectivity properties of shock-compressed plasma with strong interaction of particles

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Abstract. New results of s- and p-polarized reflectivity measurements on non-ideal plasma at the frequency of external electromagnetic field $\nu_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$, the plasma density $\rho = 1.8$ g/cm$^3$ and the parameter of Coulomb non-ideality of plasma $\Gamma = 1.4$ are presented. Using a Fermi-like density profile along the shock wave front, the reflectivity coefficients of non-ideal plasma were calculated for newly obtained experimental data. As physically expected, a single profile is sufficient to obtain good agreement with the experimental data at all investigated optical laser frequencies.

1. Introduction

Experimental investigation of the matter properties after high external energy input can be based on the interaction with electromagnetic waves. The formation of a plasma state which is localized in space requires studying the characteristics of the boundary layer—the plasma layer, directly adjacent to the boundary between the plasma and free space. In particular, the measurement of plasma parameters strongly depends on the actual properties of the transition layer. This has significant relevance in the case of dense shock-compressed plasma at extremely high temperatures and pressures.

Earlier we have measured the reflectivity factors of a dense plasma under perpendicular incidence at fixed frequencies $\nu_{\text{las}}$ [1]. It was found the plasma reflectivity was quite low, although the condition $n_e > n_{\text{crit}} = 4\pi^2 \nu_{\text{las}}^2 m_e \varepsilon_0/e^2$ (where $n_e$ is the free electron density of plasma, $n_{\text{crit}}$ is the free electron density at which an incident electromagnetic wave is totally reflected, $\nu_{\text{las}}$ is the frequency of external electromagnetic wave, $\varepsilon_0$ is the absolute dielectric permittivity of vacuum, $m_e$ and $e$ are the mass and the electron charge, accordingly) for metal-like reflectivity was valid for all densities. This indicates, that the collisionless random-phase-approximation picture is not valid. Analyses of the reflectivity data of a non-ideal plasma under perpendicular incidence have been performed in several works. Berkovsky et al [2] used a dielectric function in Born approximation. In [3] non-equilibrium effects have been included and a 2-moment model for the electrical conductivity was used in [4, 5]. The density functional theory was utilized in [6]. Several approaches with different theoretical models for explaining the optical reflectivity measurements were made in [7–9]. In these works the theory of the dielectric function with a
Figure 1. The distribution of energy reflected from the strongly correlated dense plasma in the spatial angles. The measurements were performed for the normal incidence and probing frequency $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$. Intensity in arbitrary units.

generalized Drude model has been applied. However, the reflectivity was overestimated by a factor of $\geq 2$, especially for low pressures and final densities. In [8], the idea of a smooth plasma front of non-vanishing width was proposed. Already in [1], it has been argued, that due to microscopic processes, the plasma front is far from being step-like. It was suggested that there are three spatial regions: a precursor zone with slowly increasing free electron density, the actual shock front, where an avalanche-like increase in the free electron density is encountered and a plasma zone with constant high free electron density. In [10–14], s- and p-polarized reflectivity indexes for oblique incidence of electromagnetic wave are presented and the idea of asymmetric shape of the profile is adapted. The profile parameters are functions of the final electron density $n_e$ and have been fit to the experimental data to achieve an overall good agreement between theoretical curves and experimental data points for the reflectivity at all frequencies and angles of incidence within the experimental error bars.

Within this work, the new experimental data on oblique incidence of polarized electromagnetic wave, are presented.

2. Measurement technique and results
In this paper, we report new results of s- and p-polarized reflectivity measurements on non-ideal plasma at $\Gamma = 1.4$ and $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$. The measurements of polarized reflectivity coefficients of explosively driven dense plasmas have been carried out at incident angles $\theta = 35$–$50$ degrees. These experimental points supplement ones obtained earlier.

To generate nonideal plasma, we used explosively driven shock waves which lead to compression and irreversible heating of xenon and to measure the dense xenon plasmas polarized reflectivity coefficient, a pulsed $\text{Al}_2\text{O}_3$:$\text{Cr}^{3+}$ and $\text{Y}_3\text{Al}_5\text{O}_{12}$:$\text{Nd}^{3+}$+KTP laser system with a four-channel pulse high-speed device for determination of the Stokes vector components was used [13].
Since the reflected radiation from the plasma object lies in the wide range solid angle, the radiation is lost (clipping) in the experiments with use of large interaction angles of plasma and probe electromagnetic wave. The lost radiation does not participate in the formation of the desired signal. Additional measurements of the reflected energy distribution on spatial angles were carried out to compensate this phenomenon in a special series of experiments. This distribution is used to correct the wanted signal (figure 1) and it was applied to design the new xenon cell for good compensation of the shock front distortions. Figure 2 shows the new gas cell designed for optical measurements at large interaction angles.

The results of our measurements are presented in table 1.

3. Analysis
Understanding the physics of strongly non-ideal plasmas requires a quantum statistical theory which adequately describes the behavior of strongly interacting charged particles since it plays a crucial role in such environments. Basically, the propagation of electromagnetic waves is described by the Maxwell equations. In the case of an inhomogeneous medium, the dielectric function $\varepsilon$ varies along the probing laser beam direction. We assume a quasi one-dimensional dependence on position ($z$ direction) so that $\varepsilon = \varepsilon(n_e(z))$ is a function of the $z$-dependent free electron density $n_e(z)$. In [1] it was suggested a plasma profile with three parts: precursor zone, shock front zone and plasma zone. Reinholz et al in [15] used a Fermi-like profile for a free electron density in shock wave front

$$n_{e,Fermi}(z) = \frac{n_e}{1 + \exp[-z/A - \exp(-z/B) - C]},$$

where $A$, $B$ and $C$ are fit parameters, $n_e$ is free electron density in the plasma zone from experiment.
Table 1. Results of the experiments on the s- and p-polarized reflectivities of explosively driven dense xenon plasma at $v_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$ and thermodynamic parameter values: pressure $P$, temperature $T$, mass density $\rho$, free-electron number density $n_e$, density of neutral atoms $n_a$, ionization degree $\alpha_{\text{ion}} = n_e / (n_a + n_e)$, nonideality parameter $\Gamma$ and degeneracy parameter $\Theta$.

| $\theta$ | $R_s$ | $R_p$ | $P$ (GPa) | $T$ (K) | $\rho$ (g/cm$^3$) | $n_e$ (cm$^{-3}$) | $n_a$ (cm$^{-3}$) | $\alpha_{\text{ion}}$ | $\Gamma$ | $\Theta$ |
|----------|-------|-------|-----------|--------|--------------------|-----------------|-----------------|----------------|--------|--------|
| 0        | 0.25  | 0.25  |           |        |                    |                 |                 |                |        |        |
| 10       | 0.28  | 0.24  |           |        |                    |                 |                 |                |        |        |
| 20       | 0.39  | 0.22  |           |        |                    |                 |                 |                |        |        |
| 30       | 0.55  | 0.18  | 9         | 28500  | 1.80               | $5.0 \times 10^{21}$ | $6.1 \times 10^{21}$ | 0.46           | 1.4    | 1.7    |
| 35       | 0.52  | 0.2   |           |        |                    |                 |                 |                |        |        |
| 40       | 0.58  | 0.13  |           |        |                    |                 |                 |                |        |        |
| 50       | 0.69  | 0.17  |           |        |                    |                 |                 |                |        |        |

Figure 3. Indexes of s- and p-polarized reflectivity of strongly correlated dense xenon plasma calculated in comparison to the experimental data for laser light at $v_{\text{las}} = 5.66 \times 10^{14} \text{ s}^{-1}$.

Assuming local thermodynamic equilibrium, the density profile of neutral atoms $n_a(z)$ is derived from the Saha equation with Debye shift

$$n_a(z) = n_e,\text{Fermi}(z)^\frac{1}{2} \Lambda_{\text{th}}^3 \exp \left[ \beta \left( E_0 - \frac{\kappa e^2}{4\pi\varepsilon_0} \right) \right],$$

(2)

where $\kappa$ is the screening parameter, $\Lambda_{\text{th}}$ is the thermal wavelength and $E_0$ is the ionization energy of xenon, excited states are neglected.

The reflectivity of dense plasma was derived from the solution of the Maxwell equations with the dielectric function $\varepsilon(z)$ defined by a Drude-like formula [14]. The influence of neutral particles was taken into account by the static collision frequency via a neutral contribution
Figure 4. Indexes of s- and p-polarized reflectivity of strongly correlated dense xenon plasma calculated in comparison to the experimental data for laser light at $\nu_\text{las} = 2.83 \times 10^{14}$ s$^{-1}$.

factor. When calculating polarized reflectivity indexes of dense plasma at $\rho = 2.8$ g/cm$^3$ and $\rho = 1.8$ g/cm$^3$ were obtained different sets of fit parameters ($A = 0.0525$, $B = 0.75$ at $\rho = 2.8$ g/cm$^3$ and $A = 0.021$, $B = 1.06$ at $\rho = 1.8$ g/cm$^3$). This is due to the different densities of the plasma. Results of the new reflectivity calculation using the improved algorithm for solving the variational problem and the comparison with recently measured data are shown in figures 3 and 4. It is clearly seen that the new calculation more accurately describes the experimental data (the sum of squared deviations is smaller). For the first time it was obtained the ratio of collision frequencies of electron–ion and neutrals $\nu_a/\nu_{ei} = 0.3$. From our calculation: the width of the plasma transition region $L = 200$ nm at $\rho = 2.8$ g/cm$^3$ and $L = 290$ nm at $\rho = 1.8$ g/cm$^3$.

The comparison of results for the Fermi-like profile with the step-like profile (Fresnel formula), is shown in the figure 3.

4. Conclusions
Experimental data in the region of very high temperatures and densities are very important for validating theoretical models and for fitting them to actually observed constraints. Our calculations show that Fresnel approximations do not describe the experiment satisfyingly. In contrast, the use of a smooth charge particles profile describes the experimental data more correctly. Recently, similar results for the width of the transition region have been reproduced by other works, see [16–18].

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