The optical properties of shock-compressed partially ionized strongly non-ideal plasma

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Abstract. Optical experimental data for non-ideal plasma are very important for validating theoretical models and fitting them to actually observed constraints. Within this work, new data on oblique incidence of polarized electromagnetic wave are presented. The study of polarized reflectivity properties of nonideal xenon plasma was accomplished using laser light at wavelength $\lambda_{\text{las}} = 1064$ nm and plasma density $\rho = 1.8$ g/cm$^3$. Angular dependences of s- and p-polarized reflectivities were used in the integration of Maxwell equations to construct the spatial profile of the density of charge carriers of explosively driven dense plasmas.

1. Introduction
For further development of non-ideal plasma physics, investigations of its electronic subsystem properties appear to be crucial. In order to obtain data on the transport characteristics for a wide range of thermodynamic parameters up to extremely high temperatures and pressures, the use of experiments with powerful shock waves is one of the accepted and well established options. Experiments can allow to identify areas of applicability of existing theoretical models, or can be used for fitting numerical parameters of functional relationships, that describe the behavior of matter under conditions of strong interaction between the particles and are developed on the basis of rigorous asymptotic solutions for the weakly ideal states [1–5].

Experimental studies of the plasma properties after high external energy input can be based on the interaction with electromagnetic waves. The experimental data from measurements of polarized reflectivity properties are an important cornerstone to construct theoretical models for the description of warm dense matter.

2. Measurement technique and results
In figure 1, the experimental setup is shown. The pulsed yttrium aluminum garnet laser system with higher order mode suppression of laser radiation was used for measuring the polarized reflectivity coefficients of explosively driven dense plasmas (figure 2). The probe pulse duration was $\tau_{\text{las}} = 1.2 \times 10^{-8}$ s. For our investigation we used laser radiation with 1064 nm wavelength. The laser probe beam was formed by the aspherical optical unit. In order to decrease the level of false reflexes and to augment the receiving unit aperture angle the diagnostics laser system was equipped with the aspherical lens and optical fiber. To determine the Stokes vector components,
Figure 1. Experimental setup: 1—Y$_3$Al$_5$O$_{12}$:Nd$^{3+}$ laser; 2—multichannel photodetector; 3—control computer; 4—high speed control block; 5—explosively driven generator; 6—interference filters; 7—mirror; 8—laser beam splitter; 9—aspherical lens; 10—digitizing oscilloscope; 11—gas cell; 12—diaphragm; 13—explosive chamber; 14—lens; 15—Y$_3$Al$_5$O$_{12}$:Nd$^{3+}$ amplifier; 16—KTiPO$_4$ crystal; 17—laser mirror; 18—telescope; 19—ionization sensor; 20—spectroscope; 21—polarizers.

A four channel high speed device with filters for selection of probing frequency was used. The device allows to measure the reflected laser beam intensity for four azimuthal angles.

To generate nonideal plasma state, we have used explosively driven shock waves which lead to compression and irreversible heating of xenon. The optical image of the shock wave in xenon was recorded by a high speed camera for checking the space-time plasma slug parameters (figure 3). The exposition time was $2 \times 10^{-9}$ s. In the coordinate system of the snapshot the striker motion occurred from the left to the right. For the diagnostics of plasma parameters, the 1 mm$^2$ area of the front shock wave was used. Good flatness and homogeneity of the plasma can be seen.

There is a cut-off (loss of part of a radiation) of reflected radiation in experiments at large angles of interaction between plasma and probe wave. Previously, we measured the reflected energy distribution on spatial angles [6]. This distribution was used to correct the wanted signal and to design a new gas cell (figure 4).

The measurements of polarized reflectivity coefficients of explosively driven dense plasmas have been carried out at incident angles 45$^\circ$–65$^\circ$ simultaneously for s- and p-polarization, respectively. The results of our measurements at $\lambda_{\text{las}} = 1064$ nm and the plasma density $\rho = 1.8$ g/cm$^3$ and the previously obtained data are presented in table 1.

3. Analysis

In order to determine the thermodynamic parameters of shock-compressed strongly non-ideal plasma, the shock wave velocity was measured and the plasma composition was calculated within a chemical picture [7]. The polarized reflectivity coefficient of dense plasma can be obtained
Figure 2. The probe pulsed laser system.

Figure 3. The shock wave propagation in Xe.

Figure 4. The gas cell with optical fiber cables for large angle measurements.
shown. It is clearly seen that the calculations describes the experimental data well. We obtained the best description of the experimental data. The influence of neutral particles was taken into account by the static collision frequency via a neutral contribution factor. In figure 5, results of solving Maxwell equations and the experimental s- and p-polarized reflectivity indexes are shown. It is clearly seen that the calculations describes the experimental data well. We obtained

\[ \varepsilon[\omega, n_e(z)] = 1 - \frac{\omega_{pl}^2[n_e(z)]}{\omega^2[1 + i\nu_0\omega]} \]  

(1)

with the plasma frequency \( \omega_{pl}[n_e(z)] = \sqrt{e^2 n_e(z)/(\varepsilon_0 m_e)} \), where \( m_e \) is the electron mass. The dynamic collision frequency \( \nu_0[\omega, n_e(z)] \) is calculated using the Born approximation

\[ \nu_{\text{Born}}[\omega, n_e(z)] = -i\frac{\varepsilon_0 n_i \Omega_0^2}{6\pi^2 e^2 n_e m_e} \int_0^\infty q^6 V_{ei}(q) S_i(q) \frac{\varepsilon_{\text{RPA}, \omega} - \varepsilon_{\text{RPA}, 0}}{\omega} dq \]  

(2)

for a Coulomb potential \( V_{ei} \), where \( n_i \) is the ion density, \( \varepsilon_{\text{RPA}, \omega} - \varepsilon_{\text{RPA}, 0} \) is the dielectric function in random phase approximation (RPA), \( \Omega_0 \) is the normalization volume and the structure factor was taken as \( S_i(q) = 1 \).

Taking into account the fact that components of the electric and magnetic field vectors for s-polarization are \( E_y = E_z = H_x = 0 \) and for p-polarization are \( H_y = H_z = E_x = 0 \) the Maxwell equations lead to the Helmholtz equations for the complex amplitude of the electric and magnetic fields with frequency \( \omega \)

\[ \frac{d^2 E_0(z)}{dz^2} + \frac{\omega^2}{c^2} |\varepsilon(\omega, z) - \sin^2 \theta| E_0(z) = 0, \]  

(3)

\[ \frac{d^2 H_0(z)}{dz^2} - \frac{d H_0(z)}{dz} \frac{d \ln |\varepsilon(\omega, z)|}{dz} + \frac{\omega^2}{c^2} |\varepsilon(\omega, z) - \sin^2 \theta| H_0(z) = 0, \]  

(4)

where \( \theta \) is the incident angle.

We used a Fermi-like profile for a free electron density in shock wave front with \( A, B \) and \( C \) fit parameters [9]. These parameters define the shape of the profile and have been varied for the best description of the experimental data. The influence of neutral particles was taken into account by the static collision frequency via a neutral contribution factor. In figure 5, results of solving Maxwell equations and the experimental s- and p-polarized reflectivity indexes are shown. It is clearly seen that the calculations describes the experimental data well. We obtained

Table 1. Experimental results for the s- and p-polarized reflectivities of explosively driven Xe plasma at \( \nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1} \) 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 \( \Theta \).

| \( \theta \) | \( R_s \) | \( R_p \) | \( P, \text{ GPa} \) | \( T, \text{ K} \) | \( \rho, \text{ g/cm}^3 \) | \( n_e, \text{ cm}^{-3} \) | \( n_a, \text{ cm}^{-3} \) | \( \alpha_{\text{ion}} \) | \( \Gamma \) | \( \Theta \) |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 0.28 | 0.24 | 28500 | 1.80 | 5.0 \times 10^{21} | 6.1 \times 10^{21} | 0.46 | 1.4 | 1.7 |
| 40 | 0.58 | 0.13 | 9 | 45 | 0.58 | 0.2 | 50 | 0.69 | 0.17 | 55 | 0.67 | 0.27 | 60 | 0.72 | 0.32 | 65 | 0.735 | 0.48 |
Figure 5. S- and p-polarized reflectivity indexes of strongly correlated dense plasma calculated in comparison to the experimental data for laser light at $v_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$; $L$ is the width of the plasma transition region.

from our calculations with the new experimental data values of the fit parameters $A = 0.022$, $B = 1.01$, $C = 0$ and the width of the plasma transition region $L = 290$ nm at $\rho = 1.8$ g/cm$^3$.

4. Conclusions
Within this work, the new experimental data on oblique incidence of polarized electromagnetic wave are presented. These data are very important for validation of theoretical models. Calculations with ea-collision as a factor and the use of a smooth charge particles profile describe the experimental data more correctly. We used the calculation algorithm [9] with new experimental data. Although slightly different values of the fit parameters were obtained, but the length of density profile along the shock wave front has not changed. Recently, similar results for the width of the transition region have been reproduced by other works [10–13].

We assume that there are no systematic errors related to the experimental investigations. Different approaches can be considered such as relaxation in the ionization process to produce the free electron density from the neutral Xe atoms, and the occurrence of inhomogeneities (micro-turbulences) at very small scales that are not resolved by the wavelength of the applied laser beams.
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