The interaction of laser radiation with explosively driven shock wave compressed Xe plasmas

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Abstract. The analysis of the response of dense plasma to electromagnetic waves of moderate intensity can be used as a tool to investigate the validity of the physical models describing the behavior of matter under extreme conditions. Within this work the new experimental 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 $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$ ($\lambda_{\text{las}} = 1064 \text{ nm}$) and $\nu_{\text{las}} = 5.66 \times 10^{14} \text{ s}^{-1}$ ($\lambda_{\text{las}} = 532 \text{ nm}$). The measurements of polarized reflectivity coefficients of explosively driven dense plasmas have been carried out at incident angles up to $\theta = 78^\circ$. The plasma composition was calculated within a chemical picture. The integration of Maxwell equations to construct the spatial profile of the density of charge carriers of plasmas was based on an interpolation formula for DC conductivity.

1. Introduction

The measurement of optical properties is a significant diagnostic tool for examining nonideal plasma. The analysis of the response of dense plasma to electromagnetic waves of moderate intensity can be used to investigate the validity of the physical models describing the behavior of matter under extreme conditions, high temperatures and pressures. Of particular interest are optical reflectance measurements on materials in which a transition from a dielectric to a metal-like state occurs with increasing density due to pressure ionization \cite{1-5}.

Already in \cite{1}, it has been argued, that plasma created have transitive surfaces with a density profile. Earlier we have used normal incidence reflectivity measurements to fit parameters of the density profile preliminary. Extension of experimental conditions to find the angular dependence of s- and p-polarized reflectivities at several wavelengths can be used to construct the spatial profile of the density of charge carriers in more details. It is important to interpret the experimental data correctly as the small changes of layer parameters cause the considerable variations of the total reflectivity of shock-compressed plasma.

In this paper, we report new results of s- and p-polarized reflectivity measurements of nonideal plasma at $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$ ($\lambda_{\text{las}} = 1064 \text{ nm}$) and $\nu_{\text{las}} = 5.66 \times 10^{14} \text{ s}^{-1}$ ($\lambda_{\text{las}} = 532 \text{ nm}$).
2. Measurement technique and results
The research of polarized reflectivity properties of plasma with strong particles interaction can be carried out using the technique of inclined probing by polarized electromagnetic waves of moderate intensity [6].

To generate nonideal plasma, we have used explosively driven shock waves which lead to compression and irreversible heating of xenon. To control the flatness and homogeneity of the plasma state, an optical image of the shock wave in xenon was recorded by a PCO camera. In order to research of transitive layers of explosively driven dense plasma, a pulsed RUBY+YAG system with an electrooptical shutter was used. The study of polarized reflectivity properties of nonideal xenon plasma was accomplished using laser light at \( \nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1} \) and \( \nu_{\text{las}} = 5.66 \times 10^{14} \text{ s}^{-1} \).

The four-channel pulse high-speed device has been used to determine the Stokes vector components. This device allows measuring the intensity of the reflected laser beam for four azimuthal angles and was equipped with filters for the selection of the probing frequency. Additional measurements of the reflected energy distribution on spatial angles were carried out to compensate the lost reflected radiation at large interaction angles of plasma and probe electromagnetic wave. The probe system units are shown in figures 1 and 2.

New results of our measurements are presented in tables 1 and 2. Experimental data obtained previously are shown too (\( \nu_{\text{las}} = 5.66 \times 10^{14} \text{ s}^{-1} \) and \( \theta < 70^\circ \)). For a more complete validation of physical models, experiments have been performed at a lower plasma density (\( \nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1} \) and \( \rho = 1.8 \text{ g/cm}^3 \)).

3. Analysis
To determine the thermodynamic parameters of the plasma, the shock wave velocity was measured and the plasma composition was calculated within a chemical picture [7]. Working with a grand canonical ensemble, virial corrections have been taken into account due to charge-charge interactions. Short-range repulsion of heavy particles was considered within the framework of a soft sphere model. In the parameter range of the shock wave experiments, the composition was obtained with an error of up to 15%, depending on the approximations for the equation of state.

The theoretical description of the electromagnetic wave propagation in an inhomogeneous medium has been applied to investigate the angle- and polarization dependent reflectivity at the plasma front. In accordance to the geometry of the experimental setup, an inhomogeneous plasma is considered, where the dielectric function \( \epsilon = \epsilon(n_e(z)) \) varies along the probing laser.
Table 1. Experimental results for the s- and p-polarized reflectivities of explosively driven dense xenon plasma at $\nu_{\text{las}} = 5.66 \times 10^{14}$ 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°      | 0.16 | 0.16 |         |      |      |      |      |      |      |      |
| 10°     | 0.2  | 0.12 |         |      |      |      |      |      |      |      |
| 20°     | 0.21 | 0.11 |         |      |      |      |      |      |      |      |
| 30°     | 0.3  | 0.085|         |      |      |      |      |      |      |      |
| 40°     | 0.37 | 0.083|         |      |      |      |      |      |      |      |
| 45°     | 0.48 | 0.14 |         |      |      |      |      |      |      |      |
| 50°     | 0.5  | 0.17 | 12      | 32020| 2.80 | 7.8 $\times 10^{21}$ | 5.5 $\times 10^{21}$ | 0.56 | 1.8  | 1.9  |
| 55°     | 0.58 | 0.19 |         |      |      |      |      |      |      |      |
| 60°     | 0.61 | 0.3  |         |      |      |      |      |      |      |      |
| 65°     | 0.72 | 0.43 |         |      |      |      |      |      |      |      |
| 70°     | 0.8  | 0.48 |         |      |      |      |      |      |      |      |
| 75°     | 0.87 | 0.62 |         |      |      |      |      |      |      |      |
| 78°     | 0.9  | 0.69 |         |      |      |      |      |      |      |      |

Table 2. Experimental results for the s- and p-polarized reflectivities of explosively driven dense xenon plasma at $\nu_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$ and thermodynamic parameter values.

| $\theta$ | $R_s$ | $R_p$ | $P$, 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 | 9       | 28500| 1.80 | 5.0 $\times 10^{21}$ | 6.1 $\times 10^{21}$ | 0.46 | 1.4  | 1.7  |
| 30      | 0.55 | 0.18 |         |      |      |      |      |      |      |      |

beam direction since it is a function of the spatially dependent free electron density $n_e(z)$. The propagation of electromagnetic waves is in general described by Maxwell equations. In this work the dielectric function $\epsilon(n_e(z))$ has been calculated in the long-wavelength limit with the generalized Drude formula

$$\epsilon(n_e(z)) = 1 - \frac{\omega^2_{\text{pl}}(n_e(z))}{\omega^2(1 + i\nu(\omega, n_e(z)))}$$

with a Fermi-type profile for a free electron density in shock wave front [8], the plasma frequency $\omega_{\text{pl}}(n_e(z)) = \sqrt{e^2n_e(z)/\epsilon_0m_e}$ and the dynamic collision frequency $\nu(\omega, n_e(z))$. As already found [3, 9, 10], the dependence of the reflectivity on the actually chosen approximation of the dynamical collision frequency is week. Hence, the Born approximation

$$\nu^\text{Born}(\omega, n_e(z)) = -\frac{e_0n_e\Omega_0^2}{6\pi^2e^2n_em_e} \int_0^\infty q^6V_{el}^2(q)S_i(q)\frac{\epsilon_{\text{RPA},e}(q, \omega) - \epsilon_{\text{RPA},e}(q, 0)}{\omega} dq$$

is used with a Coulomb potential $V_{el}$ and the dielectric function $\epsilon_{\text{RPA},e}(q, \omega)$ in random phase approximation (RPA). The structure factor was taken as $S_i(q) = 1$. $\Omega_0$ is the normalization
Figure 3. S- and p-polarized reflectivity indexes of strongly correlated dense plasma calculated in comparison to the experimental data for laser light at $\nu_{\text{las}} = 5.66 \times 10^{14} \text{ s}^{-1}$.

Figure 4. S- and p-polarized reflectivity indexes of strongly correlated dense plasma calculated in comparison to the experimental data for laser light at $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$.
volume. The results of solving Maxwell equations are shown in figures 3 and 4. Dashed and solid curves are the calculation for 0.5 nm, 200 nm and 800 nm plasma transition layer profile. There is also good agreement of calculations with experimental data for $\nu_{\text{las}} = 4.33 \times 10^{14}$ s$^{-1}$ and 200 nm plasma transition layer profile [11]. It is expected to complement experimental data for $\nu_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$ and $\rho = 1.8$ g/cm$^3$. It will be performed a full calculation later.

4. Conclusions

Experimental data in the region of very high temperatures and densities are difficult to obtain. However, they are very important for validating theoretical models and for fitting them to actually observed constraints. The theoretical knowledge that is gained from this research is vital for understanding experimental results and for designing new experiments and applications. Within this work, the new experimental data on oblique incidence of polarized electromagnetic wave are presented. The analysis of the experimental values of plasma reflectivity leads to a finite width of the transition layer. Different approaches using the Fresnel formulae for a step-like change of the dielectric function fail to reproduce the experimental data [12–14]. In contrast to these works, recent calculations [15, 16] using the density-functional theory to calculate the optical conductivity in dense plasmas also lead to the conclusion that a plasma transition layer profile must be assumed to explain the experimental data. A comparison with the results of these works is scheduled to perform with the accumulation of new experimental data later.

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