The investigation of polarized reflectivity of explosively driven dense plasma

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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 plasma composition was calculated within a chemical picture and the integration of Maxwell equations to construct the spatial profile of the density of charge carriers of plasma was based on an interpolation formula for dc conductivity.

1. Introduction
For further development of nonideal plasma physics, investigations of its electronic subsystem properties appear to be crucial. The experimental data from measurements of polarized reflectivity properties are an important cornerstone to construct theoretical models for the description of warm dense matter.

The reflectivity of shock-compressed dense xenon plasma using normal incidence has been investigated at wavelengths \(\lambda_{\text{laser}} = 532\text{–}1064\ \text{nm}\) [1–5]. It was found that although the condition \(n_e > n_{\text{crit}} = \omega^2_{\text{las}} m_e \epsilon_0/e^2\) for metal-like reflectivity was valid for all densities that were accessed experimentally—the reflectivity was considerably low. Already in [1], it has been argued that, due to microscopic processes, the plasma front is far from being step-like. In [6,7], experiments on the reflectivity of an explosively driven xenon plasma were performed under oblique incidence. When propagating through warm dense matter, the wave is attenuated due to absorption. Hence, the inclined reflectivity data can be used to verify the density profile from earlier work and to further test models of the dielectric function, especially for \(n_e \leq n_{\text{crit}}\).

In this paper, we report new results of s- and p-polarized reflectivity measurements of nonideal plasma at \(\nu_{\text{las}} = 2.83 \times 10^{14}\ \text{s}^{-1}\), \(\nu_{\text{las}} = 4.33 \times 10^{14}\ \text{s}^{-1}\) and \(\nu_{\text{las}} = 5.66 \times 10^{14}\ \text{s}^{-1}\). The optical measurements of polarized reflectivity indexes of dense plasma with strong particle interaction have been carried out at incident angles up to \(\theta = 78^\circ\) for \(\nu_{\text{las}} = 2.83 \times 10^{14}\ \text{s}^{-1}\) and \(\nu_{\text{las}} = 4.33 \times 10^{14}\ \text{s}^{-1}\) and up to \(\theta = 65^\circ\) for \(\nu_{\text{las}} = 5.66 \times 10^{14}\ \text{s}^{-1}\).
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—axicon, 10—digitizing oscilloscope, 11—gas cell, 12—diaphragm, 13—explosive chamber, 14—lens, 15—Y$_3$Al$_5$O$_{12}$:Nd$^{3+}$ amplifier, 16—KTP crystal, 17—electro-optical DKDP shutter, 18—laser mirror, 19—telescope, 20—mirror, 21—gas cell thermostat, 22—spectroscope, 23—Al$_2$O$_3$:Cr$^{3+}$ laser, 24—electro-optical DKDP shutter.

2. Measurement technique and results
In figure 1, the experimental setup is shown. The pulsed Al$_2$O$_3$:Cr$^{3+}$ and Y$_3$Al$_5$O$_{12}$:Nd$^{3+}$ + KTP laser system and higherorder mode suppression of laser radiation was used for measuring the dense xenon plasma polarized reflectivity indexes. For our investigation we used 1064-nm-, 694-nm- and 532-nm-channels. The probe pulse duration was $\tau_{\text{las}} = 3 \times 10^{-8}$ s. It was formed by a nonspherical optical unit. In order to minimize the measurement errors (decrease the level of false reflexes and augment the receiving unit aperture angle), the diagnostics laser system was equipped with the nonspherical receiving optical unit and with the special high speed synchronization block with the ionization gauges, located on the gas cell. To determine the Stokes vector components, a four-channel pulse high-speed device has been used. The device allowed to measure the intensity of the reflected laser beam for four azimuthal angles and was equipped with filters for selection of frequency of probing.

To generate nonideal plasma, we used explosively driven shock waves which lead to compression and irreversible heating of xenon. A detonation accelerates a metal impactor and it runs into the bottom of the experimental cell which is filled with xenon at an initial pressure of 5 MPa and produces an intense shock wave in the gas. In figure 2, the explosively driven generator is shown.

In order to control the spatial and temporal plasma slug parameters, the optical image of the shock wave in xenon was recorded by a PCO camera, see figure 3. In the coordinate system of the snapshot the metal impactor motion occurred from the right to the left. The exposition time was $5 \times 10^{-9}$ s. In this snapshot, the reflected shock wave in the air is also visible. For the diagnostics of plasma parameters, the 1.5 mm$^2$ area of the front shock wave was used. Good flatness and homogeneity of the plasma can be seen.
To increase the accuracy of measurement of dense plasma polarized reflectivity indexes the reflected light energy distribution in space was scanned. In figure 4, reflected light energy distribution is shown. In figure 5, the measurement error of dense plasma polarized reflectivity indexes depending on shock wave skew is shown too.

The results of our measurements of the dense plasma polarized reflectivity indexes are presented in tables 1–3.

3. Analysis
The thermodynamic parameters of the plasma were determined from the measured shock wave velocity. Working with a grand canonical ensemble, virial corrections have been taken into account due to charge charge interactions (Debye approximation). Short-range repulsion of heavy particles was considered within the framework of a soft sphere model \[8,9]\. In accordance with these calculations, the free electron density \(n_e = 7.1 \times 10^{21} \text{ cm}^{-3}\) has been obtained at \(\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}\) and \(n_e = 7.8 \times 10^{21} \text{ cm}^{-3}\) at \(\nu_{\text{las}} = 4.33 \times 10^{14} \text{ s}^{-1}\) and \(\nu_{\text{las}} = 5.66 \times 10^{14} \text{ s}^{-1}\).
Table 1. Experimental results for s- and p-polarized reflectivities of explosively driven dense xenon plasma at $v_{\text{las}} = 2.83 \times 10^{14}$ 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$^\circ$ | 0.37   | 0.37   |           |         |                     |                 |                 |                 |        |        |
| 10$^\circ$ | 0.41   | 0.35   |           |         |                     |                 |                 |                 |        |        |
| 20$^\circ$ | 0.47   | 0.32   |           |         |                     |                 |                 |                 |        |        |
| 30$^\circ$ | 0.52   | 0.25   |           |         |                     |                 |                 |                 |        |        |
| 40$^\circ$ | 0.64   | 0.17   |           |         |                     |                 |                 |                 |        |        |
| 45$^\circ$ | 0.65   | 0.158  |           |         |                     |                 |                 |                 |        |        |
| 50$^\circ$ | 0.7    | 0.163  | 10.5      | 29250   | 2.70                | $7.1 \times 10^{21}$ | $5.4 \times 10^{21}$ | 0.57   | 1.8    | 1.9    |
| 55$^\circ$ | 0.74   | 0.165  |           |         |                     |                 |                 |                 |        |        |
| 60$^\circ$ | 0.73   | 0.17   |           |         |                     |                 |                 |                 |        |        |
| 65$^\circ$ | 0.8    | 0.223  |           |         |                     |                 |                 |                 |        |        |
| 70$^\circ$ | 0.85   | 0.28   |           |         |                     |                 |                 |                 |        |        |
| 75$^\circ$ | 0.89   | 0.52   |           |         |                     |                 |                 |                 |        |        |
| 78$^\circ$ | 0.91   | 0.59   |           |         |                     |                 |                 |                 |        |        |

Table 2. Experimental results for s- and p-polarized reflectivities of explosively driven dense xenon plasma at $v_{\text{las}} = 4.33 \times 10^{14}$ 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$^\circ$ | 0.26   | 0.26   |           |         |                     |                 |                 |                 |        |        |
| 10$^\circ$ | 0.31   | 0.24   |           |         |                     |                 |                 |                 |        |        |
| 20$^\circ$ | 0.37   | 0.18   |           |         |                     |                 |                 |                 |        |        |
| 30$^\circ$ | 0.384  | 0.15   |           |         |                     |                 |                 |                 |        |        |
| 35$^\circ$ | 0.52   | 0.12   |           |         |                     |                 |                 |                 |        |        |
| 40$^\circ$ | 0.57   | 0.13   |           |         |                     |                 |                 |                 |        |        |
| 45$^\circ$ | 0.585  | 0.12   |           |         |                     |                 |                 |                 |        |        |
| 50$^\circ$ | 0.55   | 0.15   | 12        | 32020   | 2.80                | $7.8 \times 10^{21}$ | $5.0 \times 10^{21}$ | 0.56   | 1.7    | 1.9    |
| 55$^\circ$ | 0.61   | 0.14   |           |         |                     |                 |                 |                 |        |        |
| 60$^\circ$ | 0.72   | 0.19   |           |         |                     |                 |                 |                 |        |        |
| 65$^\circ$ | 0.79   | 0.33   |           |         |                     |                 |                 |                 |        |        |
| 70$^\circ$ | 0.78   | 0.3    |           |         |                     |                 |                 |                 |        |        |
| 75$^\circ$ | 0.82   | 0.56   |           |         |                     |                 |                 |                 |        |        |
| 78$^\circ$ | 0.87   | 0.61   |           |         |                     |                 |                 |                 |        |        |

In tables 1–3, the respective thermodynamic parameters of the dense plasma are presented too.

To investigate the angle and polarization dependent reflectivity at the plasma front, a theoretical description of the propagation of electromagnetic waves in an inhomogeneous medium has been applied.

The polarized reflectivity coefficient of dense plasma can be obtained directly from the
Table 3. Experimental results for 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.

| $\theta$ (°) | $R_s$  | $R_p$  | $P$, 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°    | 0.20  | 0.12  |         |        |                |               |                |                 |       |       |
| 20°    | 0.21  | 0.11  |         |        |                |               |                |                 |       |       |
| 30°    | 0.30  | 0.085 |         |        |                |               |                |                 |       |       |
| 35°    | 0.39  | 0.07  |         |        |                |               |                |                 |       |       |
| 40°    | 0.37  | 0.083 | 12      | 32020  | 7.8 $\times$ 10$^{21}$ | 5.0 $\times$ 10$^{21}$ | 0.56 | 1.7   | 1.9   |
| 45°    | 0.48  | 0.14  |         |        |                |               |                |                 |       |       |
| 50°    | 0.50  | 0.17  |         |        |                |               |                |                 |       |       |
| 55°    | 0.58  | 0.19  |         |        |                |               |                |                 |       |       |
| 60°    | 0.61  | 0.3   |         |        |                |               |                |                 |       |       |
| 65°    | 0.72  | 0.43  |         |        |                |               |                |                 |       |       |

Figure 6. S- and p-polarized reflectivity indexes of strongly correlated dense plasma calculated in comparison to the experimental data for laser light at $\nu_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$, $\nu_{\text{las}} = 4.33 \times 10^{14}$ s$^{-1}$ and $\nu_{\text{las}} = 5.66 \times 10^{14}$ s$^{-1}$.

solution of Helmholtz equations. In figure 6, results of solving this equations using the generalized Drude formula and the dynamical collision frequency in Born approximation [10] are shown.

Results of the calculations with layer temperature profile and electron–atom collisions as factor are shown in figure 6 too.
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, which 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. Calculations with electron–atom collisions as factor describe the experimental data more correctly.

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