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Interaction of explosively driven dense plasmas with a low-intensity laser radiation

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Abstract
The results of first experiments on reflectivity of polarized light on an explosively driven dense xenon plasma are presented. The study of polarized reflectivity properties of the plasma was accomplished using a laser light of wavelength $\lambda = 1064$ nm and at incident angles $\theta = 0$–$30°$. With density $\rho = 2.7$ g cm^{-3}, pressure $P = 10.5$ GPa and temperatures up to $T \sim 3{\cdot}10^4$ K of the investigated plasma, conditions with strong Coulomb interaction (the nonideality parameter up to $\Gamma \sim 2.0$) were present. Reflectivities, which were calculated via the Helmholtz equation incorporating a density profile for the plasma surface, are compared to the experimental results.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The investigation of properties of an electronic subsystem in a strongly correlated plasma remains an ongoing problem in the physics of high-density energy. The analysis of the response of dense plasma to electromagnetic waves of moderate intensity, e.g., via transport properties, can be used as a tool for investigating the validity of the physical models describing the behavior of matter under extreme conditions, high temperatures and pressures.

The reflectivity of a shock-compressed dense xenon plasma using normal incidence has been investigated at wavelengths 1064 nm [1, 2], 694 nm [2–4] and 532 nm [5]. Plasmas created have transitive surfaces with a density profile. Reflectivity measurements have been used to fit parameters of the density profile. Extension of experimental conditions to find the

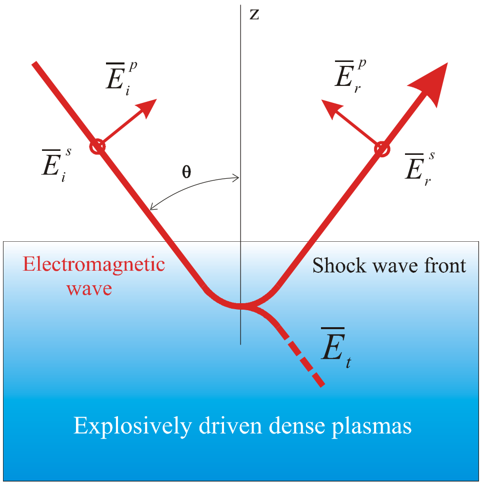

Figure 1. Interaction of plasmas with polarized electromagnetic wave.

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 detail because the small changes of layer parameters cause the considerable variations of the total reflectivity of the shock-compressed plasma.

2. The measurement technique and results

The research of transitive layers of explosively driven dense plasmas can be carried out using the technique of inclined probing by polarized electromagnetic waves. In figure 1, the scheme of interaction of plasma with an electromagnetic wave of moderate intensity is shown. To determine the Stokes's vector components, a four-channel pulse high-speed device has been used. The device allows us to measure the intensity of the reflected laser beam for four azimuthal angles and was equipped with filters for selection of frequency of probing.

In figure 2, the experimental setup is shown. To generate a nonideal plasma, we used explosively driven shock waves which lead to compression and irreversible heating of xenon. A detonation accelerates a metal impactor up to velocities of 6 km s^{-1}. The impactor 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. 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.

To measure the dense xenon plasmas polarized reflectivity coefficient, a pulsed Al_2O_3:Cr^{3+} and $Y_3Al_5O_{12}$:Nd^{3+} + KTP laser system with an electro-optical shutter based on a DKDP crystal and higher-order mode suppression of laser radiation was used. Now we used only 1064 nm channel, and further research will be executed with 694 nm and 532 nm channels. The probe pulse of about 30 ns duration 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.

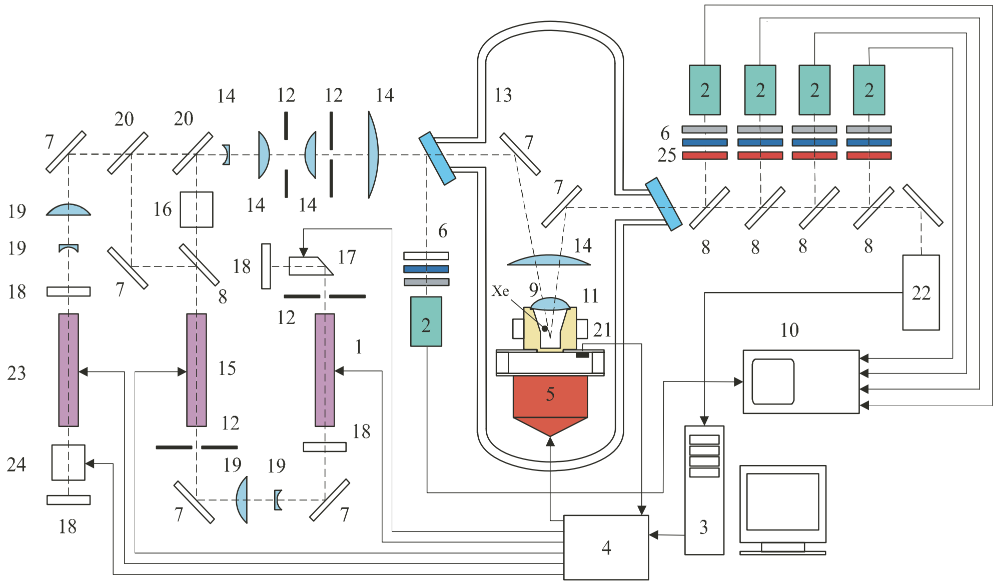

Figure 2. Experimental setup. 1: $Y_3Al_5O_{12}:Nd^{3+}$ laser, 2: multichannel photodetector, 3: control computer, 4: high-speed control block, 5: explosively driven generator, 6: interference filters, 7: mirror, 8: laser beam splitter, 9: axicon, 10: digitizing oscilloscope, 11: gas cell, 12: diaphragm, 13: explosive chamber, 14: lens, 15: $Y_3Al_5O_{12}:Nd^{3+}$ amplifier, 16: KTP crystal, 17: electro-optical DKDP shutter, 18: laser mirror, 19: telescope, 20: mirror, 21: gas cell thermostat, 22: spectroscope, 23: $Al_2O_3:Cr^{3+}$ laser, 24: electro-optical DKDP shutter.

3. Analysis

The measurements of polarized reflectivity coefficients of explosively driven dense plasmas have been carried out at incident angles $\theta = 0$, 10 and 30° simultaneously for s- and p-polarization, respectively.

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 [6–9]. 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. In accordance with these calculations, the free electron density $n_e = 7.1 \times 10^{21}$ cm^{-3} has been obtained.

During the experiments, the plasma density $\rho = 2.7$ g cm^{-3}, pressure $P = 10.5$ GPa and temperature $T = 29\,250$ K were realized. Under these conditions, the plasma is non-degenerate and can be characterized by the nonideality parameter $\Gamma = e^2(4\pi n_e/3)^{1/3}/(4\pi\varepsilon_0 k_B T) = 1.8$. The results of our measurements at the wavelengths of $\lambda = 1064$ nm and the respective thermodynamic parameters are presented in table 1 and figure 3 (circles and triangles).

The polarized reflectivity coefficient of the dense plasma can be obtained directly from the solution of the Helmholtz equations for the complex amplitude of the electric and magnetic fields with frequency ω:

$$\frac{d^2 E_0(z)}{dz^2} + \frac{\omega^2}{c^2}(\varepsilon(\omega, z) - \sin^2\theta)E_0(z) = 0, \tag{1}$$

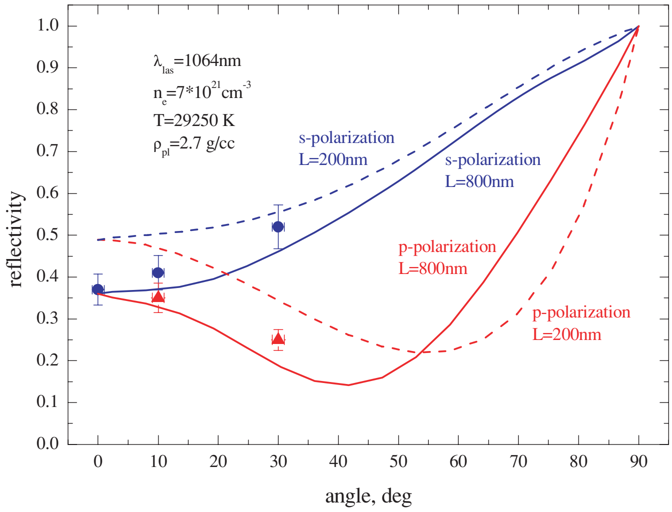

Figure 3. Angular dependence of s-(circles) and p-polarized (triangles) reflectivities of the dense plasma. Solid and dashed curves are calculations for the thickness of transitive layers, $L = 200$ nm and $L = 800$ nm.

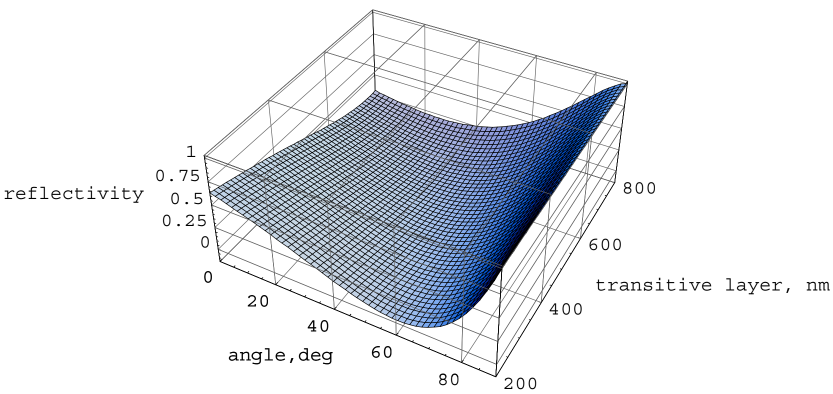

Figure 4. Angular dependence of p-polarized reflectivity versus thickness of the transitive layer. The location of angular dependence minimum shifts from large angles to small angles with increasing of transitive layer thickness.

Table 1. Experimental results for the s- and p-polarized reflectivities of explosively driven dense xenon plasma at wavelength $\lambda_{\rm laser} = 1064$ nm and thermodynamic parameter values: pressure P, temperature T, mass density ρ, free-electron number density n_e, density of neutral atoms n_a, ionization degree $\alpha_{\rm ion} = n_e/(n_a + n_e)$, nonideality parameter Γ and degeneracy parameter Θ.

θ (°)	R_s	R_p	P (GPa)	T (K)	ρ (g cm^{-3})	n_e (cm^{-3})	n_a (cm^{-3})	$\alpha_{\rm ion}$	Γ	Θ
0	0.37	0.37								
10	0.42	0.35	10.5	29 250	2.70	7.1×10^{21}	5.4×10^{21}	0.57	1.8	1.9
30	0.51	0.25								

$$\frac{d^2 H_0(z)}{dz^2} - \frac{dH_0(z)}{dz}(\log \varepsilon(\omega, z))' + \frac{\omega^2}{c^2}(\varepsilon(\omega, z) - \sin^2\theta)H_0(z) = 0. \qquad (2)$$

In figures 3 and 4, results of solving equations (1) and (2) using the generalized Drude formula [10], the dynamical collision frequency in the Born approximation [10] and an electron density profile of the plasma as obtained in work [5] are presented. We obtain a minimum in the angular dependence of the p-polarized reflectivity, $R_p(\theta)$. Its position is strongly influenced by the assumed thickness of a transitive slice of the explosively driven dense plasmas. Thus, the position of minimum can be a relative measure of layer thickness.

4. Conclusions

In this paper, we present the results of first experiments on reflectivity of polarized light on an explosively driven dense plasma. The data of the new experiments at the several wavelengths and at the sufficient set of the incident angles will allow us to fit the transitive layer parameters more precisely (comparison with [5]) as measurements will be carried out on the plasma with the same spatial profile of the density of charge carriers.

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