Optical properties of the dense xenon plasma

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Introduction. Optical reflectivity and collision processes [1–12] have attracted considerable attention recently because these processes can be used as diagnostic tools for investigating the plasma parameters in various astrophysical and laboratory plasmas. The measurements of reflectivity and theoretical analysis of the results are the common methods of investigation of the phase diagrams of substances [13], in particular, in shock wave experiments where the number of measured parameters is limited. The first study of reflectivity and the Brewster angle of the shock-compressed xenon was performed with laser radiation wavelengths λ_{las} = 1064, 694, and 532 nm in the unique experiments of Mintsev and Zaporoghets [14, 15], in which the plasma was generated by dynamic compression of gaseous xenon by a powerful shock wave. There have been many attempts to give a theoretical description of the experimental data. The main purpose of the experiment [14] was an attempt to estimate the density of the free charges and the plasma frequency of shock-compressed xenon based on measurements of the dependence of the reflectivity on the temperature and density.

The effective Ramazanov-Dzhumagulova (RD) potential of electron-ion interactions, considering the effects of static or dynamic screening and diffraction [16-18], can be written as:

$$\Phi_{ei}(r) = -Ze^2\left(e^{-B_{ei}r} - e^{-A_{ei}r}\right)\Big/\left(r\sqrt{C}\right), \tag{1}$$

In Refs. [18-20] the effective Ramazanov-Dzhumagulova-Omarbakiyeva (RDO) potential of electron-atom interaction was presented, considering the effects of static or dynamic screening and diffraction,

$$\Phi_{ea}\left(r\right) = -e^2\alpha_p\left(e^{-B_{ea}r}\left(1+B_{ea}r\right) - e^{-A_{ea}r}\left(1+A_{ea}r\right)\right)^2\Big/\left(2r^4C\right), \tag{2}$$

Fresnel formulas and dielectric function of the plasma. For the transition from the vacuum to a plasma (normal incidence), the reflection coefficient $R(\omega)$ is related to the dielectric function $\varepsilon(\omega)$ according to the well-known Fresnel formula

$$R(\omega) = \left|\frac{n-1}{n+1}\right|^2 = \left|\frac{\sqrt{\varepsilon(\omega)}-1}{\sqrt{\varepsilon(\omega)}+1}\right|^2. \tag{3}$$

For arbitrary incidence, the reflectivity of the plasma depends on the incident angle θ and polarization (s or p) of the impacting laser light. For s-polarization, the reflectivity is determined by the following relation

$$R_s = \left(\frac{\left|\cos\theta - \sqrt{\varepsilon - \sin^2\theta}\right|}{\left|\cos\theta + \sqrt{\varepsilon - \sin^2\theta}\right|}\right)^2. \tag{4}$$

For p-polarization, the reflectivity is given by the formula

$$R_p = \left(\frac{\left|\varepsilon\cos\theta - \sqrt{\varepsilon - \sin^2\theta}\right|}{\left|\varepsilon\cos\theta + \sqrt{\varepsilon - \sin^2\theta}\right|}\right)^2. \tag{5}$$

The dielectric function is defined by the Drude-Lorentz formula

$$\varepsilon(\omega) = 1 - \frac{\omega_{pl}^2}{\omega\left[\omega + i\nu(\omega)^{(1)}\right]}. \tag{6}$$

Collisions are taken into account by the total dynamical collision frequency $\nu(\omega)$ which includes in addition to the charged particle part ν_{ei} also the neutral part ν_{ea} (Matthiesen rule, see Ref. [37]), $\nu(\omega)^{(1)} = \nu_{ei}(\omega) + \nu_{ea}(\omega)$.

Results for reflectivity. Results of the reflectivity calculations using the expressions given in second section and the comparison with recently measured data for shock-compressed Xe are shown in figures 1-2, where the reflectivity is presented as function of the incident angle θ.

Figure 1 shows the dependence of the reflectivity of s-polarized and p-polarized radiation on the incident angle for electron-ion interaction (1) as well as electron-atom interaction (2) at different values of the wavelengths. Figure 2 presents the dependence of the reflectivity of s-polarized and p-polarized radiation on the incident angle for e-i interaction (1) as well as electron-atom interaction (2) in comparison with the theoretical and experimental data for $\lambda_{las} = 694nm$. Figure 2 presents results obtained on the basis of the different effective interaction potentials and comparison with the experimental data. The importance of taking into account of the dynamic screening effect in the reflectivity coefficient is clearly seen, if we compare with curves with static screening effect. The static potential does not correctly describe the experimental data with p-polarization. The use of the dynamic potentials leads to a good agreement with the experimental data only at $\theta = 0$. We conclude that the use of the dynamic potential leads to a good agreement with results obtained from simulations performed in Ref. [8].

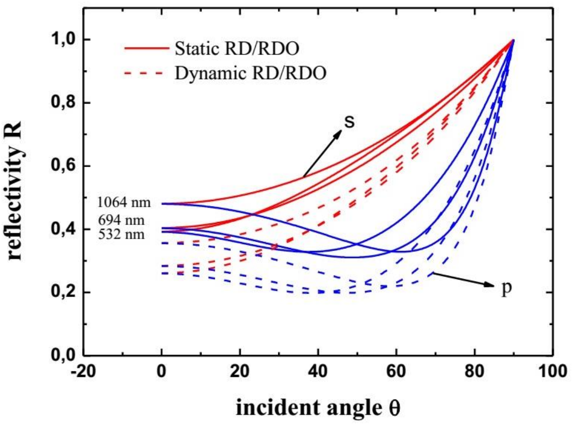

Fig. 1. Reflectivity of s-polarized (red) and p-polarized (blue) radiation for different incident angles and wavelengths, calculated within Born approximation for e-i interaction (RD potential) as well as e-a interaction (RDO potential). The dynamic screening leads to a reduced reflectivity and better agreement with the experimental results, see Figure 2.

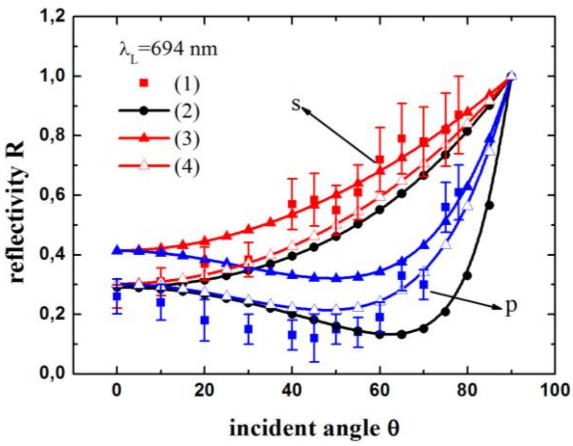

Fig. 2. Calculated reflectivity in comparison with the experimental data for $\lambda_{las} = 694 nm$. S-polarization is red, p-polarization is blue. 1-experimental data are shown as points, 2-Ref. [8]: black circle line, 3-on the basis of the static (RD/RDO) potential: solid triangle line, 4-on the basis of the dynamic (RD/RDO) potential: open triangle line.

Conclusion

Based on the dynamic treatment of the effective charged particles interaction in nonideal plasmas, the reflectivity of the plasma was investigated. The experimental values of reflectivity from a shock wave produced xenon plasma with high density, performed at incident laser radiation with different wavelengths λ_{las}, different incident angles θ and polarizations are analysed. Quantum mechanical and semiclassical methods have been used for the calculation of the collision frequency. Analysis of the results showed that the dependencies of reflectivities on the incident angle obtained with taking into account the dynamic screening are lower than the data obtained with consideration of static charge screening. Our calculations show that the systematic treatment of electron-atom interaction in addition to the electron-ion interaction is essential for the explanation of experimental results. The detailed investigation of the properties of dense plasmas, such as the dielectric function considered here, is of interest for the design of the technical installations associated with the use of the dense nonideal plasma, for example, inertial confinement fusion facilities.

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