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Reflectivity of nonideal plasmas

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Abstract
New results on optical reflectance measurements of shock-compressed dense xenon plasma at wavelengths $\lambda = 532$ nm and $\lambda = 694$ nm are reported. The investigations have been performed for nonideal plasma ($\Gamma = 0.87$–2.0) at densities $\rho = 0.27$–3.84 g cm^{-3} and pressures $P = 1.6$–17 GPa. The obtained high optical reflectance values are characteristic of a metallic fluid and are evidence for a conducting state in the shocked xenon. Reflectance measurements at different wavelengths provide information about the density profile of the shock wave front.

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1. Introduction

For further development of nonideal plasma physics, investigations of its electronic properties appear to be crucial. In particular, optical reflectance are an important diagnostic tool: the reflectivity is expected to give information on the free-charge carrier density.

Reflectivity measurements under shock wave compression have been performed for different materials [1–3]. 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 [2, 3]. So far, the reflectivity of shock-compressed dense xenon plasma had been done at the wavelengths $\lambda = 1064$ nm [3, 4] and $\lambda = 694$ nm [4–6]. In this paper, we report new results at the wavelengths $\lambda = 694$ nm and $\lambda = 532$ nm. Theoretical approaches can be checked against these new experimental findings. The description will need to go beyond the context of a Drude formula. Assuming a spatially extended density profile in the shock wave front allows a qualitatively good agreement of theory and experiment.

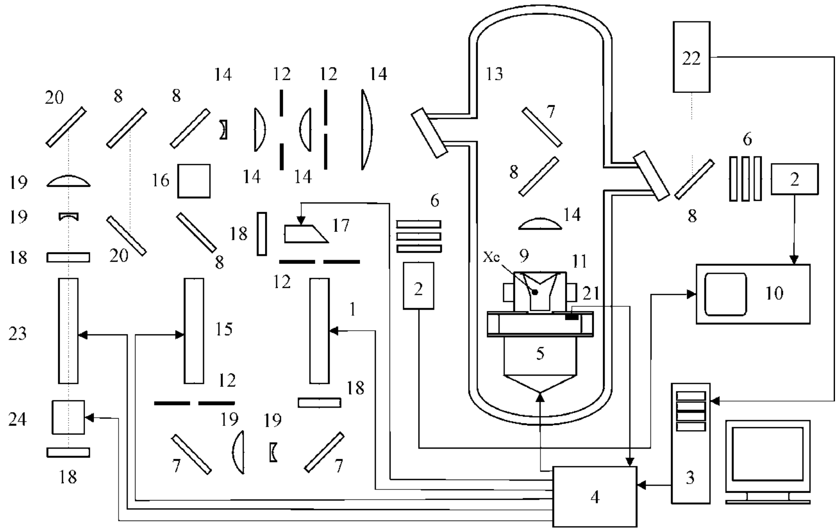


Figure 1. Experimental set-up. 1—$Y_3Al_5O_{12}$:Nd^{3+}+ laser, 2—multichannel photodetector, 3—control computer, 4—high-speed control block, 5—explosively driven generator, 6—interference filters, 7—mirror, 8—laser beam splitter, 9—axicon, 10—digitizing oscilloscope, 11—gas cell, 12—diaphragm, 13—explosive chamber, 14—lens, 15—$Y_3Al_5O_{12}$:Nd^{3+}+ three-pass 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.

2. Reflectivity measurement technique and results

To generate dense xenon plasma we used explosively driven shock waves which lead to compression and irreversible heating of the investigated gas. As the result of a detonation of high explosives a metal impactor is accelerated up to velocities of 5–6 km s^{-1}. The impactor runs into the bottom of the experimental vessel which is filled with xenon of an initial pressure of 2–5.7 MPa and produces an intense shock wave in the gas. For generating plasma at well-defined parameters it is necessary to produce plane and stationary shock waves. In order to control the flatness and homogeneity of the plasma layer, the optical image of the shock wave in xenon was recorded by a PCO camera.

To measure the dense xenon plasma reflection 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. 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 the axicon receiving optical unit and the special high speed synchronization block with the ionization gauges, located on the gas cell. Along the whole axicon caustic the condition for an adequate reception of a reflected signal was ensured. The functioning of the optical receiving unit was checked by using static and low-speed dynamic objects with a well-known reflection coefficient.

The interaction region of the laser light with the plasma layer was about 1.5 mm in diameter. With a probe radiation flux density of 10^4 W cm^{-2}, the plasma does not get noticeably further heated. The detection of the reflected radiation is carried out by multichannel broadband photodetectors. The interference filters with $\delta\lambda = 50$ Å were applied for the selection of the

Table 1. $\lambda = 1064$ nm [3].

P (GPa)	R^{exp}	T (K)	ρ(g cm^{-3})	n_e (cm^{-3})	n_a (cm^{-3})	α_{ion}	Γ	Θ
1.6	0.096	30 050	0.51	1.8×10^{21}	6.1×10^{20}	0.75	1.1	4.8
3.1	0.12	29 570	0.97	3.2×10^{21}	1.4×10^{21}	0.70	1.3	3.2
5.1	0.18	30 260	1.46	4.5×10^{21}	2.2×10^{21}	0.67	1.5	2.6
7.3	0.26	29 810	1.98	5.7×10^{21}	3.5×10^{21}	0.62	1.6	2.2
10.5	0.36	29 250	2.70	7.1×10^{21}	5.4×10^{21}	0.57	1.8	1.9
16.7	0.47	28 810	3.84	9.1×10^{21}	8.6×10^{21}	0.51	2.0	1.6

Table 2. $\lambda = 694$ nm.

P (GPa)	R^{exp}	T (K)	ρ(g cm^{-3})	n_e (cm^{-3})	n_a (cm^{-3})	α_{ion}	Γ	Θ
0.93	0.02	32 070	0.27	1.1×10^{21}	2.1×10^{20}	0.78	0.87	7.1
1.9	0.05	32 900	0.53	2.1×10^{21}	4.8×10^{20}	0.72	1.0	4.8
4.1	0.11	33 100	1.1	4.0×10^{21}	1.3×10^{21}	0.69	1.3	3.2
6.1	0.14	33 120	1.6	5.2×10^{21}	2.1×10^{21}	0.64	1.4	2.6
9.1	0.18	32 090	2.2	6.6×10^{21}	3.6×10^{21}	0.60	1.6	2.1
12.0	0.26	32 020	2.8	7.8×10^{21}	5.0×10^{21}	0.56	1.7	1.9
16.0	0.40	31 040	3.4	8.8×10^{21}	7.3×10^{21}	0.54	1.8	1.7

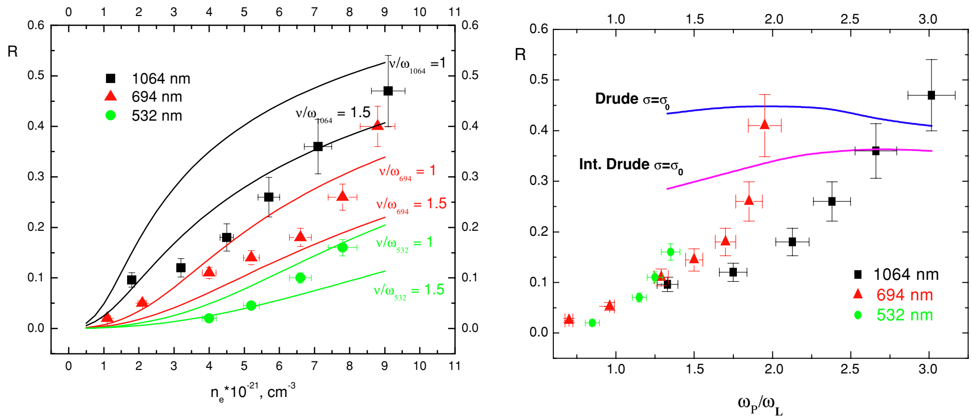
Table 3. $\lambda = 532$ nm.

P (GPa)	R^{exp}	T (K)	ρ(g cm^{-3})	n_e (cm^{-3})	n_a (cm^{-3})	α_{ion}	Γ	Θ
4.1	0.02	33 100	1.1	4.0×10^{21}	1.3×10^{21}	0.69	1.3	3.2
6.1	0.045	33 120	1.6	5.2×10^{21}	2.1×10^{21}	0.64	1.4	2.6
9.1	0.10	32 090	2.2	6.6×10^{21}	3.6×10^{21}	0.60	1.6	2.1
12.0	0.16	32 020	2.8	7.8×10^{21}	5.0×10^{21}	0.56	1.7	1.9

spectral interval. The plasma reflection coefficient is then determined from the ratio of signal of the photodetector, which recorded the reflected radiation, and the probe impulse second photodetector signal. The accuracy of the reflection coefficient is better than 10%.

3. Analysis of experimental results

The thermodynamic parameters of the plasma were determined from the measured shock wave velocity. Plasma densities of $\rho = 0.27$–3.84 g cm^{-3}, pressures of $P = 1.6$–16.7 GPa and temperatures of up to $T = 33\,000$ K were realized during the experiments, see tables 1–3. The plasma composition was calculated within a chemical picture [7]. Working with a grand canonical ensemble [8, 9], 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. In accordance with these calculations, the free electron density n_e was 1.1–9.1 cm^{-3}. Under these conditions the plasma is nondegenerate ($\Theta = k_B T/E_F = 2m_e k_B T(3\pi^2 n_e)^{-2/3}/\hbar^2 = 1.6$–$7.1$) and can be characterized by the nonideality parameter $\Gamma = e^2(4\pi n_e/3)^{1/3}/(4\pi\varepsilon_0 k_B T) = 0.87$–$2.0$. The results of the reflectivity measurements at the wavelengths of $\lambda = 1064$ nm [4], $\lambda = 694$ nm, $\lambda = 532$ nm and the respective thermodynamic parameters are presented in tables 1, 2 and 3. The reflection coefficient shows a strong increase which indicates a transition from a dielectric to a metal-like behaviour.



(*a*) (*b*)

Figure 2. Reflection coefficient versus electron density (*a*) and ratio of plasma frequency and frequency of laser (*b*) radiation. The reflectivity values calculated with the modified Drude formula and the simple integral collision frequency estimation obtained under consideration of the kinetic equation for the electron speed distribution function (with Maxwell distribution for slowly varying part) are shown (Int Drude).

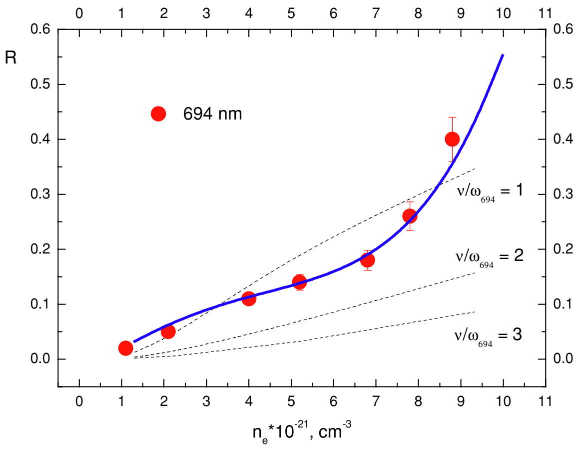


Figure 3. Reflectivity coefficient for xenon assuming profile with Richards-like decay compared with experimental results.

In figure 2, the reflection coefficient is shown as a function of the electron density n_e and as a function of the ratio of plasma frequency $\omega_P = (e^2 n_e/\varepsilon_0 m_e)^{1/2}$ and laser frequency ω_L. Assuming that the thickness of the shock wave front is smaller than the laser beam wavelength, the reflectivity can be directly calculated from the dielectric function [10, 11], for which we assume the Drude relation $\varepsilon = 1 - \omega_P^2 \big/ [\omega(\omega + i\nu)]$. Curves for constant collision frequencies ν/ω_L as parameters are included in figures 2 and 3. It can be seen that a simple Drude model for the reflectivity on a step-like density profile of the plasma front does not compare well with the experimental results.

As already shown in earlier work [10–12], assuming an electron density profile within a spatially extended shock wave front, a description of the mesurement points are possible.

Using the new results for the third wavelength, the parameterization of the density profile using a Richards-like decay was refined and a good agreement with the experimental data at the wavelength of $\lambda = 694$ nm (see figure 3) as well as at other wavelengths is obtained. The values for the reflectivity was calculated with the generalized Drude formula and the dynamical collision frequency in Born approximation [12] taken at the laser frequencies ω_L. A characteristic width of the shock wave front is about 800 nm. For a more detailed discussion, see also the article in this volume [13].

Acknowledgments

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References

[1] Löwer T, Kondrashov V N, Basko M, Kendl A, Meyer-ter-Vehn J, Sigel R and Ng A 1998 *Phys. Rev. Lett.* **80** 4000
[2] Celliers P M *et al* 2000 *Phys. Rev Lett.* **84** 5564
[3] Mintsev V B and Zaporoghets Yu B 1989 *Contrib. Plasma Phys.* **29** 493
[4] Zaporoghets Yu B, Mintsev V B, Gryaznov V K and Fortov V E 2002 *Physics of Extreme States of Matter* ed V E Fortov *et al* (Chernogolovka: IPCP) p 188 (in Russian)
[5] Reinholz H, Röpke G, Morozov I, Mintsev V B, Zaporoghets Yu B, Fortov V and Wierling A 2003 *J. Phys. A: Math. Gen.* **36** 5991
[6] Zaporoghets Yu B, Mintsev V B, Gryaznov V K, Fortov V E, Reinholz H and Röpke G 2004 *Physics of Extreme States of Matter* ed V E Fortov *et al* (Chernogolovka) p 140 (in Russian)
[7] Ebeling W 1969 *Physica* **43** 293
Ebeling W, Förster A, Fortov V, Gryaznov V K and Polishchuk A 1991 *Thermophysical Properties of Hot Dense Plasmas* (Stuttgart: Teubner)
[8] Fortov V E, Gryaznov V K, Mintsev V B, Ternovoi V Ya, Iosilevski I L, Zhernokletov M V and Mochalov M A 2001 *Contrib. Plasma Phys.* **41** 215
[9] Fortov V E *et al* 2003 *JETP* **97** 259–78
[10] Reinholz H, Röpke G, Morozov I, Mintsev V B, Zaporoghets Yu B, Fortov V and Wierling A 2003 *J. Phys. A: Math. Gen.* **36** 5991
[11] Reinholz H, Röpke G, Wierling A, Mintsev V and Gryaznov V 2003 *Contrib. Plasma Phys.* **43** 3
[12] Reinholz H, Zaporoghets Yu B, Mintsev V B, Fortov V E, Morozov I and Röpke G V 2003 *Phys. Rev.* E **68** 036403
[13] Raitza T, Reinholz H, Röpke G, Mintsev V, Zaporoghets Yu and Wierling A 2006 *J. Phys. A: Math. Gen.* **39** at press