UDC 533.9

Electrodynamical properties of the dense semiclassical plasmas

K.N. Dzhumagulova*, T.S. Ramazanov, A.K. Baidualiyeva, A. Bakirzhankyzy

Al-Farabi Kazakh National University, IETP, Faculty of physics and technology, al-Farabi 71, 050040 Almaty, Kazakhstan

**e-mail: dzhumagulova.karlygash@gmail.com*

In this work the dielectric function of the dense semiclassical collisionless plasmas was investigated on the basis of the interaction potential which takes into account the effects of diffraction in a wide range of temperatures and densities. The dielectric function was analytically and numerically investigated in approximation of high frequencies. We obtained the expression for the real part of the dielectric function for collisionless plasma in high – frequency limit within asymptotic approximation. All obtained results are in a good agreement. Taking into account of the diffraction effect in a wide region of temperature and densities can lead to perceptible change in the dielectric function.

Key words: dielectric function, collisionless plasma, interaction potential.
PACS numbers: 52.25.Mq, 52.27.Gr.

1 Introduction

It is well known that the dielectric function plays a key role in description of the electro-dynamic plasma properties. Using it one can describe the spectrum of the plasma waves, optical properties as well as many other phenomena [1-3]. In the dense plasmas the influence of the many-body effects and quantum mechanical effects increases. In this case the dielectric function can significantly differ from the dielectric function of the rarefied plasma. To adequately determine the dielectric function it is necessary to know the interaction potential of the plasma particles. Development of the particle interaction models and study of the strongly coupled dense plasmas properties on their basis are of a great fundamental and practical interest [4-9]. To take into account quantum mechanical effects in the interaction potential the special method was developed. It consists of the comparison of the classical Boltzmann's factor and the quantum mechanical Slater sum. This approach was first described in [10]. The Deutsch potential [8,9], which correctly considers the diffraction effect only at high temperatures, has the following form:

$$\Phi_{\alpha\beta}(r) = \frac{Z_\alpha Z_\beta e^2}{r}\left(1 - e^{-\frac{r}{\lambda_{\alpha\beta}}}\right). \qquad (1)$$

Here $\lambda_{\alpha\beta} = \hbar/\sqrt{2\pi m_{\alpha\beta} k_B T}$ is the de Broglie thermal wavelength; $m_{\alpha\beta} = m_\alpha m_\beta/(m_\alpha + m_\beta)$ – is the reduced mass of α and β interacted particles. In this work the following dimensionless parameters were used: $\Gamma = Z_\alpha Z_\beta e^2/(a k_B T)$ is the coupling parameter (the average distance between particles is $a = (3/4\pi n)^{1/3}$; $n = n_e + n_i$ is the numerical density of the electrons and ions; T is the plasma temperature; k_B is the Boltzmann constant); $r_s = a/a_B$ is the density parameter ($a_B = \hbar^2/m_e e^2$ is the Bohr radius).

In work [11] the interaction micropotential of the dense semiclassical plasma was obtained on the basis of the method [10] with help of interpolation of the numerical results in a wide region of temperatures and densities:

$$\Phi_{\alpha\beta}(r) = \frac{Z_\alpha Z_\beta e^2}{r}\left(1 - than(\sqrt{2}\frac{\lambda_{\alpha\beta}^2}{a^2+br^2})e^{-than(\sqrt{2}\frac{\lambda_{\alpha\beta}^2}{a^2+br^2})}\right)\times\left(1-e^{-r/\lambda_{\alpha\beta}}\right),\quad b=0.033, \quad (2)$$

where a is the average distance between particles. This micropotential (2) takes into account the quantum diffraction effect in a wide region of temperatures and densities.

Dielectric function $\varepsilon(\omega,k)$ is defined as the value characterizing the magnitude of charge screening in plasma. Dielectric function of the collisionless plasma in high – frequency limit can be presented by the following expression [1]:

$$\varepsilon(k,\omega) = 1 - \chi_e^0(k,\omega)\tilde{\varphi}_{ee}(k), \quad (3)$$

where $\tilde{\varphi}_{ee}(k)$ is the Fourier transform of the interaction micropotential between the electrons, the response function of the system of non-interacting particles is:

$$\chi_e^0(k,\omega) = -\frac{n_e}{k_B T}W\left(\frac{\omega}{k\text{v}_{Te}}\right), \quad (4)$$

where v_{Te} is the thermal velocity of the electrons, k is a wave vector.

$$W(z) = 1 - z\exp(-z^2/2) \cdot\int_0^z \exp(y^2/2)dy + i\sqrt{\frac{\pi}{2}}z\exp(-z^2/2). \quad (5)$$

Function $W(z)$ in the asymptotic expansion at the high-frequency approximation $\omega / kv_{Te} >> 1$ is

$$W(z) = iz\sqrt{\frac{\pi}{2}}\exp\left(-\frac{z^2}{2}\right) - \frac{1}{z^2} - \frac{3}{z^4} - ..... \quad (6)$$

2 Tasks and results

In this work the dielectric function of the dense semiclassical plasma was obtained on the basis of the potential (2). For obtaining of analytical expression for the dielectric function the exponents and tangent in the potential (2) were expanded and only the first term, giving the main contribution, was taken into account. The Fourier transform of such simplified form of the interaction potential (2) was deduced analytically and then we obtained the following expression for the real part of the dielectric function for collisionless plasma in high – frequency limit within asymptotic approximation

$$\mathrm{Re}(\varepsilon(k^*,\omega^*)) = 1 - \frac{(k^*)^2}{(\omega^*)^2}\cdot\left(\frac{1}{(k^*)^2+\frac{2\Gamma}{\pi r_s}} + \frac{\pi\frac{2\Gamma}{\pi r_s}}{k^*\sqrt{2b}} - \frac{\pi\left(\frac{2\Gamma}{\pi r_s}\right)^2}{k^* 2\sqrt{b}}\left(1+\frac{k^*}{\sqrt{b}}\right)\exp\left(-\frac{k^*}{\sqrt{b}}\right)\right), \quad (7)$$

here dimensionless wave vector and frequency are $\omega^* = \omega/\omega_p$, $k^* = ka$, where $\omega_p = \sqrt{4\pi n_e e^2/m_e}$ is the electron Langmuir frequency. Real part of the dielectric function within the Coulomb potential in this approach is presented by the following expression:

$$\mathrm{Re}(\varepsilon(\omega^*)) = 1 - \frac{1}{(\omega^*)^2}, \quad (8)$$

Real parts of the dielectric functions obtained by formula (7) and also for the Coulomb potential by formula (8), and for the Deutsch potential are shown in Fig. 1, 2. One can see that, the real part of the dielectric function obtained on the basis of the potential (2) (expression (7)) lies above the other curves and tends to the data obtained on the basis of the Deutsch potential at decreasing of the coupling parameter.

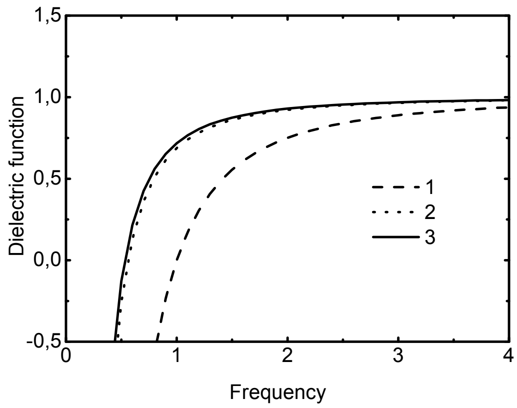

Figure 1 – The real part of the dielectric function obtained on the basis of: 1 – formula (8); 2 – the Deutsch potential; 3 – formula (7). $\Gamma = 0.5$, $ka = 0.1$, $r_s = 5$

For more precise estimation of the dielectric function we used again the equations (3), (4) and (6) but instead of an analytical expression for the Fourier transform of the potential (2), we used numerical method for its calculation. As a result we received data, which agrees qualitatively with the formula (7) (Fig. 3).

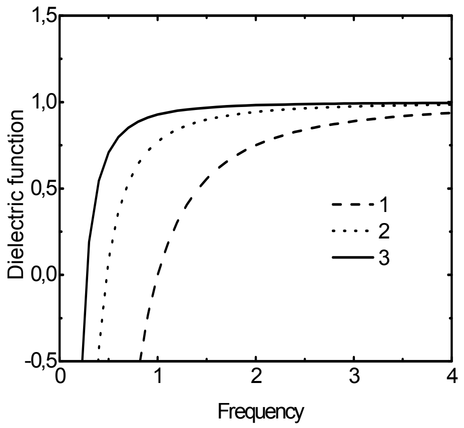

Figure 2 – The real part of the dielectric function obtained on the basis of: 1 – formula (8); 2 – the Deutsch potential; 3 – formula (7). $\Gamma = 1$, $ka = 0.1$, $r_s = 5$

In the third approach we obtained the dielectric function on the basis of the numerically calculated $W(z)$ (eq.(5)). Obtained results are presented on Fig. 4-6.

On fig. 4 and 5 one can see that the curves obtained on the basis of the Deutsch potential and potential (2) are close to each other and differ from result obtained on the basis of the Coulomb potential at increasing of the coupling parameter. Wherein the result on the basis the potential (2) differs stronger than that on the basis of the Deutsch potential. On fig. 6 the dielectric functions obtained on the basis of the potential (2) at different values of the coupling parameter are shown.

Based on all the obtained results one can conclude that taking into account of the diffraction effect in a wide region of temperature and densities can lead to perceptible change in the dielectric function.

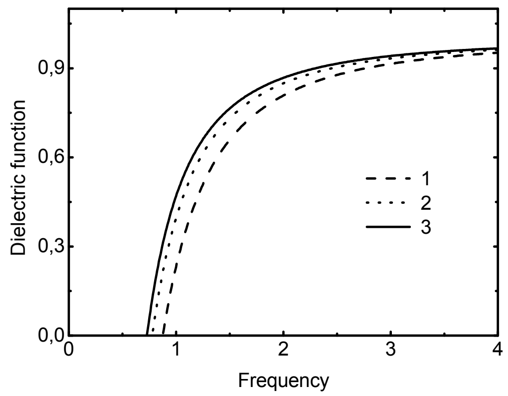

Figure 3 – Numerical calculation of the dielectric function in the asymptotic approximation obtained on the basis of: 1 – formula (8); 2 – the Deutsch potential; 3 – the potential (2). $\Gamma = 0.1$, $ka = 0.1$, $r_s = 5$

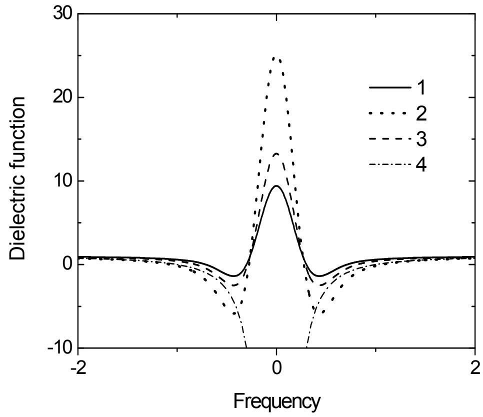

Figure 4 – Dielectric function obtained without asymptotic expansion on the basis of: 1 – the potential (2); 2 – the Coulomb potential; 3 – the Deutsch potential; 4 – formula (8). $\Gamma = 5$, $ka = 0.78$, $r_s = 1$

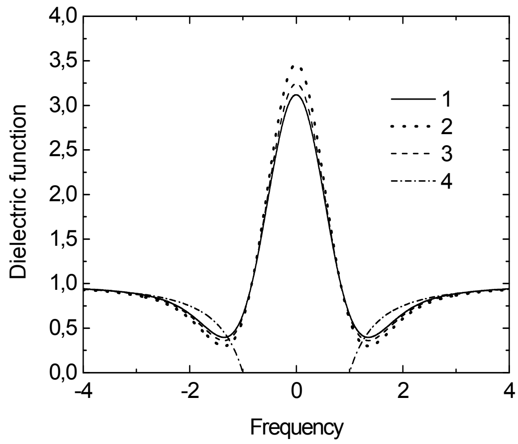

Figure 5 – Dielectric function obtained without asymptotic expansion on the basis of : 1 – the potential (2); 2 – the Coulomb potential; 3 – the Deutsch potential; 4 – formula (8). $\Gamma = 0.5$, $ka = 0.78$, $r_s = 1$

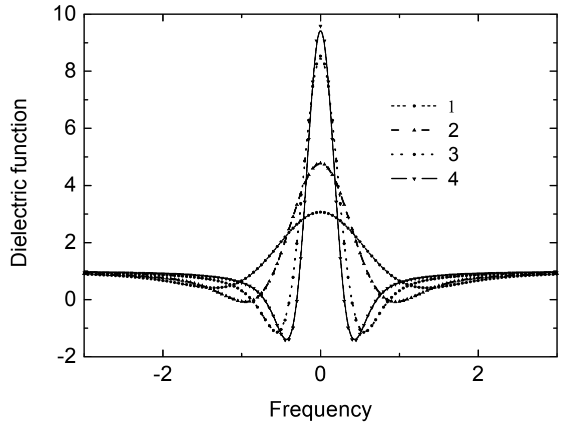

Figure 6 – Dielectric function obtained without asymptotic expansion on the basis of the potential (2) at different coupling parameter,
$ka = 0.78$, $r_s = 1$, 1) $\Gamma = 0.5$, 2) $\Gamma = 1$, 3) $\Gamma = 3$, 4) $\Gamma = 5$,

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