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Collisionless absorption in an overdense plasma with anisotropic electron distribution function

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Abstract. Collisionless absorption of linearly polarized electromagnetic wave in a plasma with anisotropic bi-Maxwellian electron velocity distribution is investigated. Due to the wave magnetic field influence on the electron kinetics in the skin layer, the wave absorption is found to significantly depend on the degree of the electron temperature anisotropy. Depending on the value of the skin layer anomaly parameter, and on the electron temperature anisotropy degree, the conditions are found when a significant decrease or increase of the collisionless absorption is expected.

PACS. 52.40.-w Plasma interactions (nonlaser) – 52.50.Jm Plasma production and heating by laser beams (laser-foil, laser-cluster, etc.)

1 Introduction

As a result of gas ionization by a powerful ultra-short laser pulse a plasma is formed exhibiting a strongly anisotropic photoelectron distribution over velocities (see, for instance [1–4]). In particular, in the regime of tunnel ionization the photoelectron distribution function is found to be close to an anisotropic bi-Maxwellian distribution [2]. Further, a qualitatively similar electron distribution function (EDF) is formed as a result of electron heating by a strong laser field through inverse bremsstrahlung [5,6]. After the plasma electron-laser interaction, the newly formed nonequilibrium EDF lasts for times of the order of ν_{e}^{-1}, ν_{e} being the effective electron collision frequency, or for times typical of the pertinent plasma instabilities development. One of such instabilities, limiting the existence time of the photoelectron nonequilibrium distribution, is the Weibel instability [7–10]. In any case, such nonequilibrium EDF corresponds to a plasma state with new physical properties. One of the peculiarities of such a plasma state is the significant anisotropy of its physical characteristics. For instance, as shown in [11], in such a plasma state a strong anisotropy of the collisional absorption of laser radiation takes place. In this paper, for this kind of plasma we investigate the peculiar features of the collisionless absorption when the skin-effect occurs. More precisely, below we investigate the absorption of a test linearly polarized field impinging normally on the surface of a plasma exhibiting an anisotropic bi-Maxwellian EDF, the test field frequency ω being much smaller than the electron plasma frequency ω_{L}. We take that the EDF symmetry axis lies in the plane coplanar to the plasma surface. With such a choice the absorption coefficient of the incident wave is determined by two components of the surface impedance, one of the two's significantly depending on the degree of anisotropy of the electron temperature. In Section 2 we derive the expressions of the surface impedance components and of the absorption coefficient. In Sections 3 and 4 we analyze analytically and numerically how the derived expressions depend on the parameter $\delta = v_{\mathrm{T}}\omega_{\mathrm{L}}/\omega c$, characterizing the degree of the skin effect anomaly, and on the parameter $\varDelta = 1 - T_x/T_\perp$, giving the electron temperature anisotropy degree. v_{T}, c, T_x and $T_\perp$, appearing in δ and $\varDelta$, are, respectively, the electron thermal velocity along the normal to the plasma surface; the speed of light; and the two plasma effective temperatures. We show that in an anisotropic plasma are possible both the decrease and the increase of absorption as compared to the case of an isotropic plasma. When $\varDelta > 0$, for any value of δ, a relative decrease of absorption is found. On the contrary, when $\varDelta < 0$ and $\delta < \max(|\varDelta|^{-1/6}, |\varDelta|^{-3/2})$, we find a significant increase of absorption of radiation with the polarization vector forming a small angle with the EDF symmetry axis. For all the other values of δ and $\varDelta < 0$ the anisotropy yields a decrease of absorption. The reported results are a consequence of the influence of the wave magnetic field on the electron kinetics in the skin layer.

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2 Impedance of an anisotropic plasma

Let us investigate a plasma with the bi-Maxwellian EDF

$$F = \left(\frac{m}{2\pi}\right)^{3/2} \frac{N}{T_\perp\sqrt{T_x}} \exp\left[-\frac{mv_x^2}{2T_x} - \frac{m}{2T_\perp}\left(v_y^2 + v_z^2\right)\right], \tag{1}$$

with N the electron density, m the electron mass, and the two effective temperatures T_x and $T_\perp$ given in energy units. EDF's like (1) are formed either as a result of tunnel ionization of atoms [2], or of electron heating through nonlinear inverse bremsstrahlung absorption [5,6]. Besides, such EDF's sometimes are used to model anisotropy effects due to nonuniformity of electron temperature [12,13].

Let us assume that the plasma occupies the half-space $z > 0$, and consider the interaction of such a plasma with a weak linearly polarized electromagnetic wave, impinging normally on the plasma surface

$$\mathbf{E}\cos(\omega t - kz), \quad z < 0, \tag{2}$$

with $\mathbf{E} = (E_x, E_y, 0) = E(\cos\phi, \sin\phi, 0)$, ϕ the angle between the electric field polarization direction $\mathbf{E}$ and the Ox-axis; ω and k the frequency and wave number of the e.m. wave, $\omega = kc$. The wave frequency ω is assumed much smaller than the electron plasma frequency $\omega_\mathrm{L} = \sqrt{4\pi e^2 N/m}$, where e is the electron charge. The wave (2) is reflected by the plasma surface and partially penetrates into the plasma, where it is absorbed as a result of interaction with the electrons. Being interested in the field inside the plasma, we will consider such physical conditions, when the influence of electron collisions may be completely neglected. Collisions may be disregarded in a sufficiently hot and not very dense plasma, in particular when are realized the conditions corresponding either to the high-frequency or to the anomalous skin effect (see, for instance [12–17]). Further, we consider the simplest boundary conditions on the plasma surface. Namely, we assume that electrons are specularly reflected by the plasma boundary. Provided these conditions are fulfilled, following the traditional approach to treat the skin effect [18,19], it is not a difficult task to find the plasma impedance. In the geometry of interaction chosen here, only two components of the impedance are important. One is Z_x, which describes the reflection and absorption of the E_x component; the other is Z_y, which defines the response to the E_y component. The quantities $Z_{x(y)}$ are related to the corresponding components of the plasma dielectric permettivity $\epsilon_{x(y)}$ through the expressions

$$Z_{x(y)} = -\frac{2\mathrm{i}}{\pi}k\int_0^\infty \frac{\mathrm{d}q}{q^2 - k^2\epsilon_{x(y)}(q)}\cdot \tag{3}$$

When the electrons have a velocity distribution like (1), the functions $\epsilon_{x(y)}(q)$ are given by

$$\epsilon_y(q) = 1 - \frac{\omega_\mathrm{L}^2}{\omega^2}J_+\left(\frac{\omega}{qv_\mathrm{T}}\right), \tag{4}$$

and

$$\epsilon_x(q) = 1 - \frac{\omega_\mathrm{L}^2}{\omega^2}J_+\left(\frac{\omega}{qv_\mathrm{T}}\right) - \Delta\frac{\omega_\mathrm{L}^2}{\omega^2}\left[1 - J_+\left(\frac{\omega}{qv_\mathrm{T}}\right)\right], \tag{5}$$

where $v_\mathrm{T} = \sqrt{T_\perp/m}$, $\Delta = 1 - T_x/T_\perp$, and the function J_+ has the form [20,21]

$$J_+(x) = J'_+(x) + \mathrm{i}J''_+(x), \tag{6}$$

$$J'_+(x) = x\exp\left(-\frac{x^2}{2}\right)\int_0^x \mathrm{d}t\exp\left(\frac{t^2}{2}\right), \tag{7}$$

$$J''_+(x) = -\sqrt{\frac{\pi}{2}}x\frac{q}{|q|}\exp\left(-\frac{x^2}{2}\right)\cdot \tag{8}$$

The differences in the functions ϵ_x and ϵ_y are due to the presence of the parameter Δ, characterizing the degree of anisotropy of the electron temperatures. The impedance components (3) determine the reflection and absorption coefficients R and A of a plasma with the anisotropic bi-Maxwellian EDF (1) according to the relations

$$R_{x(y)} = \frac{(Z_{x(y)} - 1)}{(Z_{x(y)} + 1)}, \tag{9}$$

$$R = |R_x|^2\cos^2\phi + |R_y|^2\sin^2\phi, \tag{10}$$

$$A = 1 - R. \tag{11}$$

Under the conditions considered here, the absolute values of the real and imaginary parts $Z'_{x(y)}$ and $Z''_{x(y)}$ of the corresponding impedance components $Z_{x(y)} = Z'_{x(y)} + \mathrm{i}Z''_{x(y)}$ are much smaller than unity. It allows to write the approximate expression of the absorption coefficient (11),

$$A = 4Z'_x\cos^2\phi + 4Z'_y\sin^2\phi. \tag{12}$$

The absorption coefficient (12) has been obtained under the assumption that the electron collision frequency, including both electron-electron and electron-ion collisions, is negligibly small. The departure of A from zero is due to Landau collisionless absorption. From (12) it can be seen that to describe how the absorption coefficient depends on the plasma and radiation field parameters it is sufficient to give the corresponding description of the real parts of the impedance components (3). Before reporting on the results of our investigation, a general remark on the physical nature of the absorption properties of an anisotropic plasma is appropriate. The basic reason of the new absorption properties is to be traced back to the fact that when investigating the electron motion in the skin layer in a plasma with anisotropic EDF, together with the electric field of the incident wave, it is necessary to take into account its magnetic field as well. Thanks to the fact that the magnetic field in the skin layer is considerably larger than the electric field, the influence of the former on the electron motion results much more significant even when the electrons have nonrelativistic temperatures. Under the influence of the magnetic field an important exchange of energy among the electron degrees of freedom takes place, which ultimately explains why the temperature anisotropy is able to influence the properties of the collisionles Landau damping.

3 Collisionless absorption. Analytical results

Let us consider now the characteristic features of collisionless absorption in different limiting cases, and report the results of numerical calculations of the impedance components real parts and of the absorption coefficient. With this aim, let us write the expression for the real part Z'_x in the form

$$Z'_x = \frac{2}{\pi}\delta\Omega \int_0^\infty \mathrm{d}x \frac{\mathrm{Im}(x)}{\left[\mathrm{Re}^2(x) + \mathrm{Im}^2(x)\right]}, \tag{13}$$

$$\mathrm{Im}(x) = \sqrt{\frac{\pi}{2}}\,(1-\Delta)\,\delta^2 x^3 \exp\left(-\frac{x^2}{2}\right), \tag{14}$$

$$\mathrm{Re}(x) = 1 + x^2\delta^2\left[\Delta + (1-\Delta)\,x\exp\left(-\frac{x^2}{2}\right) \times \int_0^x \mathrm{d}t\exp\left(\frac{t^2}{2}\right)\right], \tag{15}$$

with δ the parameter characterizing the degree of the skin effect anomaly in a plasma with a Maxwellian EDF defined in the introduction; $\Omega = \omega/\omega_\mathrm{L} \ll 1$. In writing down (15), it has been taken into account that $\Omega \ll 1$ and $\Omega\delta = v_\mathrm{T}/c \ll 1$. The expression for Z'_y follows from (13–15), disregarding the electron temperatures differences and letting $\Delta = 0$.

3.1 Limiting cases for $\mathbf{Z'_y}$

We start our analysis considering first the simpler function Z'_y. We report Z'_y for the two limiting cases of small and large values of the anomaly parameter δ. For $\Delta = 0$ and $\delta \ll 1$, in (13) we can neglect the departure of $\mathrm{Re}(x)$ (15) from unity, while in the denominator of (13) we omit $\mathrm{Im}(x)$. Thus, from (13) and (14) we find

$$Z'_y = \sqrt{\frac{8}{\pi}}\Omega\delta^3, \quad \delta \ll 1. \tag{16}$$

If $\delta \gg 1$, when $\Delta = 0$ the main contribution to the integral (13) comes from $x \simeq \delta^{-2/3} \ll 1$. It allows to neglect the departure of $\mathrm{Re}(x)$ (15) from unity. Then, from (13) and (14) we have

$$Z'_y = \frac{2}{3\sqrt{3}}\left(\frac{2}{\pi}\right)^{1/6}\Omega\delta^{1/3}, \qquad \delta \gg 1. \tag{17}$$

3.2 Limiting cases for $\mathbf{Z'_x}$

Let us now analyze the function Z'_x. The calculation of Z'_x is particularly simple when $\delta \ll 1$. When it takes place and additionally $(1-\Delta)\delta^2 \ll 1$, neglecting the departure of $\mathrm{Re}(x)$ from unity and the small function $\mathrm{Im}(x)$ in the denominator (13), we find

$$Z'_x = \sqrt{\frac{8}{\pi}}\Omega\delta^3(1-\Delta), \quad \delta \ll 1, \quad \delta\sqrt{1-\Delta} \ll 1. \tag{18}$$

As before, when $\delta \ll 1$ but the electron temperature anisotropy degree is high, such that $\Delta < 0$ and $\delta\sqrt{|\Delta|} \gg 1$, the main contribution to Z'_x (13) comes from $x \simeq 1/(\delta\sqrt{|\Delta|}) \ll 1$. Taking it into account, from (13–15) approximately we have

$$Z'_x \simeq \sqrt{\frac{2}{\pi}}\Omega\delta^3|\Delta| \int_0^\infty \frac{x^3}{(1-|\Delta|x^2\delta^2)^2 + \Delta^2\delta^4x^6\frac{\pi}{2}}\mathrm{d}x \simeq \frac{\Omega}{\sqrt{|\Delta|}}, \quad \delta \ll 1, \quad \Delta < 0, \quad \delta\sqrt{|\Delta|} \gg 1. \tag{19}$$

We note that when $\delta \gg 1$, the number of possible limiting cases is greater than when the reverse inequality takes place. In particular, when $1-\Delta \ll 1$, which corresponds to $T_\perp \gg T_x$, neglecting in the denominator of (13) the small corrections proportional to $(1-\Delta)$, approximately we have

$$Z'_x \simeq \sqrt{\frac{2}{\pi}}\Omega\delta^3(1-\Delta)\int_0^\infty \frac{x^3}{(1+x^2\delta^2)^2}\exp\left(-\frac{x^2}{2}\right)\mathrm{d}x \simeq \sqrt{\frac{2}{\pi}}\frac{\Omega}{\delta}(1-\Delta)\left\{\ln\delta - 1 + \frac{1}{2}(\ln 2 - C)\right\}, \quad \delta \gg 1, \quad 1-\Delta \ll 1, \tag{20}$$

where $C \simeq 0.577$ is the Euler constant. As Δ is decreased, the conditions of absorption change. If Δ is within the interval $\delta^{-2/3} \ll \Delta \ll 1$, instead of (20) for Z'_x another asymptotic expression is obtained. In such conditions it is possible to disregard the dependency of $\mathrm{Im}(x)$ (14), on Δ and the main contribution to the integral (13) comes from x values not greater than $\delta^{-2/3} \ll 1$. For such small values of x it is allowed to approximate $\mathrm{Re}(x)$ by $1 + \Delta\delta^2x^2$. As a result we may write (13) in the form

$$Z'_x \simeq \sqrt{\frac{2}{\pi}}\Omega\delta^3\int_0^\infty \frac{x^3}{(1+\Delta x^2\delta^2)^2 + \delta^4x^6\frac{\pi}{2}}\mathrm{d}x \simeq \left(\frac{2}{\pi}\right)^{1/2}\frac{\Omega}{\delta\Delta^2}\left\{\ln\left[\sqrt{\frac{2}{\pi}}\delta\Delta^{3/2}\right] - \frac{1}{2}\right\}, \quad \delta^{-2/3} \ll \Delta \ll 1. \tag{21}$$

From (21) containing the integral, one may also see that when $|\Delta| \ll \delta^{-2/3}$ the real part of the impedance component Z'_x is described by the same expression (17) as Z'_y, which corresponds to the anomalous skin-effect in a plasma with an isotropic Maxwellian EDF, but with small correction proportional to $\Delta\delta^{2/3}$,

$$Z'_x = \frac{2}{3\sqrt{3}}\left(\frac{2}{\pi}\right)^{1/6}\Omega\delta^{1/3}\left[1 - \frac{\sqrt{3}}{\pi}\Delta\delta^{2/3}\right], \quad 1 \gg \delta^{-2/3} \gg |\Delta|. \tag{22}$$

For negative values of the temperature anisotropy parameter, smaller than those considered before, and such that $\Delta < 0$ and $|\Delta| \gg \delta^{-2/3}$, the main contribution to the integral (13) comes from x values around $1/(\delta\sqrt{|\Delta|}) \ll 1$, and it allows to use the approximate expression $\mathrm{Re}(x) \simeq 1 + \Delta\delta^2x^2$. As a result, from (13–15) approximately

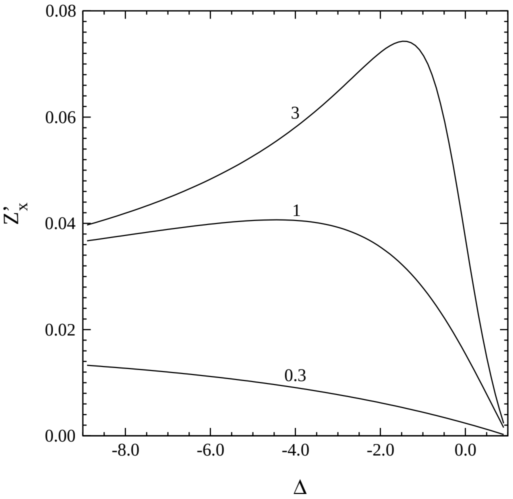

Fig. 1. The real part of the impedance component Z'_x *versus* $\varDelta = 1 - T_x/T_\perp$ the degree of temperature anisotropy. The different curves correspond to three values of the parameter $\delta = v_\mathrm{T}\omega_\mathrm{L}/\omega c$ characterizing the degree of skin-effect anomaly: $\delta = 0.3, 1, 3$. $\varOmega = \omega/\omega_\mathrm{L} = 0.1$.

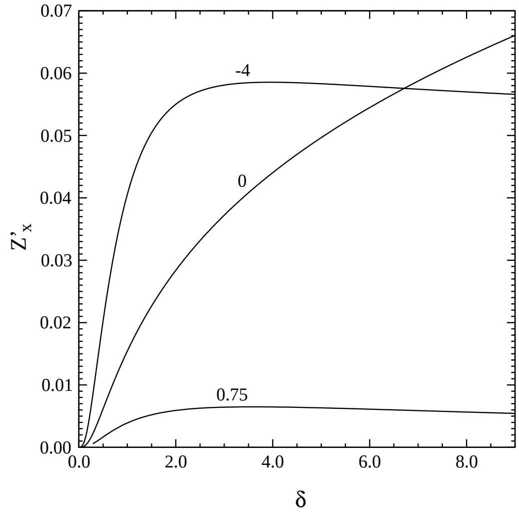

Fig. 2. The same function as in Figure 1, but *versus* δ for three values of the parameter $\varDelta$: 0.75 ($T_\perp = 4T_x$); 0 ($T_\perp = T_x$); -4 ($T_x = 5T_\perp$); $\varOmega = \omega/\omega_\mathrm{L} = 0.1$.

we find

$$Z'_x \simeq \sqrt{\frac{2}{\pi}}\int_0^\infty \frac{(1-\varDelta)\varOmega\delta^3x^3}{(1+\varDelta x^2\delta^2)^2 + (1-\varDelta)^2\delta^4x^6\frac{\pi}{2}}\mathrm{d}x$$
$$\simeq \frac{\varOmega}{\sqrt{|\varDelta|}}, \qquad \varDelta < 0,\ |\varDelta| \gg \delta^{-2/3},\ \delta \gg 1. \qquad (23)$$

The asymptotic expression (23) coincides with the expression (19) derived above, but has a different domain of applicability. Altogether the asymptotic expressions (16–23) allow to understand the behavior of the functions Z'_x and Z'_y in all the limiting situations of physical interest. They are also useful for comparisons with the results of the numerical calculations to be reported below.

4 Numerical results

In Figure 1 we report results of numerical calculations of the real part of the impedance component Z'_x as a function of $\varDelta = 1 - T_x/T_\perp$. The curves are calculated for $\varOmega = \omega/\omega_\mathrm{L} = 0.1$ and three values of the anomaly parameter $\delta = v_\mathrm{T}\omega_\mathrm{L}/\omega c = 0.3$; 1; 3. The behavior of the curve with $\delta = 0.3$ correspond to that of the asymptotic expression (18). The asymptotic expressions (18, 19) allow also to qualitatively understand the behavior of the curve with $\delta = 1$. In particular, the component Z'_x reaches the maximum at the boundary where the asymptotic expressions (18, 19) join; namely at $|\varDelta| \sim \delta^{-2}$. Finally, the behavior of the curve with $\delta = 3$ is explained by the group of asymptotic expressions (20–23). For $\delta = 3$ the function Z'_x reaches its maximum in the interval $|\varDelta| \le \delta^{-2/3}$. The absolute value of Z'_x maximum is close to that of an isotropic plasma.

In Figure 2 we report the curves of the function Z'_x *versus* δ. The curves are calculated for $\varOmega = 0.1$ and three values of the temperature anisotropy parameter $\varDelta$: 0.75 ($T_\perp = 4T_x$); 0 ($T_\perp = T_x$); and -4 ($T_x = 5T_\perp$). The curve with $\varDelta = 0$ corresponds to an isotropic plasma and describes also the behavior of the function Z'_y. Its behavior corresponds also to the well known dependencies (16) and (17). From Figure 2 we see that the component Z'_x at $\varDelta = 0.75$ is considerably smaller then at $\varDelta = 0$. The behavior of the curve at $\varDelta = 0.75$ and small δ corresponds to the expression (18), while for large δ corresponds to the expression (20). The curve with $\varDelta = -4$ ($T_x = 5T_\perp$) for large δ lies below the curve with $\varDelta = 0$, while for small δ it shows a significant relative increase of the Z'_x component. Such a behavior of Z'_x follows from the asymptotic expressions (18, 19, 23) as well.

In Figures 3a and 3b we report the results of calculations of the collisionless absorption coefficient A (12), as a function of the angle ϕ, formed by the polarization vector of the absorbed wave with the EDF symmetry axis. Figure 3a shows the curves corresponding to $\delta = 9$ and three values of the anisotropy parameter $\varDelta = -4$ ($T_x = 5T_\perp$); 0 ($T_x = T_\perp$); and 0.75 ($T_\perp = 4T_x$). According to Figure 3a, for the chosen plasma and laser parameters, a relative decrease of absorption takes place as compared with the case of an isotropic plasma. Besides, the absorption coefficient in a plasma with $\varDelta \neq 0$, is found to grow monotonously with the angle ϕ increase. The dependencies of A *vs.* ϕ, for $\delta = 0.3$ and the same values of $\varDelta$ as in Figure 3a, are shown in Figure 3b. We note that the curve with $\varDelta = 0.75$ is qualitatively similar to the corresponding curve of Figure 3a. A different behavior, instead, is shown by the curve with $\varDelta = -4$ ($T_z = 5T_\perp$). In fact, at variance with the curve of Figure 3a, a significant increase of absorption in an anisotropic plasma is observed. The dependency of A on the angle ϕ changes as well. For $\delta = 0.3$ and $\varDelta = -4$ the absorption maximum occurs at $\phi = 0$, when the wave field is polarized along the EDF symmetry axis.

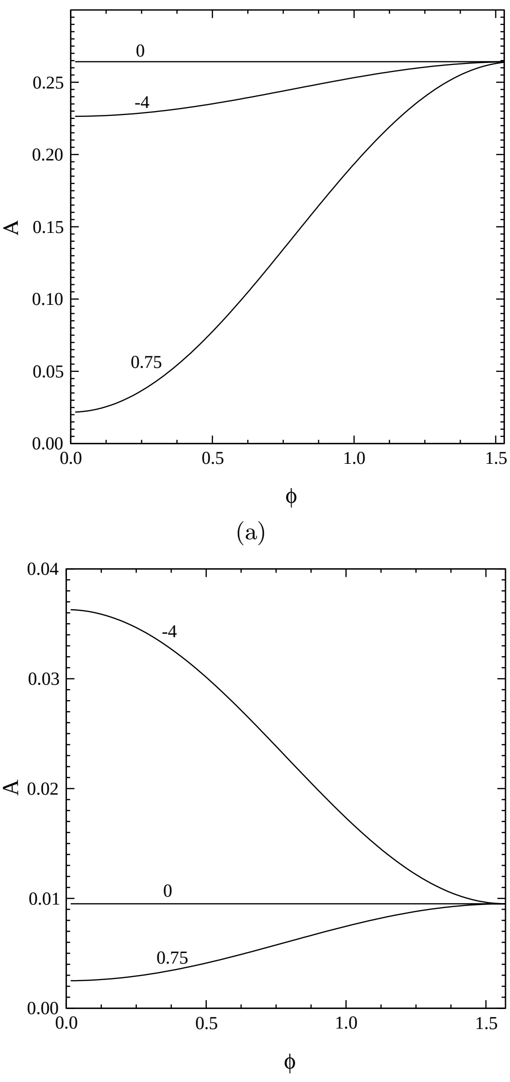

Fig. 3. (a) Collisionless absorption coefficient A *versus* ϕ the angle between the polarization vector of the e.m. wave and the EDF symmetry axis, in a plasma with $\delta = 9$ and for three values of the temperature anisotropy parameter $\Delta = -4$ ($T_x = 5T_\perp$); 0 ($T_\perp = T_x$); 0.75 ($T_\perp = 4T_x$). (b) The same function as in (a), but for $\delta = 0.3$.

5 Conclusions

We have investigated, analytically and numerically, for wide intervals of the pertinent physical parameters, the basic properties of the collisionless absorption of linearly polarized radiation by a plasma possessing an anisotropic bi-Maxwellian electron velocity distribution function. The reported results show significant differences as compared with the case of plasma with an isotropic EDF. The physical reason, to which the differences are to be traced back, is that in the conditions of an anisotropic EDF one needs to take into account the magnetic field influence on the electron kinetics inside the skin-layer. The absorption properties established above have been obtained using a relatively simple model concerning the sharpness of the plasma boundary and the mirror-like character of electron reflection. They may serve as basis of further investigations, concerning more involved conditions of interaction of probe waves with highly nonequilibrium anisotropic plasmas, and may be subjected to verification in relatively simple experiments.

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References

1. P.B. Corkum, N.H. Burnett, F. Brunel, Phys. Rev. Lett. **62**, 1259 (1989).
2. N.B. Delone, V.P. Krainov, J. Opt. Soc. Am. B **8**, 1207 (1991).
3. W.P. Leemans, C.E. Clayton, W.B. Mori, K.A. Marsh, A. Dyson, C. Joshi, Phys. Rev. Lett. **68**, 321 (1992).
4. J.C. Kieffer, J.P. Matte, H. Pepin, M. Chaker, Y. Beaudoin, T.W. Johnston, C.Y. Chien, S. Coe, G. Mourou, J. Dubau, Phys. Rev. Lett. **68**, 480 (1992).
5. B.N. Chichkov, S.A. Shumsky, S.A. Uryupin, Phys. Rev. A **45**, 7475 (1992).
6. P. Porshnev, S. Bivona, G. Ferrante, Phys. Rev. E **50**, 3943 (1994).
7. V.P. Silin, S.A. Uryupin, JETP **84**, 59 (1997).
8. A. Bendib, K. Bendib, A. Sid, Phys. Rev. E **55**, 7522 (1997).
9. G. Ferrante, M. Zarcone, S.A. Uryupin, Phys. Plasmas **8**, 2918 (2001).
10. G. Ferrante, M. Zarcone, S.A. Uryupin, Phys. Rev. E **64**, 046408 (2001).
11. G. Ferrante, M. Zarcone, S.A. Uryupin, Phys. Plasmas **8**, 4745 (2001).
12. A.A. Andreev, E.G. Gamaly, V.N. Novikov, A.N. Semakhin, V.T. Tikhonchuk, JETP **74**, 963 (1992).
13. A.A. Andreev, K.Yu. Platonov, J.-C. Gauthier, Phys. Rev. E **58**, 2424 (1998).
14. W. Rozmus, V.T. Tikhonchuk, Phys. Rev. A **42**, 7401 (1990).
15. T.-Y. Brian Yang, W.L. Kruer, R.M. More, A.B. Langdon, Phys. Plasmas **2**, 3146 (1995).
16. T.-Y. Brian Yang, W.L. Kruer, A.B. Langdon, T.W. Johnston, Phys. Plasmas **3**, 2702 (1996).
17. P. Mulser, S. Pfalzner, F. Cornolti, in *Laser Interaction with Matter*, edited by G. Velarde, E. Minguez, J.M. Perlado (World Scientific, Singapore, 1989), p. 142.
18. E.M. Lifshitz, L.P. Pitaevskii, *Physical Kinetics* (Pergamon, Oxford, 1981).
19. S. Ichimaru, *Basic Principles of Plasma Physics* (Benjamin, Reading, MA, 1973), p. 84.
20. A.F. Alexandrov, L.S. Bogdankevich, A.A. Rukhadze, *Principles of Plasma Electrodynamics* (Springer-Verlag, Berlin, 1984).
21. R.C. Davidson, in *Basic Plasma Physics*, edited by A.A. Galeev, R.N. Sudan (North-Holland, Amsterdam, 1983), Vol. 1, p. 519.