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The inverse Bremsstrahlung absorption in the presence of Maxwellian and non-Maxwellian electrons

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Inverse Bremsstrahlung absorption (IBA) of an intense laser field in plasma containing Maxwellian and non-Maxwellian (with Kappa and q-nonextensive distribution functions) electrons is studied analytically. Our results show that IBA decreases with an increase in temperature at high intensities and a decrease in plasma density for all kinds of distribution functions. Another striking result is that IBA is independent of the laser intensity at low intensity but is dependent on it when the intensity is going to rise. Also, it could be find that the behavior of the absorption as the function of laser intensity for the Kappa distribution with $\kappa = 10$ at low intensity is close to that for the Maxwellian distribution, but at high intensity it is close to that in the presence of q-nonextensive electrons with $q = 0.9$. These results provide insights into the inverse Bremsstrahlung absorption in the laser–plasma interactions.

Keywords: laser–plasmas interaction, inverse Bremsstrahlung absorption, Maxwellian distribution, Kappa distribution, q-nonextensive distribution

PACS: 52.20.Fs, 52.25.Dg, 52.38.–r, 52.38.Dx **DOI:** 10.1088/1674-1056/ab4173

1. Introduction

As we know, laser–plasmas interaction is one of the contemporary problems and has applications from plasmas diagnostics and x-ray radiation generation to fusion.[1] The most important absorption mechanism in laser–plasmas interactions is collisional absorption by the inverse Bremsstrahlung (IBA) process. The collisional absorption, or IBA, is the radiation absorbed by electrons when they scatter in the Coulomb field of ions.[2]

Re-discovering of this absorption mechanism is required to check the electrons distribution function which plays the main role in this mechanism. Maxwellian distribution function has been usually assumed in many works related to the laser–plasmas interactions.[3,4] This distribution is valid only for systems in thermodynamic equilibrium. Sometimes it could be found that the ions distribution function is Maxwellian but the electrons are generally in near-thermal equilibrium.[5]

However, through observation (i.e., the experimental data), it emerges that space plasma is far away from its equilibrium state.[6,7] Non-Maxwellian electrons could cause plasma to deviate from thermodynamic equilibrium.[8] In a fusion system, the electrons distribution is not perfectly Maxwellian, therefore the system which will be considered in this work is of interest because it deviates from the equilibrium state. For the exact discussion of IBA especially in plasma fusion, a non-Maxwellian distributions such as q-nonextensive distribution and Kappa distribution functions that would be observed in this kind of plasmas will be considered here.[9]

In recent years, great attention has been paid to the use of non-extensive statistic mechanics or Tsallis statistics in cases that Maxwellian function is inapplicable, e.g., in long-range interactions and correlations.[7,10] Renyi acknowledged the non-extensive generalization of the Boltzmann–Gibs–Schannon (BGS) entropy for statistical equilibrium in 1955.[11] Then, it was investigated and proposed by Tsallis in 1988.[12] This distribution is explained by a non-extensive parameter (q) that relates the basic dynamics of the plasmas system and measures the quantity of its non-extensivity.[13] The q-nonextensive distribution describes power-law distribution functions for $q \neq 1$, and it gives a Maxwellian distribution function when $q \to 1$.[7,14]

If the plasmas electrons distribution function has a superthermal power-law tail with high energies, it is better to use Kappa distribution instead of Maxwellian distribution function for electron.[9] The Kappa distribution function at high velocities obeys an inverse power, and, when $\kappa \to \infty$, it approximates the Maxwellian distribution.[15] Generally, this function gets both in and out of thermodynamic equilibrium.

Another issue in the laser–plasmas interaction is the average energy absorption rate per unit volume, $\bar{\varepsilon}$. The average energy absorption is the conversion of energy between the oscillating electric field of laser and plasmas (matter), which strongly depends on the electrons distribution function.[16]

For better understanding of absorption, it is better to study the fractional absorption and the averaged energy absorption by using non-Maxwellian distribution functions. In this paper, we deal with the fractional absorption (α) and the average energy absorption ($\bar{\varepsilon}$) using the kinetic theory and the ballistic model (BM), proposed by Mulser *et al.*[4] for several distribution functions including Maxwellian, q-nonextensive, and

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Kappa distribution functions.

The paper is organized as follows. In Section 2, the equations of absorption and average energy absorption are presented. Then, the equations of distribution functions are given too. By applying these distribution functions, the results are used to investigate the absorption and the average energy absorption in Section 3. Finally, Section 4 is devoted to the summary and conclusion.

2. The basic equation

We assume an under-dense plasmas in the presence of a laser electric field, E, at the wavelength of $\lambda = 800$ nm (resonance absorption does not occur at this wave length[3]). The evolution of the fractional absorption in the plasmas space is given by[17]

$$\alpha = 1 - \exp(-2k_i L), \tag{1}$$

where L is the plasmas length which t is assumed to be 5 λ, and k_i can be written as

$$k_i = \frac{\overline{\nu_{ei}(t)}}{c}\left(\frac{n}{n_c}\right)\left(1-\frac{n}{n_c}\right)^{-1/2}, \tag{2}$$

where c is the light velocity, $\overline{\nu_{ei}(t)}$ is the average collision frequency, and n and n_c are the plasmas density and the critical plasma density, respectively. They are assumed as $n = 0.3n_c$, unless mentioned. We use the ballistic model for $\overline{\nu_{ei}(t)}$, which is given as[4]

$$\overline{\nu_{ei}(t)} = K\overline{\frac{1}{v_{os}^3(t)}\int_0^{v_{os}(t)} 4\pi f(v)\, v^2 \mathrm{d}v}, \tag{3}$$

where $v_{os}(t)$ as the oscillatory velocity of an electron during one laser period is $v_{os}(t) = v_0 \sin(\omega t)$, and the initial velocity of an electron $v_0 = E_0/\omega$, with E_0 and ω being the strength of the electric field and the laser field frequency. There is also $K = Z^2\omega_p \ln\Lambda$ (in this study, atomic units (a.u.) have been used), in which $Z = 1$, $\omega_p = \sqrt{4\pi n}$ (ω_p is the plasma frequency), and $\ln\Lambda$ as the Coulomb logarithm is given by $\ln\Lambda = \frac{1}{2}\ln\left[1 + (b_{max}/b_{min})^2\right]$. The equations $b_{max} = v_{th}/\omega$ and $b_{min} = 1/v_{th}^2$ refer to the large impact parameter and the small impact parameter, respectively. Moreover, v_{th} is the electron thermal velocity, and $f(v)$ is the electron velocity distribution function. Here, we have used the following three distribution functions. The three-dimensional Maxwellian distribution function is given by

$$f(v) = \frac{1}{\left(2\pi v_{th}^2\right)^{3/2}}\exp\left(-\frac{v^2}{2v_{th}^2}\right). \tag{4}$$

Conventionally, the three-dimensional q-nonextensive distribution function is given by[18]

$$f(v) = C_q\left[1-(q-1)\left(\frac{mv^2}{2k_B T_e}\right)\right]^{\frac{1}{q-1}}, \tag{5}$$

where the normalization constant characteristics are

$$C_q = n\frac{\Gamma\left(\frac{1}{1-q}\right)}{\Gamma\left(\frac{1}{1-q}-\frac{3}{2}\right)}\left[\frac{m(1-q)}{2\pi k_B T_e})\right]^{3/2} \quad \text{for } -1 < q < 1, \tag{6}$$

$$C_q = n\frac{(3q-1)}{2}\frac{\Gamma\left(\frac{1}{q-1}+\frac{3}{2}\right)}{\Gamma\left(\frac{1}{q-1}\right)}\left[\frac{m(q-1)}{2\pi k_B T_e})\right]^{3/2} \quad \text{for } q > 1. \tag{7}$$

Here m is the electron mass, and k_B is the Boltzmann constant. Also, q denotes the non-extensivity degree of the system whose acceptable limit for the absorption is $0.35 < q < 0.9$.

For considering the absorption by using the q-nonextensive function, we substitute Eq. (5) into Eq. (1) and use Eq. (3) to obtain

$$\alpha = 1 - \exp\left(\left(\frac{-8\pi n^2 LK}{cn_c\sqrt{1-\frac{n}{n_c}}}\times\left(\frac{\Gamma\left(\frac{1}{1-q}\right)}{\Gamma\left(\frac{1}{1-q}-\frac{3}{2}\right)}\left[\frac{(1-q)}{2\pi k_B T_e}\right]^{\frac{3}{2}}\right)\right)\times\overline{\frac{1}{v_{os}^3(t)}\int_0^{v_{os}(t)}\left[\left[1-(q-1)\left(\frac{v^2}{2k_B T_e}\right)\right]^{\frac{1}{q-1}}\right]v^2\mathrm{d}v}\right). \tag{8}$$

At last, the three-dimensional Kappa distribution function is given by[9,19]

$$f(v) = \frac{1}{v_{th}^3(\pi\kappa)^{3/2}}\frac{\Gamma(\kappa+1)}{\Gamma\left(\kappa-\frac{1}{2}\right)}\left[1+\frac{1}{\kappa}\frac{v^2}{v_{th}^2}\right]^{-(\kappa+1)}, \tag{9}$$

where Γ is the gamma function, and κ is the spectral index. The Kappa distribution is equivalent to the q-nonextensive one under the transformation between the q characteristic and the κ index.[6]

The equation for the averaged energy absorption rate per unit volume is written as[20]

$$\bar{\varepsilon} = \omega_p^4 \ln\Lambda\overline{\frac{1}{\nu_{os}(t)}\int_0^{v_{os}(t)} f(v)\, v^2 \mathrm{d}v}. \tag{10}$$

This energy absorption is related to the distribution function. The next section of this paper presents an investigation of the fractional absorption and the averaged energy absorption rate per unit volume using the Maxwellian distribution function, the q-nonextensive distribution function, and the Kappa distribution function.

3. Results and discussion

We have studied the fractional absorption (α) and the average energy absorption ($\bar{\varepsilon}$) for unmagnetized and homogeneous plasmas. In Subsection 3.1, using the q-nonextensive distribution function, we have calculated the effects of laser intensity, temperature, and density on α and $\bar{\varepsilon}$. Then, in Subsection 3.2, by the use of the same function, these effects have been compared with respect to the results of Maxwellian distribution and Kappa distribution functions.

3.1. The study of absorption using the q-nonextensive distribution function

In this subsection, by using Eq. (8), we investigate the effective parameters on the absorption. One of these parameters is the intensity. Figure 1 shows the absorption coefficient of various q characteristics vs. the intensity of laser in the q-nonextensive distribution for $T_e = 5$ eV and $n = 0.3n_c$. According to this figure, at low intensities, namely, 10^{11}–10^{13} W/cm^2, the variation of the absorption function is fixed with respect to the laser intensity (it is noted that the highest rates of absorption occur within the range of this intensity). Then, above the intensity of 10^{13} W/cm^2, the absorption falls. Finally, for intensities higher than 10^{15} W/cm^2, there occurs no absorption. The maximum rate of absorption (α_{max}) is about 30% for $q = 1$ (i.e., the Maxwellian function). At $q = 0.35$, where the minimum acceptable characteristic exists, the maximum absorption is about 2% in the intensity range of 10^{11}–10^{13} W/cm^2.

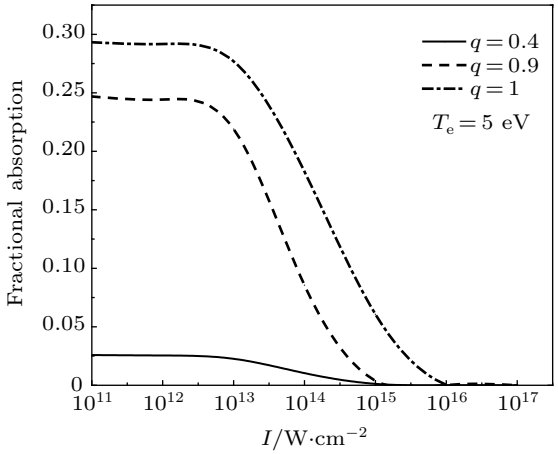


Fig. 1. The absorption function vs. the laser intensity at $T_e = 5$ eV, $n = 0.3n_c$ for $q = 0.4$, 0.9, and 1 (the Maxwellian function). The absorption has the maximum value at $q = 1$ (the Maxwellian function) with respect to other q characters.

The α_{max} in the q-nonextensive distribution is 25% at the intensity of 10^{12} W/cm^2 that occurs at $T_e = 5$ eV, and the minimum value of absorption (α_{min}) is 10% at $T_e = 30$ eV (see Fig. 2). Figure 2 displays the dependence of the fractional absorption on the laser intensity at various temperatures (this figure is plotted for $q = 0.9$ at temperatures 5 eV, 10 eV, and 30 eV). As it can be seen, α_{max} is 25% at the intensity of 10^{11} W/cm^2 that occurs at $T_e = 5$ eV, and the minimum value (α_{min}) of absorption is 10% at $T_e = 30$ eV. The absorption decreases at low temperatures, for example, at 5 eV and 10 eV, and at intensities higher than 10^{13} W/cm^2. However, for high temperatures, such as 30 eV, it drops at intensities higher than 10^{14} W/cm^2. Also, it is zero at the temperature of 30 eV at high intensities, as compared to other temperatures.

Variations of the q characteristic change the absorption. Figure 3 depicts the absorption as a function of the q characteristic at 10^{12} W/cm^2 for $T_e = 4$ eV, 5 eV, 10 eV, and 30 eV. According to Fig. 3, firstly, with a rise in the value of q, the fractional absorption rises too. Secondly, at a low temperature, namely, lower than 5 eV, with an increase in the temperature, the fractional absorption increases too. Above the temperature of 5 eV, the absorption decreases until T_e is 30 eV. Here, the absorption is at its lowest value.

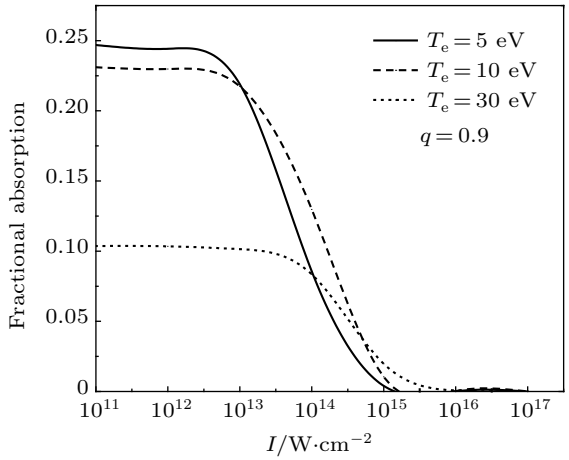


Fig. 2. The fractional absorption vs. the laser intensity for $q = 0.9$, $n = 0.3n_c$ at $T_e = 5$ eV, 10 eV, 30 eV. α is decreased with an increase in the temperature and intensity. The maximum rate of absorption is about 25% at $T_e = 5$ eV at intensities of 10^{11}–10^{13} W/cm^2.

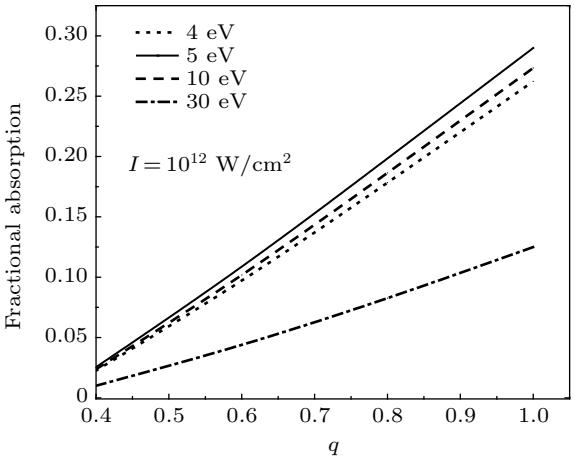


Fig. 3. Variation of the absorption with q at 10^{12} W/cm^2 for $T_e = 4$ eV, 5 eV, 10 eV, 30 eV. The absorption increases with an increase in q and temperature above $T_e = 5$ eV.

Figure 4 indicates the absorption for the q-nonextensive function in diverse densities, for $q = 0.4$, 0.6, 0.8, and 1 at T_e of 4 eV and the intensity of 10^{13} W/cm^2. When the plasma density increases, the absorption increases too; α_{max} is about 90% at $n = 0.9n_c$ for $q = 1$ (Maxwellian function). The absorption increases nonlinearly when q rises.

Our results show that for all of the q values, α_{max} occurs at $I = 10^{12}$ W/cm^2. For example, for $q = 0.8$, the rate of the fractional absorption is 20%. Figure 5 is provided to study the absorption with respect to q for various intensities at $T_e = 5$ eV. It can be deduced that the increase of the absorption is linear with the growth of q at intensities of 10^{12}–10^{13} W/cm^2, but for the other intensities, namely, 10^{14}–10^{15} W/cm^2, this increase is nonlinear. At the intensity of 10^{15} W/cm^2, with an

increase in q, the absorption does not change much and is almost 5% for $q = 1$. Whereas the maximum absorption occurs at $I = 10^{12}$ W/cm^2, we study the variation of the absorption with the temperature at this laser intensity. Figure 6 shows the absorption variation for $q = 0.4$, 0.7, and 0.9. As it can be seen, α_{max} occurs at T_e of 6 eV, and the absorption for $q = 0.9$ and 0.7 is almost 25% and 16%, respectively. The absorption has a direct relationship with the temperature up to $T_e = 6$ eV. Above this temperature, however, the absorption begins to decrease.

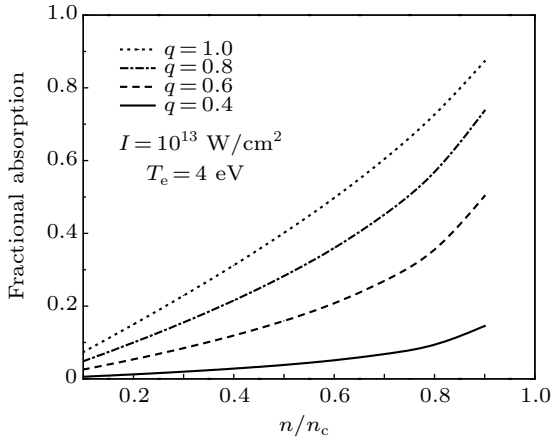


Fig. 4. The fractional absorption as a function of the density for $q = 0.4$, 0.6, 0.8, 1 at $T_e = 4$ eV and the intensity of 10^{13} W/cm^2. As the density of plasma increases, the absorption increases too.

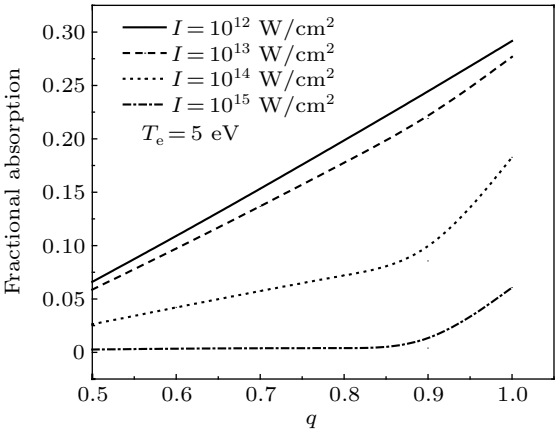


Fig. 5. Variation of the absorption with q for $T_e = 5$ eV, $n = 0.3n_c$ at the intensities of 10^{12}–10^{15} W/cm^2. The absorption as a function of q is linear at the intensities of 10^{12}–10^{13} W/cm^2. For other intensities, i.e., 10^{14}–10^{15} W/cm^2, the increase of the absorption is nonlinear with the growth of q.

The average energy absorption depends to the distribution function. The results based on the q-nonextensive distribution are plotted in Figs. 7 and 8. Figure 7 depicts the variation of the average energy absorption ($\bar{\varepsilon}$) with respect to the laser intensity when $q = 0.8$ at various temperatures. According to Fig. 7, if the temperature rises, the average energy absorption increases, and the peak of the graphs moves to high intensities.

In Fig. 8, $\bar{\varepsilon}$ versus the laser intensity is shown at the T_e of 4 eV for several q values. As observed, $\bar{\varepsilon}$ has the maximum value for the Maxwellian function (here, q is 1 for the q-nonextensive distribution), and the average energy absorption decreases with a decrease in the q characteristic. At $q = 0.4$, $\bar{\varepsilon}$ has the minimum value. This peak in the graphs is created at intensities about 10^{14}–10^{15} W/cm^2. When the electron temperature is increased, the peaks advance to higher intensities.

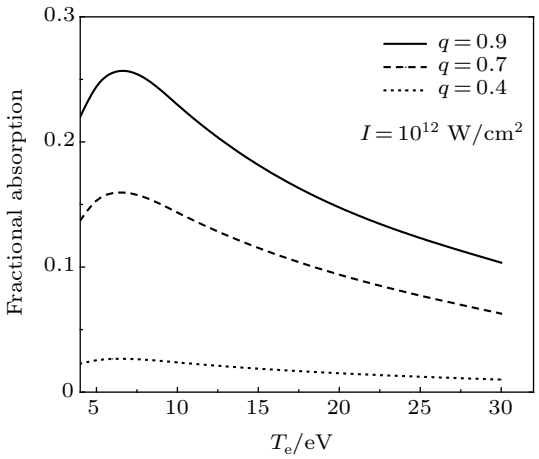


Fig. 6. Variation of the absorption with the temperature for $q = 0.4$, 0.7, 0.9 at $I = 10^{12}$ W/cm^2. The absorption has a direct relation with the temperature up to $T_e = 6$ eV. Above this temperature, the absorption decreases.

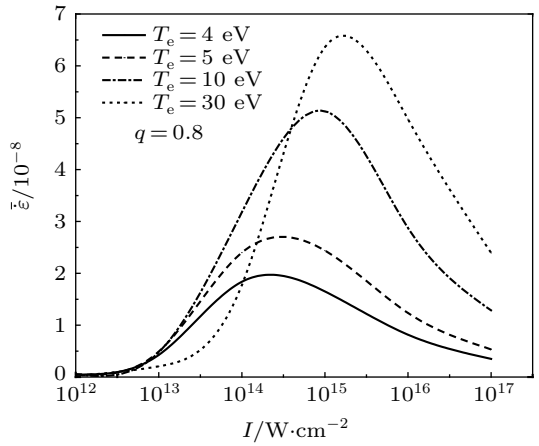


Fig. 7. Variation of the average energy absorption with respect to the laser intensity at $q = 0.8$ for $T_e = 4$ eV, 5 eV, 10 eV, 30 eV. The $\bar{\varepsilon}$ increases and the peaks move to high intensities as the temperature increases.

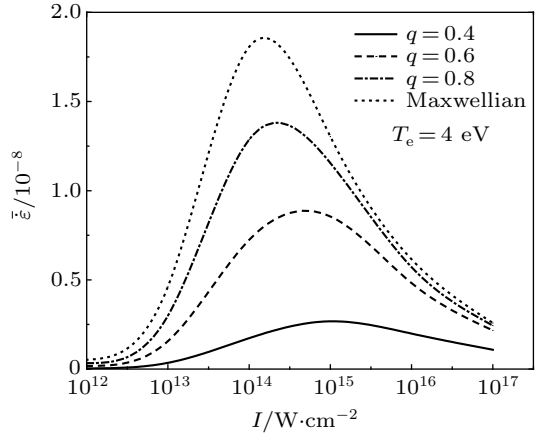


Fig. 8. The $\bar{\varepsilon}$ as a function of the intensity of laser at $T_e = 4$ eV for the q-nonextensive distribution with $q = 0.4$, 0.6, 0.8, 1. The peaks lie at intensities about 10^{14}–10^{15} W/cm^2. With a rise in the temperature, the peaks advance to higher intensities.

3.2. Comparison of absorption using the three distribution functions

Now, we consider the absorption based on distribution functions (4), (5), and (9). In Fig. 9, the fractional absorption is illustrated as a function of the laser intensity at $T_e = 5$ eV and $n = 0.3n_c$. Figure 9 is provided to study and compare the absorption rates using the Maxwellian distribution, the Kappa distribution, and the q-nonextensive functions. The absorption based on the Kappa distribution is close to that based on the Maxwellian function at all intensities. Whenever the κ index increases, the absorption moves close to the Maxwellian function. When $\kappa \to \infty$, the Kappa distribution is equal to the Maxwellian function. This result is true for low intensities, but, at high intensities, this function coincides with the q-nonextensive function. As it can be seen in Fig. 9, the q-nonextensive function has the lowest absorption at all intensities except at intensities higher than 10^{14} W/cm^2 where it equals the Kappa distribution function at $\kappa = 10$.

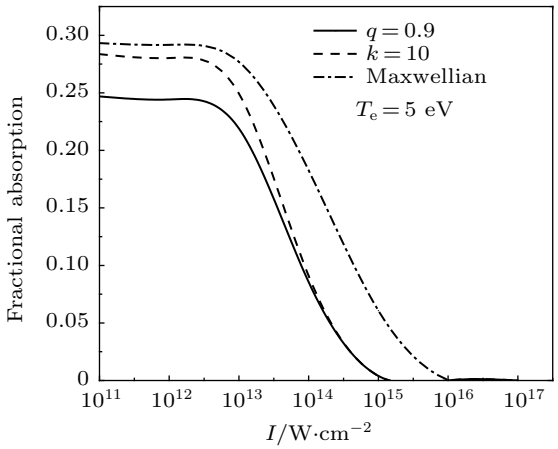


Fig. 9. Comparison of the fractional absorption of the Maxwellian function, the Kappa distribution, and the q-nonextensive distribution. The absorption in the Kappa distribution is closer to that in the Maxwellian function than the q-nonextensive function. The Maxwellian function has the highest rate of absorption at all the intensities.

For all of the distribution functions, α_{max} occurs at T_e of 6 eV. Figure 10 shows the absorption as a function of temperature for the Maxwellian distribution, the Kappa distribution (with $\kappa = 10$), and the q-nonextensive distribution (with $q = 0.9$) at the same intensity ($I = 10^{12}$ W/cm^2). The rate of absorption is almost 30%, 28%, and 25% for the three distribution functions, respectively. The absorption increases as the temperature rises to 6 eV. Above this temperature, the absorption decreases as the temperature increases.

Figure 11 presents the relationship of the average energy absorption and the laser intensity at the same temperature (5 eV) for all the three distribution functions. As it can be seen, the lowest $\bar{\varepsilon}$ is obtained for the q-nonextensive distribution with $q0.8$. For $q = 1$ (where the q-nonextensive function is identical to the Maxwellian function), $\bar{\varepsilon}$ is at its maximum. The average energy absorption belonging to the Kappa distribution is closer to that of the Maxwellian function than the q-nonextensive distribution. The peaks of these graphs are set at the intensities of about 10^{14}–10^{15} W/cm^2. Once the electron temperature rises, these peaks advance to higher intensities. For example, at the T_e of 30 eV, the peaks of the graphs lie at the intensities of about 10^{15}–10^{16} W/cm^2.

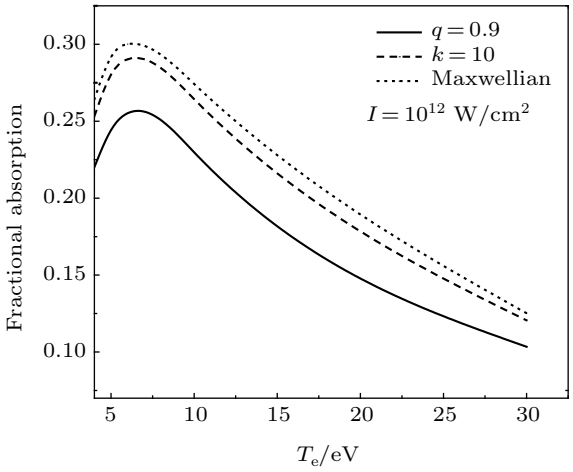


Fig. 10. Variation of the absorption with the temperature for the Maxwellian distribution, $\kappa = 10$, and $q = 0.9$ at $I = 10^{12}$ W/cm^2. The absorption has a direct relation with temperature up to $T_e = 6$ eV. Above this temperature, the absorption decreases.

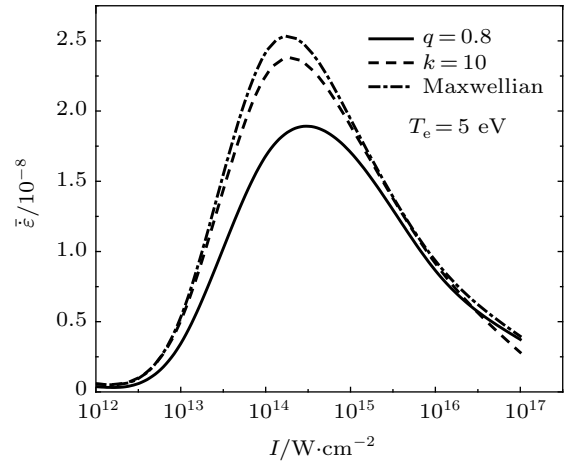


Fig. 11. The $\bar{\varepsilon}$ vs. the laser intensity for the Maxwellian function, the q-nonextensive distribution (with $q = 0.8$), and the Kappa distribution (with $k = 10$) at $T_e = 5$ eV. $\bar{\varepsilon}$ for the Kappa distribution is closer to that for the Maxwellian function than the q-nonextensive distribution at all the intensities.

4. Summary and discussion

In this study, the kinetic theory and the BM model were investigated for the average energy absorption using various distribution functions. The results showed that, when the q-nonextensive distribution is used, α is independent of the laser intensity at low values, but the fractional absorption decreases at high laser intensities. Also, the absorption is increased as the q parameter rises and the temperature decreases at different laser intensities. However, at the intensity of 10^{13} W/cm^2, the absorption keeps the same at the temperature of 4–5 eV as the q parameter is increased. Regarding α as a function of the plasma density, it increases nonlinearly. Also, $\bar{\varepsilon}$, as a function of the laser intensity, has its maximum for the average energy

absorption at various temperatures. As it was observed, when the temperature and the q characteristic increase, the average energy absorption increases too. In this study, we investigated and compared the absorption using the Maxwellian distribution, Kappa distribution, and q-nonextensive distribution functions. The absorption rate for the Kappa distribution is closer to that for the Maxwellian function than the q-nonextensive distribution at all intensities. The absorption at $\kappa \to \infty$ for the Kappa distribution and at $q = 1$ for the q-nonextensive function is equal to that for the Maxwellian distribution function. Also $\alpha_{\max}$ occurs at the T_e of 6 eV for all the three distribution functions. The rate of the average energy absorption for the Kappa distribution is closer to that for the Maxwellian function than the q-nonextensive distribution. The graph peaks of the average energy absorption proved to appear at the intensities of about 10^{14}–10^{15} W/cm^2, and by a rise in the temperature, they would move to higher intensities.

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