Radiation temperature of ECE in bi-Maxwellian tokamak plasma

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Abstract

The effect of supra-thermal electron on the radiation temperature is evaluated in the case of relativistic bi-Maxwellian. The small amount of supra-thermal electron results in the deviation from temperature in Maxwellian. The parameter dependences of deviation on the electron temperature of supra-thermal electron and modes are interpreted from viewpoint of the relativistic effects of supra-thermal electron. It is the relativistic effects of supra-thermal electron of the same mode and the higher harmonic mode used for temperature measurement on the thermal electron of the same mode used.

1. Introduction

For the measurement of electron temperature profile, the 2nd harmonic extraordinary mode (X mode) of electron cyclotron emission (ECE) in magnetically confined plasmas is usually observed in perpendicular to the magnetic field (*B*) along the equatorial plane [1]. The ECE spectra are changed by the relativistic, Doppler, absorption and refraction effects. The characteristics of ECE spectra are also changed by the electron distribution function ($f_e(p)$). For instance, the discrepancy between ECE and Thomson scattering were found in JET when the $T_e > 7$ keV, there were indications that bulk electrons are becoming non-Maxwllian [2]. Krevenski pointed out that ECE and Thomson scattering measurements reflect local properties in momentum space of $f_e(p)$ to which the diagnostics are sensitive [3]. Here, the effect of supra-thermal electron on the radiation temperature (T_e^{rad}) from ECE is evaluated in the case of relativistic bi-Maxwellian. In the relativistic bi-Maxwellian, the thermal and supra-thermal parts of distribution function are represented to be average and high energy part, respectively [4].

The computational model is given in section 2. The calculation results of ECE spectra and T_e^{rad} in the case of bi-Maxwellian are presented in section 3 and 4. Summary is presented in section 5.

2. Calculation methods

The computational model in bi-Maxwellian is almost the same as ref. 5 basically except for emissivity. The emissivity is used the Trubnikov's formula [6]. The thermal and supra-thermal electron are assumed to be Maxwellian distribution functions of low and high temperature, *i.e.*, $f_e(p, T_e^{th}, T_e^{sp}) = f_e^{Max}(p, T_e^{th}) + f_e^{Max}(p, T_e^{sp})$,

$f_e^{Max}(p, T_e)$, T_e^{th}, T_e^{sp} are spherically symmetric relativistic Maxwellian, the temperature of

thermal and supra-thermal electron. Absorption coefficient is assumed to be obtained from the emissivity by applying Kirchhoff's law for thermal and supra-thermal electron, respectively.

The ray refractive index for wave propagation is taken as unity in tenuous plasma and the ECE is assumed to propagate in a straight line on the equatorial plane; *i.e.*, the refraction is neglected. The *B* is proportional to the major radius inversely. The plasma parameters used in calculation are as follows: the major radius, *R*, and the minor radius, *a* are 3.4 m and 1 m, respectively, the toroidal *B* is 4 T, and the profiles of the electron temperature of thermal and supra-thermal electrons, $T_e^{th}(r)$, $T_e^{sp}(r)$ are a parabolic function. The central electron temperature of thermal electron, $T_e^{th}(0)$ is taken to be 20 keV. For supra-thermal electron, $T_e^{sp}(0) = 50$, 100, and 150 keV. The profile of the thermal electron density, $n_e^{th}(r)$ is uniform. The profile of the super-thermal electron density, $n_e^{sp}(r)$ is uniform. The values of $n_e^{th}(0)$ and $n_e^{sp}(0)$ are taken to be 5×10^{19} m^{-3} and from 1×10^{15} m^{-3} to 5×10^{19} m^{-3}, respectively. Only in Fig. 3, $n_e^{sp}(r)$ and $T_e^{sp}(r)$ are center localized profiles.

3. ECE Spectra in relativistic bi-Maxwellian

The dependence of ECE spectra for the X mode and ordinary mode (O mode) on uniform n_e^{sp} are shown in Fig. 1 in the case of $T_e^{sp}(0) = 50$ keV, $n_e^{th}(0) = 5 \times 10^{19}$ m^{-3}. The supra-thermal electron affects the 2nd harmonics more than higher harmonics for X and O modes. Even if $n_e^{sp}(0)/n_e^{th}(0)$ is about 1% in the case of $T_e^{sp}(0) = 50$ keV, the supra-thermal electron affects the 2nd harmonics in ECE spectra of X mode. The supra-thermal effect on ECE spectra of O mode is less sensitive than that of X mode in the case of $T_e^{sp} = 50$ keV.
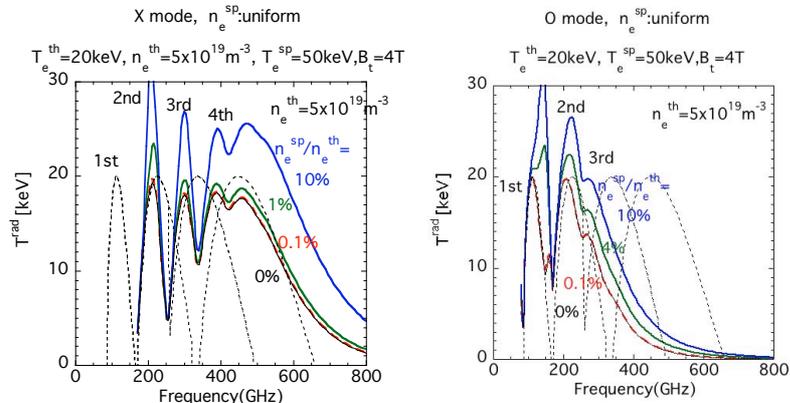

Fig. 1. Dependence of X and O mode ECE spectra on uniform n_e^{sp} in the cases of $T_e^{th}(0) = 20$ keV, $n_e^{th}(0) = 5 \times 10^{19}$ m^{-3}, $T_e^{sp}(r) = 50$ keV.

4. Radiation temperature in relativistic bi-Maxwellian

Here, the T_e^{rad} is obtained from 2nd harmonic X mode and fundamental O mode of ECE spectra. The maximum T_e^{rad} in the cases of relativistic bi-Maxwellian is discussed. When the $n_e^{sp}(0)$ increases to $n_e^{th}(0)$, the T_e^{rad} increases from $T_e^{th}(0)$ toward $T_e^{sp}(0)$. In the case of low $n_e^{sp}(0)$, T_e^{rad} is close to the $T_e^{th}(0)$. The deviation of T_e^{rad} between the bi-Maxwellian and the Maxwellian is defined: $\Delta T_e \equiv T_e^{rad}(bi\text{-}Max) - T_e^{rad}(Max)$, where $T_e^{rad}(bi\text{-}Max)$ and $T_e^{rad}(Max)$

are T_e^{rad} in bi-Maxwellian and Maxwellian, respectively. The dependence of $\Delta T_e/T_e$ on uniform n_e^{sp} are shown in Fig. 2, where T_e is T_e^{true}(Max). The small amount of supra-thermal electron affects the T_e^{rad}. The n_e^{sp} in the case of $\Delta T_e/T_e = 10\%$ ($\equiv n_e^{sp10\%}$), for the 2nd harmonic X mode and fundamental O mode are estimated. The n_e^{sp} is uniform profile. For $T_e^{sp} = 50$keV, the estimated $n_e^{sp10\%}$ in the case of the T_e^{rad} from the 2nd harmonic X mode is smaller than that in the case of the T_e^{rad} from fundamental O mode. For $T_e^{sp} = 150$keV, the estimated $n_e^{sp10\%}$ in

Fig. 2. Dependence of $\Delta T_e/T_e$ for the 2nd X mode, and fundamental O mode on uniform n_e^{sp} in the cases of $T_e^{th}(0) = 20$ keV, $n_e^{th}(0) = 5\times10^{19}$ m⁻³, $T_e^{sp}(r) = 50$ keV.

the case of the T_e^{rad} from the 2nd harmonic X mode is comparable to that in the case of the T_e^{rad} from fundamental O mode.

The general expression of radiation temperature is evaluated in the case of bi-Maxwellian [7]. Using the expression and approximations ($j^{sp}/(j^{th} + j^{sp})$ ($\equiv Rj$) < 1, and T_e^{th}/T_e^{sp} < 1), we obtain the following scaling: $\Delta T_e/T_e = (T_e^{sp} - T_e^{th})/T_e^{sp} \times j^{sp}/(j^{th} + j^{sp})$, where the value of jth, j^{sp} are the emiisivity of thermal and supra-thermal electrons at the contributed point. That is, $\Delta T_e/T_e$ is proportional to the ratio of Rj. These results in Fig. 2 are interpreted from the two viewpoints using the scaling. One is the relativistic effect of supra-thermal electron of the mode used for T_e^{rad} measurement (e.g. 2nd harmonic X mode) on the thermal electron of the same mode used for T_e^{rad} measurement. The relativistic broadening effect of 2nd harmonic of thermal electron due to the 2nd harmonic of the supra-thermal electron is bigger than that of the fundamental mode of the thermal electron due to the fundamental mode of the supra-thermal electron. The value of Rj for 2nd harmonic X mode is bigger than that for
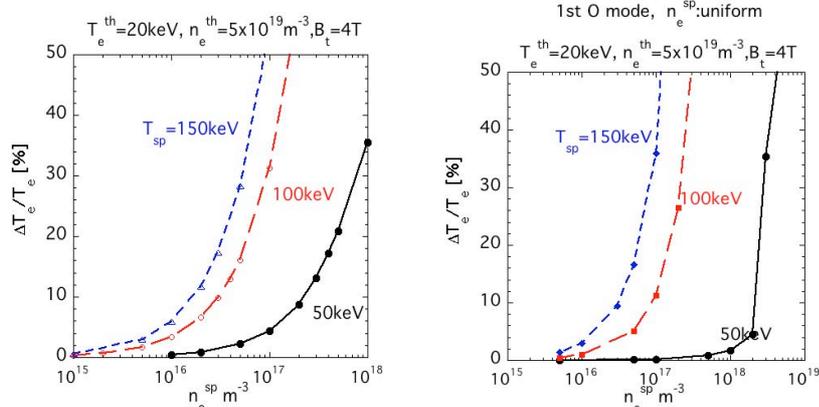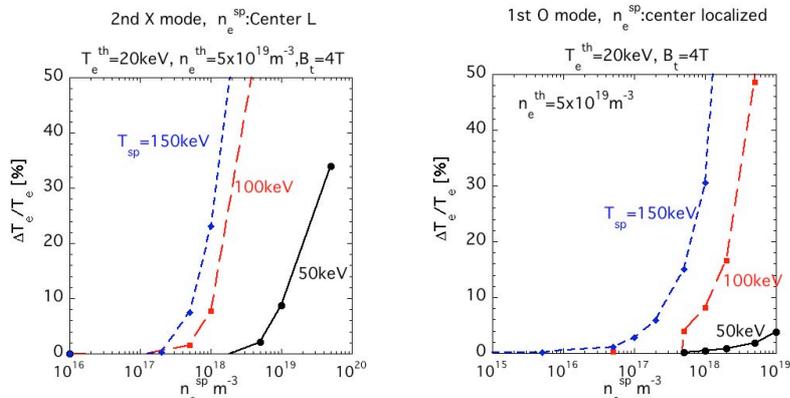

Fig. 3. Dependence of $\Delta T_e/T_e$ on center localized $n_e^{sp}(0)$ in the cases of $T_e^{th}(0) = 20$ keV, $n_e^{th}(0) = 5\times10^{19}$ m⁻³, $T_e^{sp}(r) = 50$ keV for the 2nd X mode and fundamental O mode.

fundamental O mode for T_e^{sp} = 50 keV. Therefore, for T_e^{sp} = 50 keV, the T_e^{rad} from the 2nd harmonic X mode is more sensitive to the super-thermal electron than that from fundamental O mode. The other is the relativistic effect of supra-thermal electron of the higher harmonic used mode (e.g. 3rd harmonic X mode) on the thermal electron of the used mode (e.g. 2nd X mode). When the T_e^{sp} is high in the case of the 2nd harmonic X mode (or fundamental O mode) as mode used, the effect of relativistic broadening of the supra-thermal 3rd (or 2nd) harmonics affects on the thermal 2nd harmonic (or fundamental) mode effectively. The value of Rj for 2nd harmonic X mode is comparable with that for fundamental O mode for T_e^{sp} = 150 keV. Therefore, T_e^{sp} = 150 keV, the sensitivity of T_e^{rad} from the 2nd harmonic X mode to the super-thermal electron is almost the same as that from fundamental O mode. The dependence of $\Delta T_e/T_e$ on center localized n_e^{sp} is shown in Fig. 3. The obtained T_e^{rad} in the center localized n_e^{sp} case is less sensitive to supra-thermal electron than that in the uniform n_e^{sp} case.

The dependence of $\Delta T_e/T_e$ on $T_e^{sp}(0)$ is shown in Fig. 4 for the 2nd harmonic X mode. When the $T_e^{sp}(0)$ increases, the $\Delta T_e/T_e$ is proportional to $T_e^{sp}(0)$, and the results is not contradict the scaling of $\Delta T_e/T_e$ ($\propto (T_e^{sp} - T_e^{th})/T_e^{sp}$) roughly.
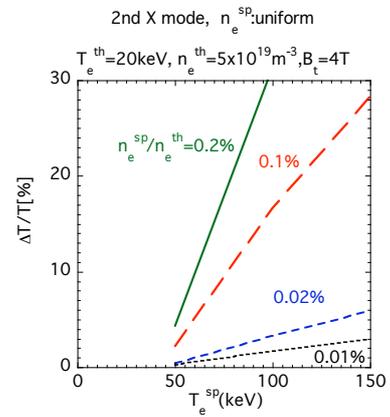

Fig. 4. Dependence of $\Delta T_e/T_e$ on $T_e^{sp}(0)$ in the cases of $T_e^{sp}(r) = 50$ keV for the 2nd X mode,.

5. Summary

The effect of supra-thermal electron on the T_e^{rad} from ECE, that is obtained from fundamental O mode and 2nd harmonic X mode, is evaluated in the case of the relativistic bi-Maxwellian. The small amount of supra-thermal electron ($n_e^{sp}(0)/n_e^{th}(0) \sim 1\%$) affects on the T_e^{rad}. The deviation from $T_e^{rad}(Max)$ is evaluated. The parameter dependences of the deviation on T_e^{sp} and modes are interpreted from the two viewpoints. One is the relativistic effect of supra-thermal electron of the mode used for T_e^{rad} measurement on the thermal electron of the same mode used. The other is the relativistic effect of supra-thermal electron of the higher harmonic used mode on the thermal electron of the same mode used.

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