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Tandem Mirror Transport Study with AIC Fluctuations

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Abstract

A energy transport model including the effects of Alfvén ion cyclotron fluctuations is presented to explain hot-ion-mode experiments in the tandem mirror GAMMA 10. The zero-dimensional transport equations of ion and electron temperatures coupled with the quasilinear effects of the Alfvén ion cyclotron modes are derived and solved numerically for the steady state. It is shown that the present model can well reproduce the experimental results in GAMMA 10.

Keywords:

tandem mirror, GAMMA 10, energy transport, transport equation, Alfvén ion cyclotron mode, quasilinear diffusion

1. Introduction

In hot-ion-mode experiments of the tandem mirror GAMMA 10, strongly anisotropic hot ions in the central cell are produced by the ion cyclotron range of frequencies (ICRF) heating [1,2]. Namely, the perpendicular temperature $T_{\perp i}$ of the ion is 3–10keV, and the parallel temperature $T_{\parallel i}$ is several hundreds eV. Then, the temperature anisotropy $T_{\perp i}/T_{\parallel i}$ of the ion becomes large to exceed 10. Therefore, in GAMM10, Alfvén ion cyclotron (AIC) fluctuations are observed to be excited due to this strong anisotropy of the ion temperature [3,4]. On the other hand, the electron temperature T_e in the central cell is typically 0.1–0.2keV, and the typical value of $T_{\perp i}/T_{\parallel e}$ is more than 3.

Now, our question is what kinds of transport processes have a role to decide the ion and electron temperatures in the hot-ion-mode experiments of GAMMA 10. In this paper, we study energy transport processes in the hot-ion-mode experiments of GAMMA 10 to explain the experimental results. We here construct a model of transport equations for the ion and electron temperatures based on a point model. The model includes the quasilinear effects of AIC fluctuations in addition to standard classical processes such as collisional relaxation, collisional end losses, and charge exchange losses, because the AIC fluctuations have been actually observed in the hot-ion-mode experiments. It is found that the quasilinear velocity-space diffusion due to the AIC fluctuations can contribute to temperature relaxation, that is, isotropization of the anisotropic ion temperature. We here assume that there exists additional energy loss for the cold component of the ion with $T_{\parallel i}$ besides collisional end losses. This additional energy loss for the cold component of the ion is of importance, as it forces to obstruct the temperature relaxation. As the candidate for the additional loss mechanism, radial transport of the passing cold ions in the transition region [5], or, anomalous diffusion loss to the end due to the AIC fluctuations [6] may be considered. By solving numerically the transport equations for the ion and electron temperatures for the steady state, we show that the present model can well reproduce the results on the

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hot-ion mode experiment of GAMMA 10. We also show that both effects of the ion temperature relaxation due to the AIC fluctuation-induced quasilinear diffusion, and the additional energy loss for the cold ions are of importance to explain the hot-ion mode experiments.

In the following section, we derive the zero-dimensional transport equations for the ion and electron temperatures including the quasilinear effects of the AIC fluctuations, which are solved numerically for the steady state in section 3. In section 4, we summarize the results obtained in this paper.

2. Energy Transport Model

In this section, we construct a model for energy transport in the hot-ion-mode plasma of the tandem mirror GAMMA 10 based on a point model. We here assume that the plasma is sustained by ICRF only, and that there is no electron cyclotron resonance heating (ECRH) for ion-confining potential formation. We here consider a model of power flow chart shown in Fig.1. Then, we assume the transport equations for the ion and electron temperatures in the hot-ion-mode plasma given as

$$\frac{\mathrm{d}}{\mathrm{d}t}(nT_{\perp i}) = P_{\mathrm{RF}} - \frac{nT_{\perp i}}{\tau_{\mathrm{cx}}} - n\nu(T_{\perp i} - T_{\parallel i}) - 2\int_{-\infty}^{\infty} \mathrm{d}k\, 2\gamma E - \frac{n(T_{\perp i} - T_{\mathrm{e}})}{\tau_{\mathrm{ei}}}, \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(nT_{\parallel i}) = n\nu(T_{\perp i} - T_{\parallel i}) + \int_{-\infty}^{\infty} \mathrm{d}k\, 2\gamma E - \frac{nT_{\parallel i}}{2\tau_{\mathrm{i}\parallel}} - \frac{nT_{\parallel i}}{2\tau_{\mathrm{ad}}} - \frac{n(T_{\parallel i} - T_{\mathrm{e}})}{2\tau_{\mathrm{ei}}}, \tag{2}$$

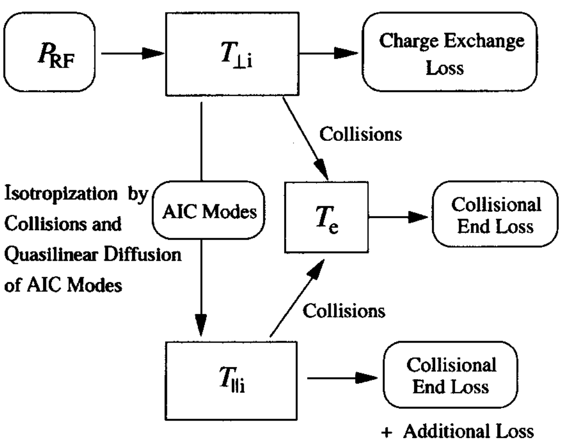

Fig. 1 Power flow chart in the present model for the hot-ion-mode experiment of GAMMA 10.

$$\frac{\mathrm{d}}{\mathrm{d}t}(nT_{\mathrm{e}}) = \frac{n}{\tau_{\mathrm{ei}}}\left(\frac{2T_{\perp i} + T_{\parallel i}}{3} - T_{\mathrm{e}}\right) - \frac{nT_{\mathrm{e}}}{\tau_{\mathrm{e}\parallel}}, \tag{3}$$

where P_{RF} is the ICRF power, τ_{cx} the charge exchange time, τ_{ei} the electron drag time, $\tau_{\mathrm{i}\parallel}$ the collisional confinement time for the cold ion component, τ_{ad} the additional energy-loss time, $\tau_{\mathrm{e}\parallel}$ the electron confinement time, and ν given by

$$\nu[s^{-1}] = \frac{C}{T_{\parallel}^{3/2}[\mathrm{keV}]}\frac{1}{A^2}\left[-3 + (A+3)\frac{\arctan\sqrt{A}}{\sqrt{A}}\right],$$

$$A = \frac{T_{\perp i}}{T_{\parallel i}} - 1 \tag{4}$$

is the temperature isotropization rate ($C = 90$) [7]. The characteristic times are given by $\tau_{\mathrm{e}\parallel} = 3C_{\mathrm{e}}T_{\mathrm{e}}^{3/2}(\phi_{\mathrm{e}}/T_{\mathrm{e}}) \exp(\phi_{\mathrm{e}}/T_{\mathrm{e}})/2(\phi_{\mathrm{e}}/T_{\mathrm{e}} + 1)$ ($C_{\mathrm{e}} = 5.4 \times 10^{-4}$), $\tau_{\mathrm{i}\parallel} = C_{\mathrm{i}}T_{\mathrm{i}}^{3/2}$ ($C_{\mathrm{i}} = 0.03$), and $\tau_{\mathrm{ei}} = C_{\mathrm{I}}T_{\mathrm{e}}^{3/2}$ ($C_{\mathrm{I}} = 0.32$), when the τ is in second, the T is in keV and $n = 2 \times 10^{12}\mathrm{cm}^{-3}$ for the density is assumed.

The ambipolar potential ϕ_{e} is here determined from the ambipolar condition given by $1/\tau_{\mathrm{ep}} = 1/\tau_{\mathrm{i}\parallel} + 1/\tau_{\mathrm{ad}}$, where τ_{ep} is the particle confinement time of the electron, given by $\tau_{\mathrm{ep}} = 2\tau_{\mathrm{e}\parallel}(\phi_{\mathrm{e}}/T_{\mathrm{e}} + 1)/3$. This ambipolar condition is then reduced to the following equation:

$$\frac{C_{\mathrm{i}}}{C_{\mathrm{e}}}\left(\frac{T_{\parallel i}}{T_{\mathrm{e}}}\right)^{3/2} = \left[1 + \frac{\tau_{\mathrm{i}\parallel}}{\tau_{\mathrm{ad}}}\right]\frac{\phi_{\mathrm{e}}}{T_{\mathrm{e}}}\exp\left(\frac{\phi_{\mathrm{e}}}{T_{\mathrm{e}}}\right). \tag{5}$$

The spectral energy density $E(k,t)$ of the AIC fluctuations in eqs.(1) and (2) is defined by $E = \tilde{B}_k\tilde{B}_{-k}/2\mu_0$, where $\tilde{B}_k$ is the Fourier component of the AIC-mode magnetic fluctuation, and is assumed to obey the following wave kinetic equation:

$$\frac{\partial}{\partial t}E(k,t) = 2\gamma(k)E - \alpha(k)E^2, \tag{6}$$

where $\gamma(k)$ is the linear growth rate of the AIC mode, which is determined from the linear dispersion relation [8,9]:

$$\varepsilon_{\mathrm{L}}(\omega, k, T_{\perp i}, T_{\parallel i}) = 1 - \left(\frac{ck}{\omega}\right)^2 - \frac{\omega_{\mathrm{pe}}^2}{\omega(\omega + |\omega_{\mathrm{ce}}|)} + \frac{\omega_{\mathrm{pi}}^2}{\omega^2}\left[\frac{\omega}{|k|\mathrm{v}_{\parallel i}} Z\left(\frac{\omega - \omega_{\mathrm{ci}}}{|k|\mathrm{v}_{\parallel i}}\right) + \frac{1}{2}\left(1 - \frac{T_{\perp i}}{T_{\parallel i}}\right) Z'\left(\frac{\omega - \omega_{\mathrm{ci}}}{|k|\mathrm{v}_{\parallel i}}\right)\right] = 0, \tag{7}$$

where ω_{p} is the plasma frequency, ω_{c} the cyclotron frequency, $\mathrm{v}_{\parallel i}$ ($= \sqrt{2T_{\parallel i}/m_{\mathrm{i}}}$) the ion thermal speed, c the speed of light, and $Z(x)$ the plasma dispersion function.

In the derivation of eq.(7), we assume a bi-Maxwellian distribution for the ion and cold electrons. We also assumed $(\omega_{pi}/ck)^2 \ll 1$ and $(\omega/ck)^2 \ll 1$, which are satisfied for the AIC modes, in the derivation of (1) and (2). The similar ion-temperature relaxation due to the AIC modes has been discussed in ref.10. The present analysis on the quasilinear relaxation of the ion temperature is the same as the result of ref.10 under the assumption of $(\omega_{pi}/ck)^2 \ll 1$ and $(\omega/ck)^2 \ll 1$.

3. Power Flow in Steady State

In this section, we consider the steady-state power flow in a hot-ion-mode plasma, based on the transport model obtained in the previous section. By solving eqs.(1)-(3) and (5) simultaneously, we can determine $T_{\perp i}$, $T_{\parallel i}$, T_e and ϕ_e when $E(k)$ and $\gamma(k)$ for the AIC fluctuations, τ_{cx} and τ_{ad} are given.

We have to estimate the integral of the spectral energy density $E(k)$ to solve eqs.(1) and (2). We here assume that the spectral energy density $E(k)$ is proportional to $\gamma(k)$. This assumption can be realized if α is constant in eq.(5). In this case, the integral of the spectral energy density in eqs.(1) and (2) are given by

$$\int_{-\infty}^{\infty} dk\gamma(k)E(k) = W \frac{\int_{-\infty}^{\infty} dk\gamma^2}{\int_{-\infty}^{\infty} dk\gamma},$$

$$W = \int_{-\infty}^{\infty} dk E(k), \tag{8}$$

where W is the total wave energy density of the AIC fluctuations. Then, we can determine $T_{\perp i}$, $T_{\parallel i}$, T_e and ϕ_e when we fix τ_{cx}, τ_{ad} and W. We here assume τ_{cx} = 10 ms and $n = 2 \times 10^{12}\mathrm{cm}^{-3}$ as the typical values obtained in the hot-ion-mode experiments.

In Fig.2, we show the ion and electron temperatures ($T_{\perp i}$: solid line, $T_{\parallel i}$: dashed line, T_e: chain line and $T_{\perp i}/T_{\parallel i}$: dotted line) as a function of the ICRF power P_{RF}/n in the case of τ_{ad} = 4ms and $W/n = 10^{-4}$keV. This value of W corresponds to the magnetic fluctuations of about 2gauss. The ion and electron temperature s go up with the increase of the ICRF power. We see that $T_{\perp i}/T_{\parallel i} \approx 9$ and $T_{\parallel i}/T_e \approx 3$ for $T_{\perp i} \approx 3 - 6$keV. These temperature ratios are close to the results of the hot-ion-mode experiments of GAMMA 10 with the AIC fluctuations.

On the other hand, we show the ion and electron temperatures (the notation is the same as Fig.2) as a function of the ICRF power in Fig.3 for the case of $\tau_{ad} = \infty$ and $W = 0$ to compare with Fig.2. In this case, we see that $T_{\perp i}/T_{\parallel i} \approx 6$ and $T_{\parallel i}/T_e \approx 2$ $T_{\perp i} \approx 3 - 7$keV. These temperature ratios differs from the experimental results of GAMMA 10. That is, in this case the electron and parallel ion temperatures become larger than those in Fig.2 for a given $T_{\perp i}$. This is because collisional energy relaxation becomes more stronger as the confinement time for the cold ion component is longer.

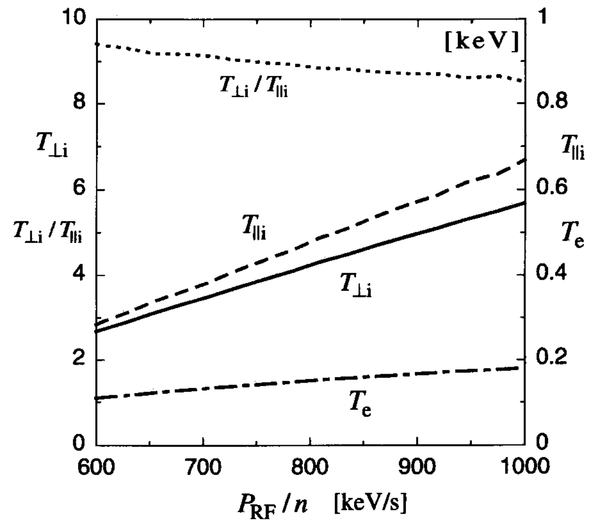

Fig. 2 Ion and electron temperatures as a function of the ICRF power P_{RF}/n for τ_{ad} = 4ms and $W/n = 10^{-4}$keV. $T_{\perp i}/T_{\parallel i} \approx 9$ and $T_{\parallel i}/T_e \approx 3$ for $T_{\perp i} \approx 3 - 6$keV.

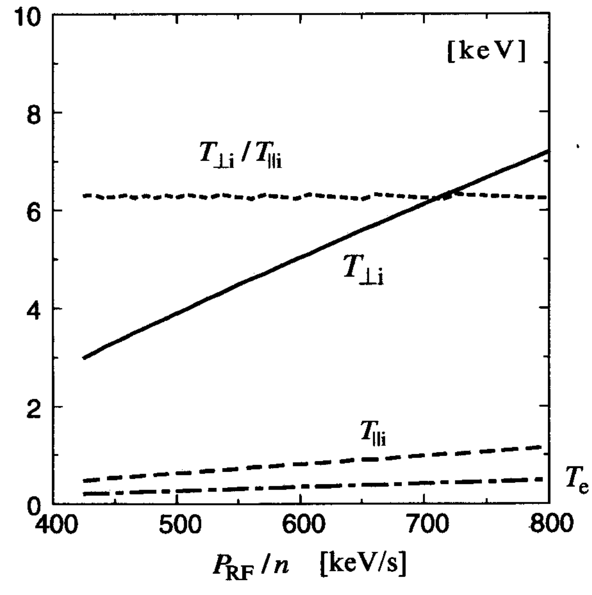

Fig. 3 Ion and electron temperatures as a function of the ICRF power P_{RF}/n for $\tau_{ad} = \infty$ and $W = 0$. $T_{\perp i}/T_{\parallel i} \approx 6$ and $T_{\parallel i}/T_e \approx 2$ for $T_{\perp i} \approx 3 - 7$keV.

4. Conclusions

In this section, we summarize the energy transport study on the hot-ion-mode experiments of GAMMA 10 obtained in this paper. We have shown numerically that the present model of energy transport including both the quasilinear diffusion effects of the AIC fluctuations, and additional energy loss besides the collisional end loss for the cold ions can well explain the experimental results on the hot ion mode of GAMMA 10, where the AIC modes have been observed actually. The effect of ion plugging effects by ECRH neglected in this paper will be reported in future.

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