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Study of ion kinetic effects on plasma distributions by anisotropic-ion-pressure plasma fluid simulation

Keishi Homma[1], Satoshi Togo[1], Tomonori Takizuka[2], Yuki Homma[3], Kenzo Ibano[2], Kazuma Emoto[1], Mizuki Sakamoto[1]
[1] Plasma Research Center, University of Tsukuba, [2] Graduate School of Engineering, Osaka University, [3] National Institutes for Quantum Science and Technology
e-mail (speaker): honma_keishi@prc.tsukuba.ac.jp

Currently, efforts are being made to improve edge plasma transport simulations to establish methods for controlling the heat load on the divertor.

In plasma fluid models primarily used for scrape-off layer (SOL) plasma, the conductive heat flux along magnetic field lines is represented by the Spitzer-Härm (SH) heat flux $q^{||SH}$[1]. However, the actual heat flux becomes smaller than the SH heat flux when the mean-free path is longer than the SOL characteristic length. This is referred to as the kinetic effect. In the SONIC code [2,3], a free streaming energy (FSE)-limited model is employed for the kinetic effect. According to the SONIC simulation of JA DEMO [4], the kinetic effect of ion heat flux leads to remarkable changes in the SOL plasma profiles [3]. In these simulations, however, the anisotropy between the ion temperature parallel and perpendicular to the magnetic field direction, denoted as $T_{\mathrm{i}||}, T_{\mathrm{i}\perp}$, which might be significant in the low-collisionality regime [5], have not been considered.

In this study, we aim to study the ion kinetic effects in the presence of anisotropic ion pressure. A plasma fluid model based on the anisotropic ion pressure (AIP model) [6,7] is applied to a tandem mirror device GAMMA 10/PDX which exhibits significant ion pressure anisotropy [8]. In the AIP model, the ion conductive heat flux is evaluated based on a simple FSE-limited model [6].

$$q_\sigma^{||\mathrm{FSE}} = \left[1 + \frac{\left|q_\sigma^{||\mathrm{SH}}\right|}{\alpha_\sigma q_\sigma^{\mathrm{FS}}}\right]^{-1} q_\sigma^{||\mathrm{SH}} \; (\sigma \in \{\mathrm{i}||, \mathrm{i}\perp\}) \quad (1)$$

$$q_\sigma^{||\mathrm{SH}} = -\kappa_\sigma^{||\mathrm{SH}}(\partial T_\sigma/\partial s), \qquad q_\sigma^{||\mathrm{FS}} = p_\sigma\sqrt{T_{\mathrm{i}||}/m_\mathrm{i}} \quad (2)$$

Here, $\kappa_\sigma^{||\mathrm{SH}}$ represents the SH thermal conductivity, T is the temperature, p is the pressure, m_i is the ion mass, and s is the coordinate in the magnetic field direction. Equation (1) describes the FSE-limited model using the harmonic mean of $q_\sigma^{||\mathrm{SH}}$ and $q_\sigma^{||\mathrm{FS}}$, where $q_\sigma^{||\mathrm{FS}}$ is the free-streaming heat flux as a collisionless limit. The kinetic effects occur depending on collisionality, and the degree of these effects is defined by the heat flux limiter coefficients (α_σ). Note that, in the AIP model, the parallel ion conductive heat flux is divided into two components $q_{\mathrm{i}||}^{||}$ and $q_{\mathrm{i}\perp}^{||}$ which transport the parallel and perpendicular energy components in the parallel direction, respectively. In this study, we vary the value of α_σ and change the kinetic effects in each component.

Figure 1 shows the spatial distribution of ion temperature anisotropy ($T_{\mathrm{i}\perp}/T_{\mathrm{i}||}$) in the GAMMA 10/PDX device for various $\alpha_{\mathrm{i}||}$ values with fixed $\alpha_{\mathrm{i}\perp} = 0.5$. By the increase of $\alpha_{\mathrm{i}||}$, both $T_{\mathrm{i}||}$ and $T_{\mathrm{i}\perp}$ in the central region ($|s| < 2.8$ m) are decreased. On the other hand, it is found that the anisotropy is unchanged ($T_{\mathrm{i}\perp}/T_{\mathrm{i}||} \approx 2.5$). Simulations are conducted in a uniform magnetic field system with the same collisionality. By increasing $\alpha_{\mathrm{i}||}$, an increase in $T_{\mathrm{i}\perp}/T_{\mathrm{i}||}$ is observed clearly. As a common phenomenon in both systems, increasing $\alpha_{\mathrm{i}||}$ leads to an increase in $q_{\mathrm{i}||}^{||}$ (> 0) and a resultant decrease in $T_{\mathrm{i}||}$. Moreover, the nonlinear changes in the plasma distribution also affect $q_{\mathrm{i}\perp}^{||}$. In the case of GAMMA 10/PDX, particle flow is hindered due to mirror confinement, and the conductive heat flux is comparable in magnitude to the convective heat flux. As a result, the decrease in $q_{\mathrm{i}\perp}^{||}$ (< 0) brings about a decrease in $T_{\mathrm{i}\perp}$. That is why the change in $T_{\mathrm{i}\perp}/T_{\mathrm{i}||}$ is minimal in GAMMA 10/PDX. In the presentation, the effect of $\alpha_{\mathrm{i}\perp}$ on the plasma distribution is also discussed.

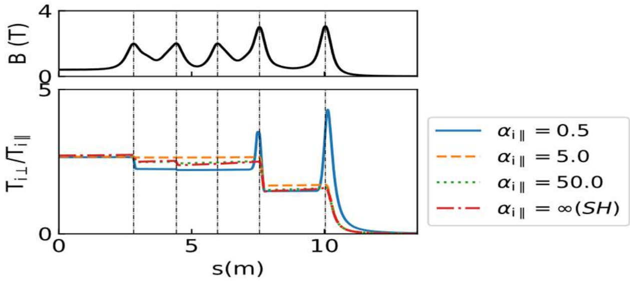

Figure 1. Spatial distributions of magnetic field intensity B in GAMMA 10/PDX and ion temperature anisotropy $T_{\mathrm{i}\perp}/T_{\mathrm{i}||}$ for various $\alpha_{\mathrm{i}||}$ values. The center ($s = 0$) is a symmetric point.

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