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速度分布関数に基づく発散磁場中のイオン比熱比の解析

Analysis of the ion adiabatic index in diverging magnetic fields based on the velocity distribution function

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The ion adiabatic index γ plays an important role in the thermofluid description relating the density (n) variation with the pressure (p) variation via an adiabatic equation. It also affects the sheath boundary condition of the ion flow (i.e. the Bohm criterion [1]) via the ion sound speed $c_s \equiv ((\gamma T_{i||}+T_e)/m_i)^{1/2}$ where $T_{i||}$, T_e and m_i denote the parallel ion temperature, the electron temperature and the ion mass. The value of γ has been studied in homogeneous magnetic fields (B) numerically [2, 3]. However, effects of inhomogeneous B on the value of γ have not been fully understood although such a situation commonly appears in cosmic plasmas as well as various application fields of the plasma physics like fusion reactors and thrusters.

A method to evaluate γ in inhomogeneous B based on the ion velocity distribution function f has been developed in this study by generalizing the derivation of the generalized Bohm criterion [1]. An adiabatic equation based on the CGL model [4] is used; $\mathrm{d}/\mathrm{d}t(p_{i||}n^{-\gamma}B^{\gamma-1}) = 0$. Here, $p_{i||} \equiv nT_{i||}$ is the parallel ion pressure. By combining this adiabatic equation with the –1st, 0th and 1st $v_{||}$-moment equations of the Vlasov equation, a formula relating γ with f is obtained as follows;

$$-\frac{eE_{||}}{m_\mathrm{i}}\int\frac{f(v_{||})}{v_{||}^2}\mathrm{d}v_{||}+\frac{1}{2B}\frac{\mathrm{d}B}{\mathrm{d}s}\int\frac{v_\perp^2 f(v_{||},v_\perp)}{v_{||}^2}\mathrm{d}\boldsymbol{v} = eE_{||}\frac{n}{\gamma T_{\mathrm{i}||}-m_\mathrm{i}u_{||}^2}-\frac{T_{\mathrm{i}\perp}}{\gamma T_{\mathrm{i}||}-m_\mathrm{i}u_{||}^2}\frac{n}{B}\frac{\mathrm{d}B}{\mathrm{d}s}. \qquad (1)$$

Here, $v_{||}$ and $v_\perp$ are the parallel and perpendicular velocity of ions. The parallel coordinate is denoted by s. Notations e, $E_{||}$, $u_{||}$ and $T_{i\perp}$ represent the elementary charge, the parallel electric field, the parallel ion flow and the perpendicular ion temperature. Note Eq. (1) reduces to the usual result of the generalized Bohm criterion [1] when $\mathrm{d}B/\mathrm{d}s = 0$. Using Eq. (1) instead of the adiabatic equation may enable us to evaluate γ from f measured at a single position which is a superior merit from an experimental point of view.

The method is applied to the diverging B region in an end cell of a tandem mirror device GAMMA 10/PDX in this study in order to verify it. A simple analytical model is considered to generate f at arbitrary positions: (i) a monotonically-decreasing potential (Φ) profile is given, (ii) f at the mirror center is given by a bi-Maxwellian, (iii) ions in the loss cone move conserving energy and the magnetic moment. First, a numerical solution obtained by a plasma fluid model [5] is used as a model plasma of GAMMA 10/PDX.

Parallel profiles of B and Φ shown in Fig. 1 (a) are given to the analytical model and f is diagnosed at three positions; s = 10.3, 11.9 and 13.45 m. As shown in Fig. 1 (b), each $f(v_{||})$ has a potential cut-off in the low-$v_{||}$ side and a tail in the high-$v_{||}$ side, generating finite heat conduction. Moment quantities computed from the obtained f agree well with those of the fluid simulation result [5]. The values of γ computed by Eq. (1) at s = 10.3, 11.9 and 13.45 m are about 0.9, 2.2 and 2.4, respectively, indicating that heat conduction is dominant right out of the mirror throat, and then heat convection becomes dominant downstream. This result agrees with the shift of $f(v_{||})$ shown in Fig. 1 (b). Results from the ion energy analyzers at GAMMA 10/PDX will also be discussed in the presentation.

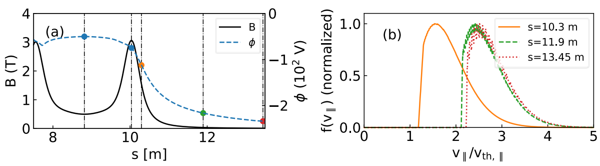

Fig. 1 (a) Profiles of B and Φ, and (b) $f(v_{||})$ at 3 diagnosed positions.

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