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トロイダルジャイロ運動論的方程式のモーメント分離解法の開発

Development of a moment extract approach to the toroidal gyrokinetic simulation

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Numerical analyses of plasma instabilities which are closely related to the turbulent transport are important for the confinement improvement. While explicit schemes (e.g.: Runge-Kutta-Gill (RKG) scheme) are widely adopted to numerical codes like GKV [1], the time step size is severely restricted by the CFL condition when the kinetic electrons are included. Therefore, it is crucial to develop a fast and accurate time integration technique to overcome the time step limitation.

The moment extract approach is proposed in the previous research [2]. In this approach, the drift kinetic equation (DKE) is rewritten into the 0th and the 1st order moment equations, and the remnant kinetic equation. It is found that stiff advection terms due to the rapid phase velocity can be separated by this technique. Thus, application of the implicit scheme only to these "fast" advection terms enables us to solve efficiently the DKE, which is the key in the gyrokinetic simulation with kinetic electrons.

Here, we aim to apply this approach to toroidal plasmas, where non-uniformity of the magnetic field should be taken into account. Thus, we have extended the moment-extract approach to the non-uniform magnetic field system. The DKE is defined as

$$\frac{\partial f_e}{\partial t}+v_\parallel\frac{\partial f_e}{\partial z}=-\frac{q_e}{T_{e0}}v_\parallel F_M\left(\frac{\partial\varphi}{\partial z}+\frac{1}{c}\frac{\partial A_\parallel}{\partial t}\right)+\frac{\mu}{m_e}\frac{\partial B}{\partial z}\frac{\partial f_e}{\partial v_\parallel}.$$

Here, we separated the DKE to the 0th moment, the 1st moment, and the remnant kinetic equations, such that

$$\frac{\partial n_e}{\partial t}=-n_0\left(\frac{\partial U_\parallel}{\partial z}-\frac{1}{B}\frac{\partial B}{\partial z}U_\parallel\right), \tag{1}$$

$$n_0 m_e\frac{\partial U_\parallel}{\partial t}=-q_e n_0\left(\frac{\partial\varphi}{\partial z}+\frac{1}{c}\frac{\partial A_\parallel}{\partial t}\right)-\frac{\partial}{\partial z}\left(n_e T_0+n_0 T_\parallel\right)+\frac{1}{B}\frac{\partial B}{\partial z}n_0\left(T_\parallel-T_\perp\right), \tag{2}$$

and

$$\frac{\partial h_e}{\partial t}+v_\parallel\frac{\partial h_e}{\partial z}=\left[\left(1-\frac{m_e v_\parallel^2}{T_{e0}}\right)\frac{\partial U_\parallel}{\partial z}+\frac{v_\parallel}{T_{e0}}\frac{\partial T_\parallel}{\partial z}+\left(\frac{\mu_e}{T_{e0}}U_\parallel-\frac{U_\parallel}{B}-\frac{v_\parallel}{B}\frac{T_\parallel-T_\perp}{T_{e0}}\right)\frac{\partial B}{\partial z}\right]F_M+\frac{\mu}{m_e}\frac{\partial B}{\partial z}\frac{\partial h_e}{\partial v_\parallel} \tag{3}$$

where $h_e=f_e-\left[\left(n_e/n_0\right)+\left(m_e/T_0\right)v_\parallel U_\parallel\right]F_M$.

Here, we examine the fractional time step scheme with the 2nd order Adams-Bashforth and Crank-Nicolson (ABCN) method and RKG scheme. Figure 1 shows the oscillation of the electrostatic potential at $z=0$ in the non-uniform magnetic field of by $B=B_0\left(1-0.1\cos z\right)$, with Courant number $C_L=2.15$. It is found that ABCN scheme successfully reproduces the stable oscillation, while the RKG scheme doesn't due to the numerical instability. We have also carried out a detailed error analysis and the convergence tests of which details will be reported at the meeting.

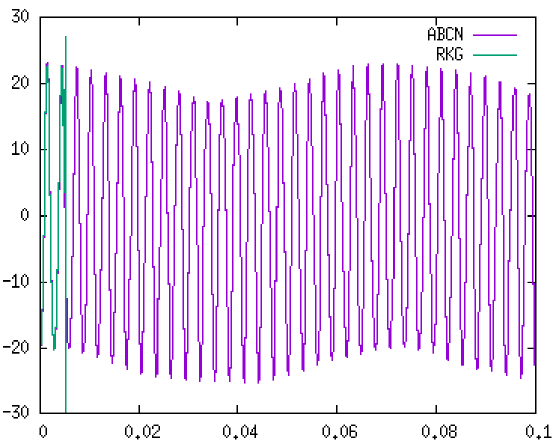

Fig.1 : Oscillation of the electrostatic potential in the non-uniform magnetic field $B=1-0.1\cos z$ with $C_L=2.15$ obtained by the ABCN and RKG schemes.

[1] T. -H. Watanabe, et al, Nucl. Fusion **46**, 24 (2006).
[2] T. -H. Watanabe, et al, P2-37, ITC25, Gifu (2015).