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Fokker-Planck modeling for energetic particles at tokamak ramp-up phases
トカマクランプアップフェーズにおける高エネルギー粒子のフォッカー・プランクモデリング

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In a tokamak plasma, the distribution function in the velocity space of a fast ion is distorted due to magnetic compression or expansion when the equilibrium evolves in time. Heating power and driven current by fast ions are also subject to the distortion. A modeling of the magnetic distortion has been developed and implemented in a bounce-averaged Fokker-Planck modeling in an integrated code suite TOPICS for the first time. The integrated simulation applied to a JT-60SA 2.3 MA plasma shows that the heating power and the neutral beam driven current increases by about 10 % due to the effect of the magnetic distortion in the plasma current ramp-up phase.

1. Introduction

Fast ion modeling is a key component in a tokamak integrated code in terms of accurate evaluation of heating and current drive by fast ion. The orbit following Monte-Carlo modelings such as OFMC [1], ASCOT [2] and DELTA5D [3] are widely used for the fast ion analysis in a steady state, but are unsuitable for the transient analysis because they require large numerical cost especially when the equilibrium evolves. Instead, we employ the Bounce-Averaged Fokker-Plank (BAFP) modeling for the fast ion analysis and integrate in our integrated code suite TOPICS [4-6] for the transient analysis. In the transient phase, such as the current ramp-up phase, the distribution function of the fast ion would be distorted being affected by the variation of the magnetic field. The heating power and the driven current by the fast ion are also subject to the magnetic distortion.

2. Bounce-Averaged Fokker-Planck Modeling Integrated in TOPICS

An evolution equation for the bounce-averaged distribution function $\mathcal{F}$ is written as [7]

$$\frac{\partial \mathcal{F}}{\partial t} = -\left\langle \nabla_v \cdot \Gamma_c \right\rangle_B - \left\langle \frac{e}{m} E_{//} \frac{\partial \mathcal{F}}{\partial v_{//}} \right\rangle_B + \left\langle S \right\rangle_B - \left\langle \nu_{loss} \right\rangle_B \mathcal{F} \quad (1)$$

where t is a time slower than a bounce period τ_B, Γ_c is the flux in the velocity space, e and m are the charge and the mass of the fast ion species respectively, $E_{//}$ is the parallel electric field, $v_{//}$ is the speed parallel the magnetic filed, S is the particle source that arises from ionization and charge-exchange for the neutral beam (NB) species and fusion reactions for the α particles, ν_{loss} is the frequency corresponds to the fast ion thermalization and assimilation into the bulk ion. The bounce-average operation on a quantity Q is defined as

$$\left\langle Q \right\rangle_B \equiv \frac{1}{\tau_B} \oint \frac{Q\,\mathrm{d}s}{v \cos\eta_B} \quad (2)$$

where $\tau_B = \oint \mathrm{d}s / \left(v \cos\eta\right)$ is the bounce period, $\mathrm{d}s$ is the line element along the field line, v and η are the speed and the pitch angle of the particle velocity respectively. The path integral is undertaken along the particle orbit, going around on the poloidal plane for the passing particles, and between the two turning points for the trapped particles. The deviation of the magnetic flux surface is neglected. The BAFP equation is solved to obtain $\mathcal{F}$ and then the fast ion current, pressure and heating powers are calculated. These terms are used in the transport solver of TOPICS to obtain the plasma parameters. The equilibrium solver of TOPICS obtains the magnetic fluxes and provides them to the BAFP solver and the transport solver.

3. Adiabatic Magnetic Distortion of the Distribution Function of the Fast Ion

When the two time slices of the equilibrium magnetic field are given, v and η at the new time slice can be obtained using the two adiabatic invariants, the magnetic moment and the longitudinal invariant. The longitudinal invariant is roughly expressed as

$$\mathcal{J} = \oint m v_{//} \, \mathrm{d}s \approx m v_{//} (2\pi q R) \quad (3)$$

where q is the safety factor and R the major radius. In the current ramp-up phase, as the I_{p} increases, inversely, q decreases; then $v_{//}$ increases. This leads to the adiabatic magnetic distortion of the distribution function of the fast ion.

4. Integrated Simulation with the Effect of the Adiabatic Magnetic Distortion

Using the integrated code with the modeling of the adiabatic magnetic distortion, we have performed an example simulation of a current ramp-up phase of a JT-60SA [8] plasma. Operation conditions imposed in the simulation are as follows. The plasma current ramps up at the rate of $\dot{I}_{\mathrm{p}} = 0.4$ MA s^{-1} from 1.5 s to 5.0 s so that the flat-top current reaches $I_{\mathrm{p}} = 2.3$ MA. A negative-ion-based NB with the accelerating energy of 500 keV and the power of 5 MW has been injected from 2.5 s. The distribution function of the fast ion due to the NB is solved by the BAFP with the adiabatic magnetic distortion model. Figure 1 shows the NB driven current comparing the cases with and without the

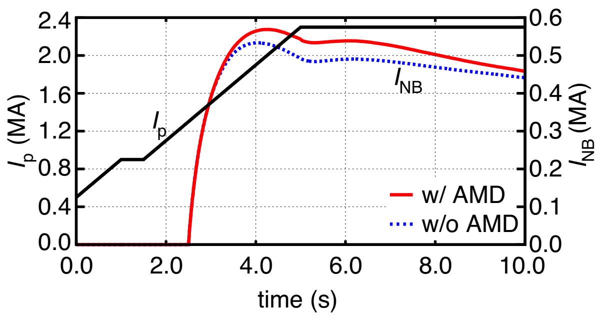

Fig. 1. Time evolution of the NB driven current

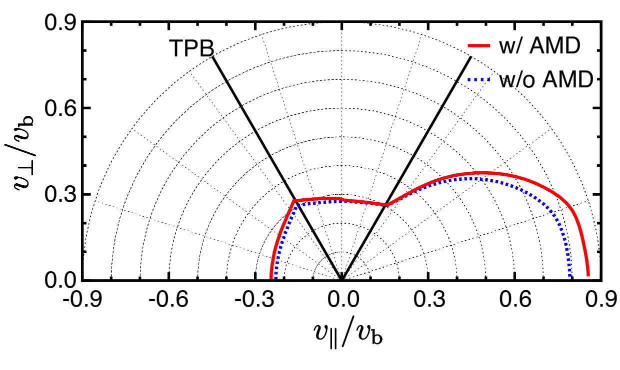

Fig. 2. Distortion of the distribution function of the NB-induced fast deuteron (TPB denotes the boundary between the trapped orbit and the passing orbit)

effect of the adiabatic magnetic distortion. The adiabatic magnetic distortion increases the driven current about 10 % at 5.0 s. The effect of the adiabatic magnetic distortion is diminishing as the q profile approaches the quasi-steady state. Figure 2 shows the contour of the distribution function of the NB-induced fast deuteron at 5.0 s. The NB birth point on the phase space locates almost at $v_{//} \approx v_{\mathrm{b}}$ where v_{b} is the beam injection speed. The collisions slow the fast ion down from the birth point to the thermal velocity. On the other hand, the fast ion is pulled up to the high energy side by the adiabatic magnetic distortion. This distortion results in the increase in the driven current.

5. Summary

In tokamaks with the NB injection or the fusion reactions, fast ion plays a key role in terms of the heating and the current drive. The transient analysis via the integrated modeling is required to achieve the robust approach to the higher performance plasma. However, the effect of the evolving equilibrium on the fast ion has never been studied. We have developed the adiabatic magnetic distortion model to take into account the effect of the evolving equilibrium and implemented it in the BAFP modeling for the fast ion analysis. In an integrated simulation applied to a JT-60SA plasma, the adiabatic magnetic distortion increases the NB driven current by 10 % during the current ramp-up phase. The introduction of the adiabatic magnetic distortion model makes the integrated modeling consistent with the evolving equilibrium.

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