GLOBAL ELECTROMAGNETIC SYMMETRY-BREAKING EFFECTS ON MOMENTUM TRANSPORT AND CURRENT GENERATION IN TOKAMAKS

[1]Z. X. Lu, [1]G. Meng, [1]C. Angioni, [1]E. Fable, [2]H. Y. Lyu, [4]Y. Chen, [1]Ph. Lauber, [1]R. McDermott, [3]F. Zonca, [1]M. Hoelzl, ASDEX Upgrade Team

[1]Max Planck Institute for Plasma Physics, 85748 Garching, Germany
[2]University of Science and Technology of China, Hefei 230026, China
[3]Center for Nonlinear Plasma Science; C.R. ENEA Frascati, C.P. 65, 00044 Frascati, Italy
[4]Center for Integrated Plasma Studies, University of Colorado at Boulder, Boulder, CO 80309, United States
Email: zhixin.lu@ipp.mpg.de

Abstract. Symmetry breaking in the global gyrokinetic solution modifies the plasma current density profile and plays a critical role in the development of observed intrinsic ion rotation. Current generation affects MHD equilibrium and instabilities. Plasma rotation can suppress microinstabilities and prevent MHD mode locking, thereby improving confinement and stability. In ITER, the external torque from neutral beam injection (NBI) is insufficient to drive a strong toroidal rotation, and intrinsic sources of rotation are expected to play a significant role [1]. Current DEMO designs and the early phase of ITER will largely rely on the intrinsic rotation due to the absence of NBI. Previous rotation studies were in the electrostatic limit, ignoring electromagnetic modes/effects [2,3,4].

This contribution presents a new global gyrokinetic code TRIMEG [5,6,7] and addresses the electromagnetic (EM) effect on current generation and momentum transport. As shown in Fig. 1, our study demonstrates that the magnetic flutter effect contributes significantly to current generation, highlighting the importance of the electromagnetic model in predicting turbulence-driven current. A large-scale current is observed in addition to the fine-structure current reported in [8,9]. Regarding the ion momentum transport, the equilibrium profile influences both the magnitude and shape of the ion rotation. For the first time, global nonlinear electromagnetic gyrokinetic simulations are applied to predict the intrinsic toroidal rotation profiles of an AUG H-mode plasma with ECRH only. A nonlinear simulation based on the ASDEX Upgrade (AUG) experimental profiles, with a reduced normalized device size, directly produces an intrinsically generated parallel velocity profile. The simulated velocity profile has a comparable magnitude to the experimentally measured one in the region where the instability is excited, as shown in Fig. 2.

Method and parameters. The electromagnetic gyrokinetic code TRIMEG introduced in [5] has been further significantly developed, with recent upgrades of the electromagnetic scheme and high-order finite element method [6,7]. The flux diagnostics of particle, heat and parallel momentum has been implemented for all particle species, including both electrons and ions. Specifically, the fluxes due to the scalar potential $\delta\phi$ and the parallel component of the vector potential $\delta A_\parallel$ are separated according to $\Pi_{\delta\phi}=\int dv^3\boldsymbol{b}\times\nabla\delta\phi/B$ and $\Pi_{\delta A_\parallel}=-\int dv^3\boldsymbol{b}\times v_\parallel\nabla\delta A_\parallel/B$. The flux contributions from the electrostatic scalar potential and the parallel component of the vector potential are analyzed separately to quantify their respective roles. All results in this work are from nonlinear simulations. We consider circular magnetic surfaces with parameters chosen as: (A) Cyclone-like, and (B) those corresponding to the AUG discharge #26170 at ~3.86 s [10]. For the Cyclone case, the plasma temperature is tuned to study the cases with different orbit width by shifting the normalized device size $a/\rho_i=180$ to 90, where ρ_i is the ion Larmor radius. For the AUG case, it is an H-mode, with about 2.2 MW of ECRH heating power, at 2.5 T and 0.6 MA.

Results and analyses. The parallel momentum fluxes of ions and electrons exhibit two distinct spatial scale structures: a fine-scale structure between two rational surfaces and a larger-scale structure, as shown in Fig. 1 for the most unstable mode n=10. This finite-structure current was also observed in previous GEM simulations using the arbitrary wavelength solver [8]. Electromagnetic effects bring in minor corrections to the ion momentum flux since as β changes from 0.5% to 2%, the contribution due to the scalar potential is small. However, the current profile can be significantly altered by the electromagnetic effect on the electron parallel momentum flux. As β increases from 0.5% to 2%, the flutter-induced electron flux, $\Pi_{\delta A_\parallel}$, becomes a significant contributor to the total electron flux, reaching half the magnitude of the $E\times B$ velocity flux $\Pi_{\delta\phi}$. More importantly, unlike in the low-β case, $\Pi_{\delta\phi}$ is influenced by the high-β and exhibits a large-scale flux structure.

The flow profile is predicted self-consistently by the nonlinear gyrokinetic simulation, without the need of solving an additional transport equation by only extracting the predicted momentum flux from the gyrokinetc simulation, and compared with the experimental measurements. The general feature of a hollow rotation profile observed in ASDEX Upgrade ECRH H-modes is reproduced by nonlinear simulations. AUG parameters are used in the simulation, with the reduced normalized device size $a/\rho_i = 90$. The multi-n nonlinear simulation is run with global effects such as self-consistent background profile variation. The evolution of the ion parallel momentum flux $\Pi_{\parallel,i}$ is shown in Fig. 2 (left), where the radial spreading of structure is visible from the linear to the nonlinear stage. The parallel velocity is calculated in the nonlinear stage as shown in Fig. 2 (right). In the region where the instability is strong (0.2<r/a<0.6), the simulation result follows the trend of the experimental measurement, while near the inner and outer boundary, more realistic simulations are needed taking into account more realistic a/ρ_i value and advanced boundary treatment.

Summary. The new electromagnetic global gyrokinetic code TRIMEG enables the study of turbulence-driven ion momentum transport and current generation on an equal footing. For turbulence-driven current, multi-scale structures are identified. In the high-β (2%) case, the electromagnetic correction in fine-scale flux reaches half of that driven by the electrostatic scalar potential. The general feature of a hollow ion toroidal rotation profile observed in ECRH H-modes in ASDEX Upgrade has been reproduced by global nonlinear electromagnetic gyrokinetic simulations. This work provides evidence that turbulence can be controlled to modify current and rotation profiles by adjusting equilibrium parameters, particularly the density and temperature gradients and curvatures. Future work aims to perform simulations at reactor-relevant values of a/ρ_i.

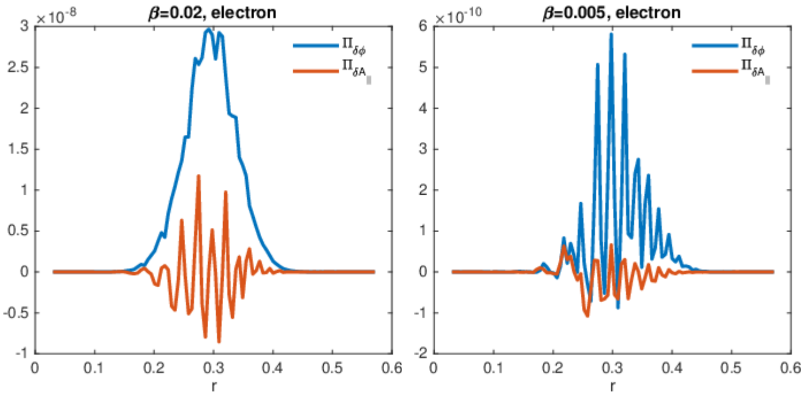

Fig. 1 The parallel momentum flux of electrons for β=0.5% and 2% (economic Cyclone parameters, n=10).

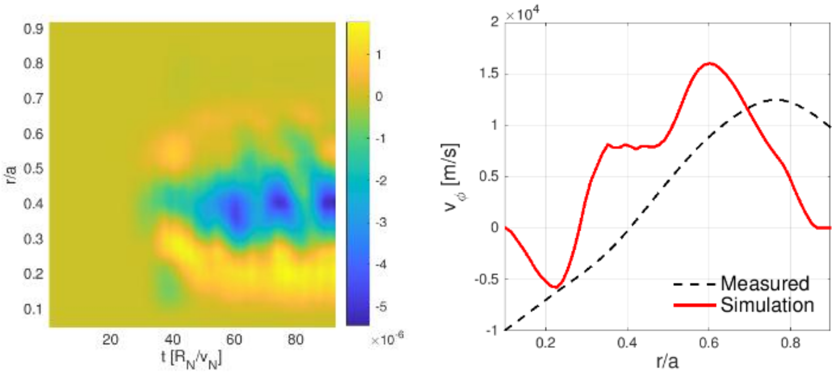

Fig. 2 The time evolution of the ion parallel momentum flux $\Pi_{\parallel,i}$ (left). The parallel velocity from multi-n simulation and from experiment measurement (right).

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