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A compact collisionless gyro-Landau-fluid multi-mode multi-scale turbulence transport modeling in tokamak plasmas

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ABSTRACT

- Orienting towards a whole-device integrated simulation, a compact collisionless Landau-fluid multi-mode multi-scale turbulence transport modeling is constructed based on GLF (for ITG mode) and Weiland (for TEM) models ;
- A initial value code—extended fluid code (ExFC), is developed to finalize the closure of the modeling through benchmarking with GK codes;
- Application: effects of 3D helical islands on ITG turbulent transport during the core ion heating are simulated;
- Results: flux-driven ITG turbulence can penetrate or spread into the magnetic islands which are static or propagate along the electron diamagnetic drift direction, leading to ion heat transport enhancement; The mechanism may result from the formation of an array of potential dipoles around the islands.

BACKGROUND

- Fusion plasma is a flux-driven, open system in dynamic quasi-steady state;
- Flux-driven turbulence is characterized by multi-mode multi-scale fluctuations which produce global transport;
- Integrated modelling simulation is utilized to study such transport properties under consistently considering dynamic coupling among the plasma equilibrium, stability, turbulence, source/sink and profiles;
- Advanced fluid modeling including critical kinetic effects may be a favorable alternative, besides GK simulations;
- Typical modeling: TGLF, Weiland model for trapping electron dynamics;
- Reduced fluid model of tokamak plasma turbulence and transport is worthwhile to be developed.

Compact collisionless fluid turbulence transport modeling

- The model is constructed combining GLF and Weiland model for TEM based on the adjustment of the ratio of specific heats for non-adiabatic species as well as their coefficients of the Landau damping;
- The compactness of the model is characterized by the lowest order moment equation system;
- Typically, a set of 5-field equations governing the electrostatic ITG-TEM turbulent transport are expressed as follows:

$$d_t n_e = -\omega_{dte}(n_0\phi - T_{e0}n_e - n_0 T_e) + D_n\nabla_\perp^2 n_e + S_{ne}$$

$$d_t T_e = -T_{e0}\omega_{dte}[(\Gamma_e - 1)(\phi - \tau_{en}\, n_e) - (2\Gamma_e - 1)T_e] - \Lambda_e\sqrt{8m_e\, T_{e0}/m_i\,\pi}\,|\nabla_\parallel|T_e + \tau_E^{ei}(T_i - T_e) + D_{Te}\nabla_\perp^2 T_e + S_{Te}$$

$$d_t\Omega = -T_{i0}a(\partial_r \ln n_0 + \partial_r \ln T_{i0})\partial_\theta\nabla_\perp^2\phi + f_c a\partial_r \ln n_0 \partial_\theta\phi - \nabla_\parallel v_\parallel + \omega_{di}[(1 + \tau_{in}f_c)\phi + T_i + \tau_{in}f_t n_e] + \Lambda_0 f_t\omega_{dte}(\phi - T_e - \tau_{en}n_e) + D_U\nabla_\perp^2\Omega$$

$$d_t v_\parallel = -(1 + \tau_{in}f_c)\nabla_\parallel\phi - \nabla_\parallel T_i - \tau_{in}f_t\,\nabla_\parallel n_e + D_v\nabla_\perp^2 v_\parallel$$

$$d_t T_i = -T_{i0}(\Gamma_i - 1)\nabla_\parallel v_\parallel + T_{i0}\omega_{di}[(\Gamma_i - 1)(\phi + \tau_{in}f_c\phi + \tau_{in}f_t n_e) + (2\Gamma_i - 1)T_i] - \Lambda_i\sqrt{8T_{i0}/\pi}\,|\nabla_\parallel|T_i + \tau_E^{ei}(T_e - T_i) + D_{Ti}\nabla_\perp^2 T_i + S_{Ti}$$

Here $\Omega = n_e/n_0 - \nabla_\perp^2\phi$, $n_e/n_0 = (1 - f_t)(\phi - \langle\phi\rangle)/T_{e0} + f_t\, n_{et}/n_0$, $f_t = (2/\pi)\sqrt{2r/R}$, $f_c = 1 - f_t$, $\omega_{di} = 2\varepsilon(\cos\theta\,\partial_\theta/r + \sin\theta\,\partial_r)$, $\omega_{dte} = 2\varepsilon(1/4 + 2\hat{s}/3)q\partial_\varphi/r$, $[f,g] = (\partial_r f\partial_\theta g - \partial_\theta f\partial_r g)/r$, $d_t = \partial_t + [\phi,\ \cdot\,]$, $\varepsilon = a/R$, $\tau_{en} = T_{e0}/n_0$, $\tau_{in} = T_{i0}/n_0$.

ExFC code and closure through benchmarking with GK codes

- ExFC: 3D FDM code to determine the adjustable closure coefficients;
- ExFC: versions from 3-field ITG with adiabatic electron (ITG-AE), 5-field ES ITG-TEM to 6-field EM ITG- TEM- KBM with MHD and more.
- It is benchmarked linearly versus GK simulations for the eigenvalues of ITG, TEM, KBM modes and the collisionless damping of the zonal flows while optimizing the closure coefficients.

Fig.1 Benchmarking of ITG-AE version of ExFC.$\Gamma_i = 4.75/3$, $\Lambda_i = 0.75$. The data for FULL and GT3D simulations are extracted directly from Ref. 12 for comparison of (left) eigenvalues of ITG mode; (right) Collisionless damping of the zonal flow compared with Rosenbluth-Hinton theory(dashed).

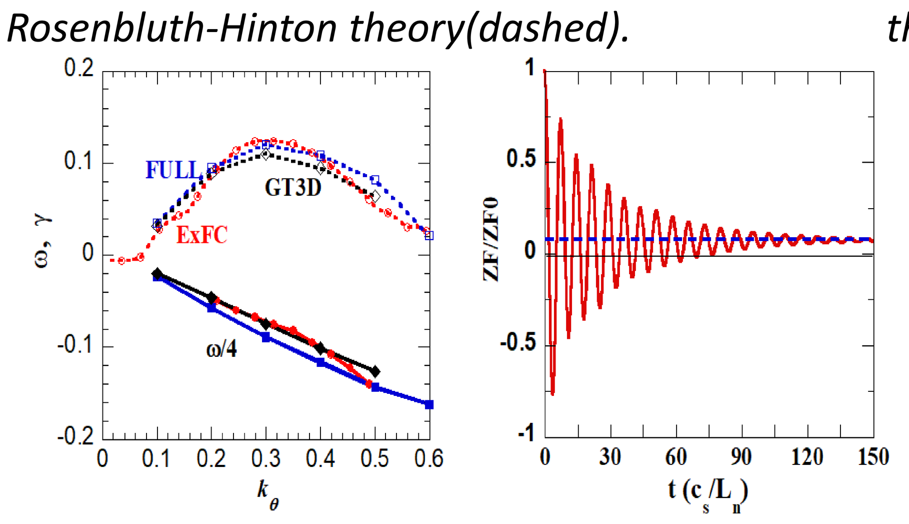
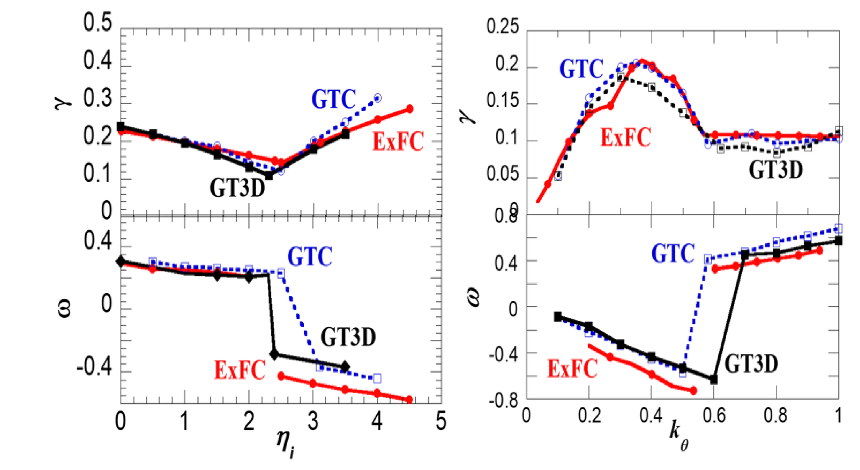


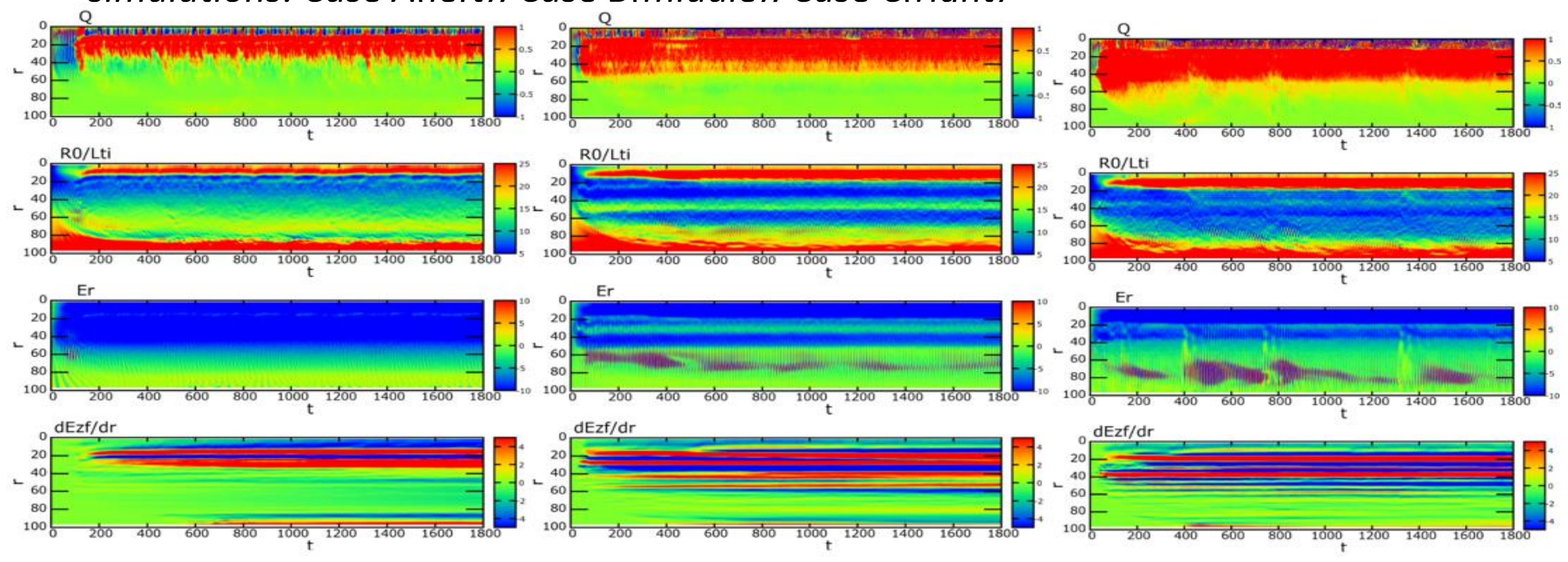
Fig.2 Benchmarking of ITG-TEM version. $\Gamma_0 = 2.5$, $\Gamma_i = 4.75/3$, $\Lambda_i = 0.5$. $\Gamma_e = 3.875/3$, $\Lambda_e = 0.125$. The data for GTC and GT3D simulations are extracted directly from Ref.12 for comparison of (left) eigenvalues of ITG and TEM modes vs η_i; (right) Spectral distribution of the linear eigenvalues of ITG and TEM modes.



Effects of 3D island on flux-driven ITG turbulence transport

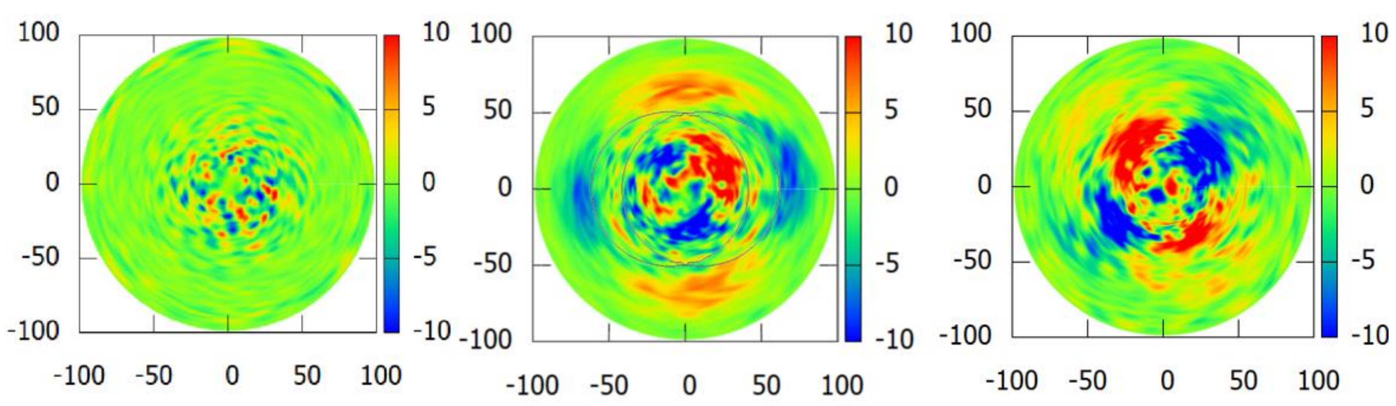
- For a rotating magnetic island, the perturbed flux is expressed as
$$\psi = \psi_0(r)\cos(m_I\theta - n_I\varphi - \omega_I t)$$
- Case A: reference without islands; Case B: static (2, 1) islands with width $w = 20\rho_i$ embedded in the plasma near $r = a/2$; In Cases C and D, the magnetic island propagates along the electron or ion diamagnetic drift directions with $\omega_I = 0.2\omega_*$.

Fig.4 Spatio-temporal evolution of the turbulent heat flux, ion temperature gradient scale length, radial electric field and the zonal flow levels for 3 simulations: Case A(left): Case B(middle): Case C(right)



- ✓ In a flux-driven turbulent plasma, the ITG turbulence could penetrate or spread into the magnetic island so that the larger magnetic island enhances the heat transport.

Fig.5 Contour plots of the potential in the quasi-steady state for 3 simulations: Case A(left); Case B(middle); Case C(right).



- ✓ Cases B and C evidently display an array of potential dipoles,
- ✓ The positive/negative potentials spread across the islands so that a stronger positive radial electric field appears in the island region.
- It is inferred that such potential dipoles may be responsible for the transport enhancement by the islands in Cases B and C through the dipole generated radial (or/and probably poloidal) electric field dynamics.