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Transport Model with Flow

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Introduction

Flow effect is crucial for improved confinement such as H-mode, ITB etc.

Conventional approach:

Turbulence suppression due to **E×B** shearing $\quad \square = \frac{\square_0}{1+\square_E^2}$

Hierarchical model

Direct interaction between transport and flow

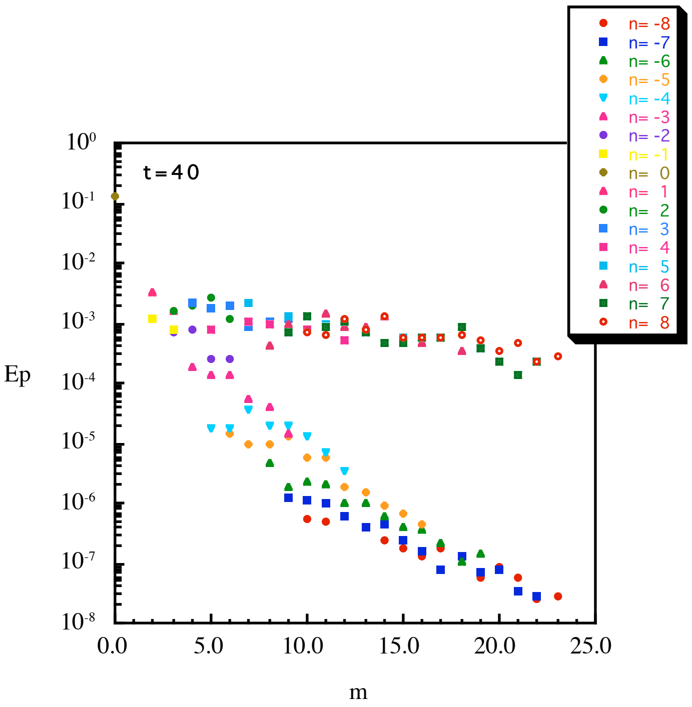
(Extended transport model)

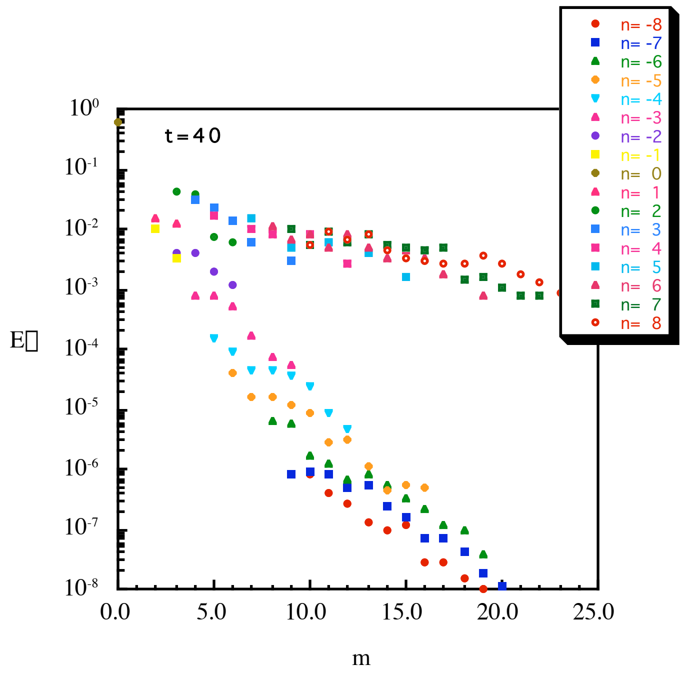
So far zonal flow is generated by micro-turbulence (ITG)

How much macro-scale (MHD) affect zonal flow generation?

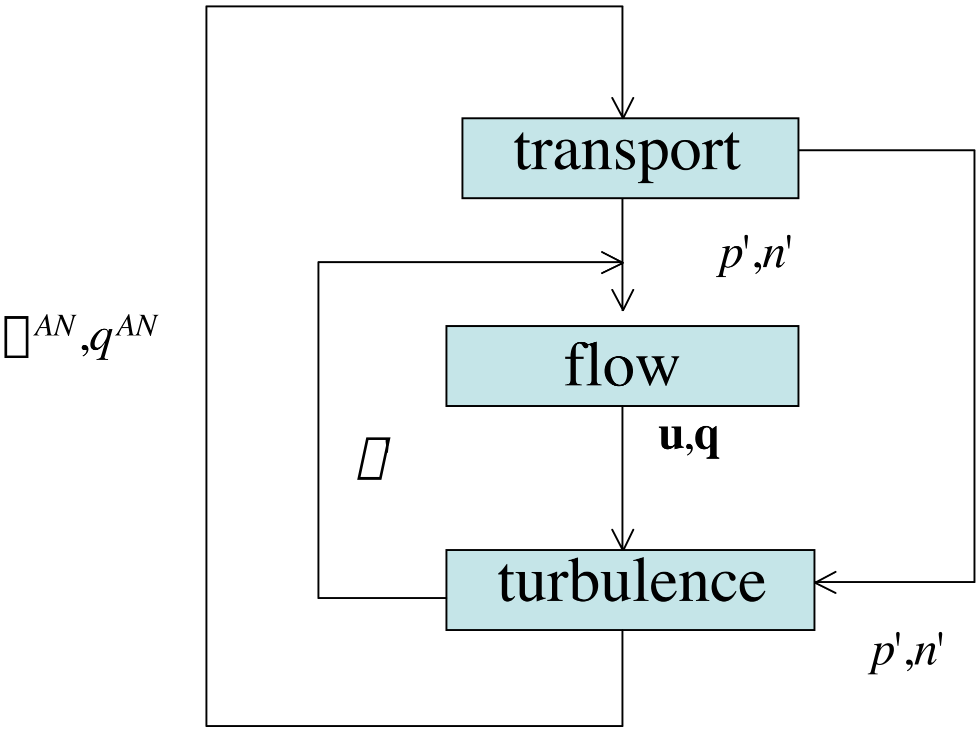
Energy Spectrum of MHD Turbulence

m/n=0/0 mode is generated.





Hierarchical transport model with flow



Check Experiment and Simulation: Φ'

Neoclassical flow

$$nV_T \simeq -\frac{c}{eB_p}(p' + en\Phi' + \alpha n T_i')$$

$$nV_p \simeq -\frac{c}{eB}\alpha n T_i'$$

Interaction with turbulence gives

$$\Phi' \to \tilde{\Phi}'_{0,0}$$

$$p' \to p' + \tilde{p}'_{0,0} \qquad n' \to n' + \tilde{n}'_{0,0}$$

$$T' \to T' + \tilde{T}'_{0,0} \qquad B' \to B' + \tilde{B}'_{0,0}$$

$$B_p' \to B_p' + \tilde{B}'_{p0,0}$$

Transport Model(Plasma Confinement, Hazeltine and Meiss)

$$\frac{\partial n}{\partial t}+\frac{1}{r}(r\Box)'=0 \qquad (1)$$

$$\frac{3}{2}\frac{\partial p_e}{\partial t}+\frac{1}{r}\left[r\left(q_e+\frac{5}{2}T_e\Box\right)\right]'=\Box 3\frac{m_e}{m_i}n\frac{T_i\Box T_e}{\Box_{ei}}+J_{//}\Box\Box\Box[T_i(\ln n)'\Box 0.17T_i'] \qquad (2)$$

$$\frac{3}{2}\frac{\partial p_i}{\partial t}+\frac{1}{r}(rq_i)'=3\frac{m_e}{m_i}n\frac{T_i\Box T_e}{\Box_{ei}}+\Box[T_i(\ln n)'\Box 0.17T_i'] \qquad (3)$$

$$\frac{\partial B_p}{\partial t}=c\Box' \qquad (4)$$

$$\Box=\Box\left(\frac{r}{R}\right)^{1/2}\frac{\Box_p^2}{\Box_e}n\left[1.12\left(1+\frac{T_i}{T_e}\right)(\ln n)'+0.43(\ln T_e)'+0.19(\ln T_i)'\right]\Box 2.44n\left(\frac{r}{R}\right)^{1/2}c\frac{\Box}{B_p}+\tilde{\Box}$$

$$q_e=\Box\left(\frac{r}{R}\right)^{1/2}\frac{\Box_p^2}{\Box_e}p_e\left[\Box 1.53\left(1+\frac{T_i}{T_e}\right)(\ln n)'+1.81(\ln T_e)'+0.27\frac{T_i}{T_e}(\ln T_i)'\right]\Box 1.75n\left(\frac{r}{R}\right)^{1/2}c\frac{\Box}{B_p}+\tilde{q}_e$$

$$q_i=\Box 0.48\left(\frac{r}{R}\right)^{1/2}\frac{\Box_p^2}{\Box_e}\left(\frac{m_iT_e}{m_eT_i}\right)^{1/2}nT_i'+\tilde{q}_i$$

$$J_{//}=\frac{p_e}{B_p}\left(\frac{r}{R}\right)^{1/2}\left[-2.44\left(1+\frac{T_i}{T_e}\right)(\ln n)'-0.69(\ln T_e)'+\frac{T_i}{T_e}(\ln T_i)'\right]+\left[1-1.95\left(\frac{r}{R}\right)^{1/2}\right]\sigma_{//}E+\tilde{J}_{//}$$

$$E=\left[1-1.95\left(\frac{r}{R}\right)^{1/2}\right]^{-1}\sigma_{//}^{-1}\left\{\frac{c}{4\pi}\frac{1}{r}\frac{\partial}{\partial r}rB_p-\frac{p_e}{B_p}\left(\frac{r}{R}\right)^{1/2}\right.$$

$$\left.\times\left[-2.44\left(1+\frac{T_i}{T_e}\right)(\ln n)'-0.69(\ln T_e)'+\frac{T_i}{T_e}(\ln T_i)'\right]\right\}+\tilde{E}$$

$$\Gamma=\left\langle \tilde{n}\frac{c\mathbf{B}\times\nabla\tilde{\phi}}{B^2}\cdot\nabla r\right\rangle$$

$$q_a=\frac{5}{2}\left\langle \tilde{n}\frac{\tilde{p}_a}{m_a\Omega_a B}\mathbf{B}\times\nabla\tilde{T}_a\cdot\nabla r\right\rangle$$

Parallel momentum balance and heat flow equation

Ohm's law(4) and parallel ion flows are generally described by

$$\langle \mathbf{B}\cdot\mathbf{F}_{a1}\rangle + \langle n_a e_a \mathbf{B}\cdot\mathbf{E}^{(A)}\rangle = \langle \mathbf{B}\cdot\square\cdot\square_a\rangle + \langle \tilde{n}_a e_a \mathbf{B}\cdot\square\tilde{\square}\rangle + \left\langle m_a n_a \mathbf{B}\cdot\frac{d\mathbf{u}_a}{dt}\right\rangle$$

$$\langle \mathbf{B}\cdot\mathbf{F}_{a2}\rangle = \langle \mathbf{B}\cdot\square\cdot\square_a\rangle + \frac{5}{2}\langle \tilde{n}_a \mathbf{B}\cdot\square\tilde{T}_a\rangle + \left\langle \frac{m_a}{T_a}\mathbf{B}\cdot\frac{\partial Q_a}{\partial t}\right\rangle$$

$$\mathbf{Q}_a = \mathbf{q}_a + \frac{5}{2}p_a\mathbf{u}_a$$

Reduced model: eq.(4) and

$$nV_T \square\square \frac{c}{eB_p}(p' + en\square' + \square nT_i')$$

$$nV_p \square\square \frac{c}{eB}\square nT_i'$$

Ion flow does not appear in transport model in explicit form!

Nonambipolar, nonaxisymmetric Flux

Based on generated turbulence field, we might construct transport model for nonaxisymmetric system.

$\langle u_{//}B \rangle, \square$ can be determined by

steady-state momentum balance equation

$$\square_a \left\{ \langle \mathbf{B} \cdot \square \cdot \overleftrightarrow{\square}_a^{NC} \rangle + \langle \mathbf{B} \cdot \square \cdot \overleftrightarrow{\square}_a^{turb \,\square\, NC} \rangle \right\} = 0$$

ambipolar condition

$$\square_a \square_a^{turb \,\square\, NC} = 0$$

where

$$\square_{na}^{i} = \frac{1}{e_i \square} \langle \square V \square \square \square' \cdot \square \cdot \overleftrightarrow{\square}_i \rangle$$

$$\langle \mathbf{u}_{i1} \cdot (\mathbf{F}_{i1} + n_i e_i \mathbf{E}) \rangle = \square \langle u_{//i} B \rangle \frac{e_i \square'}{\langle I \rangle} \square_{bp}^{i} + \frac{1}{n_i} (\square_{ps}^{i} + \square_{cl}^{i}) \frac{\partial P_i}{\partial V} \square e_i (\square_{na}^{i} + \square_{bp}^{i}) \frac{\partial \square}{\partial V}$$

Hierarchical Transport Model

- Step I : linear stability of resistive ballooning mode with flow(matrix method)
- Step II: flow generation due to resistive ballooning mode turbulence
- Step III: resistive ballooning turbulence with transport and flow (self-consistent treatment