Inter-Species Collisionless Energy transfer by drift wave-zonal flow Turbulence

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Outline

- *We reconsider the classic problem of " turbulent heating" and the inter-species transfer of energy in drift wave turbulence*

- Motivation: Transfer vs Transport ⟶ Roles in energy budget
  - Consider

    Net volumetric heating ⟶ Does turbulence heat a given volume of plasma?

    Electron ⟶ ion collisonless energy transfer channels

- Calculate and Estimate Energy Transfer Channels

  Electron cooling : quasilinear

  Ion heating : quasilinear, nonlinear, Ion Pol & Dia

- Implication for ITER/Result and discussion

  Turbulent vs collisonal transfer

  Turbulent transport vs Turbulent transfer

- Special Topics ongoing:

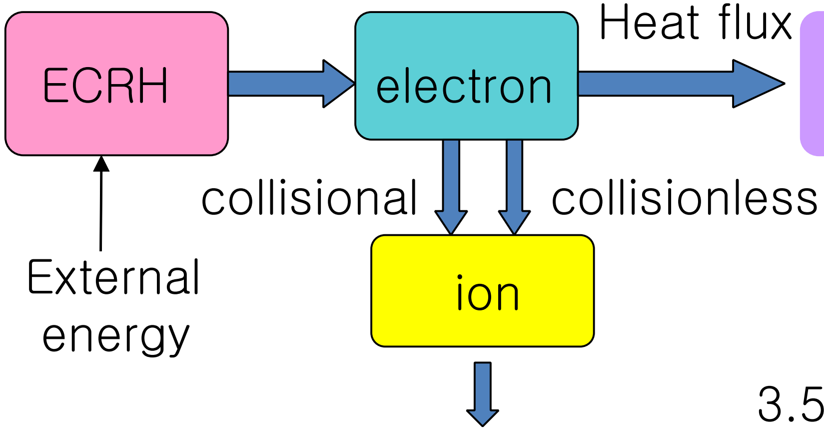
  Nonlinear electron cooling in CTEM

  Origin of temperature profile "stiffness"

- Conclusion

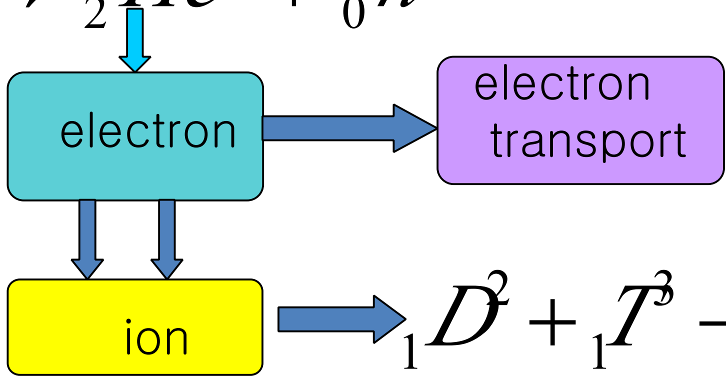
Background

- ITER: collisionless, electron heated plasma
- Two stages in energy flow $\frac{3}{2}n\frac{\partial T_e}{\partial t} + \nabla\cdot Q_e = \left\langle \tilde{E}\cdot\tilde{J}_e \right\rangle - n\nu_{e,i}\frac{m_e}{m_i}\left(T_e - T_i\right) + \dots$



3.5 Mev 14.1 Mev

$${}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1$$



$${}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1$$

- What is ultimate fate of the energy? ➡ Collisionless energy transfer mechanisms?

Motivation

- Transfer vs Transport

$$\frac{3}{2}n\frac{\partial T_\alpha}{\partial t}+\underbrace{\nabla\cdot Q_\alpha}_{\text{Transport}}=\underbrace{\left\langle \tilde{E}\cdot\tilde{J}_\alpha\right\rangle}_{\text{collsionless transfer}}\underbrace{\mp n\nu\frac{m_e}{m_i}\left(T_e-T_i\right)}_{\text{Collisional transfer}}+\ldots \text{heat balance;}\quad \alpha=e,i$$

$\rightarrow Q$ heat flux, energy loss by turbulent transport

$$\rightarrow\left\langle \tilde{E}\cdot\tilde{J}_\alpha\right\rangle\begin{cases}\text{turbulent heating for single species: electron cooling, ion heating}\\ \text{electron and ion collisionless energy transfer, local energy "soure" or " sink"}\end{cases}$$

$\rightarrow \mp n\nu\frac{m_e}{m_i}\left(T_e-T_i\right)$: electron and ion heat transfer by collisions

★ ITER: *low collisionality, electron heated plasma*

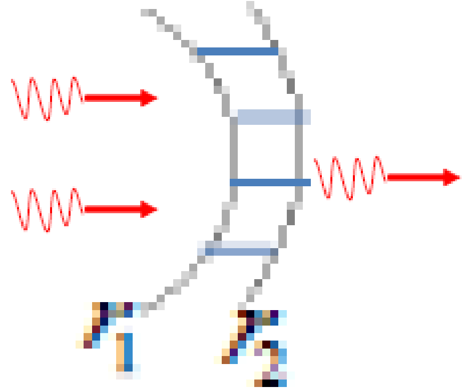
- Collisionless energy transfer likely dominant!!

- Issues with turbulent heating: $\langle \tilde{E}\cdot\tilde{J}\rangle = \sum_{\alpha=e,i}\langle \tilde{E}\cdot\tilde{J}_{\alpha}\rangle$

★ Classic Question:

- Is the *net heating* zero?(Manheimer 77)

- If periodic boundary condition , no boundary contributions to $\langle \tilde{E}\cdot\tilde{J}\rangle$, so $\langle \tilde{E}\cdot\tilde{J}\rangle = 0$



But

$$\int dr\langle \tilde{E}\cdot\tilde{J}\rangle = -\tilde{\varphi}\tilde{J}_r\Big]_{r_1}^{r_2} + \cancel{\int dr(\nabla\cdot\tilde{J}\tilde{\varphi})} \neq 0$$

→ Boundary effect in a finite annular region

Surface term survives! → Net heating

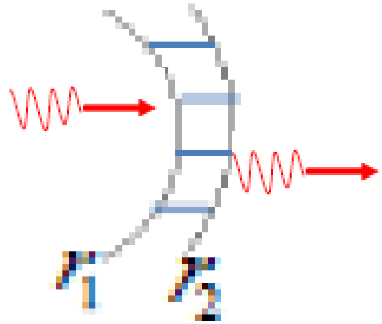
★ Point : $\left\langle \tilde{E}\cdot\tilde{J}\right\rangle \neq 0$

- *Another perspective*: wave energy theorem

$$\frac{\partial W}{\partial t}+\vec{\nabla}\cdot\vec{S}+\left\langle \vec{E}\cdot\vec{J}\right\rangle = 0$$

$W \equiv$ Wave energy density

$S \equiv$ wave energy density flux



- At steady state

$$\int_{r_1}^{r_2} dr\left\langle \tilde{E}\cdot\tilde{J}\right\rangle = -S_r \Big]_{r_1}^{r_2}$$

$$S_r = V_{gr,r}\varepsilon_\omega = -2\frac{\rho_s^2 k_r k_\theta \varepsilon_\omega V_* \varepsilon_\omega}{\left(1+k_\perp^2\rho_s^2\right)^2}$$

➡ wave energy flux differential ➡ *net heating* $\left\langle \tilde{V}_r\tilde{V}_\theta\right\rangle = \sum -k_r k_\theta \left|\tilde{\varphi}\right|^2$

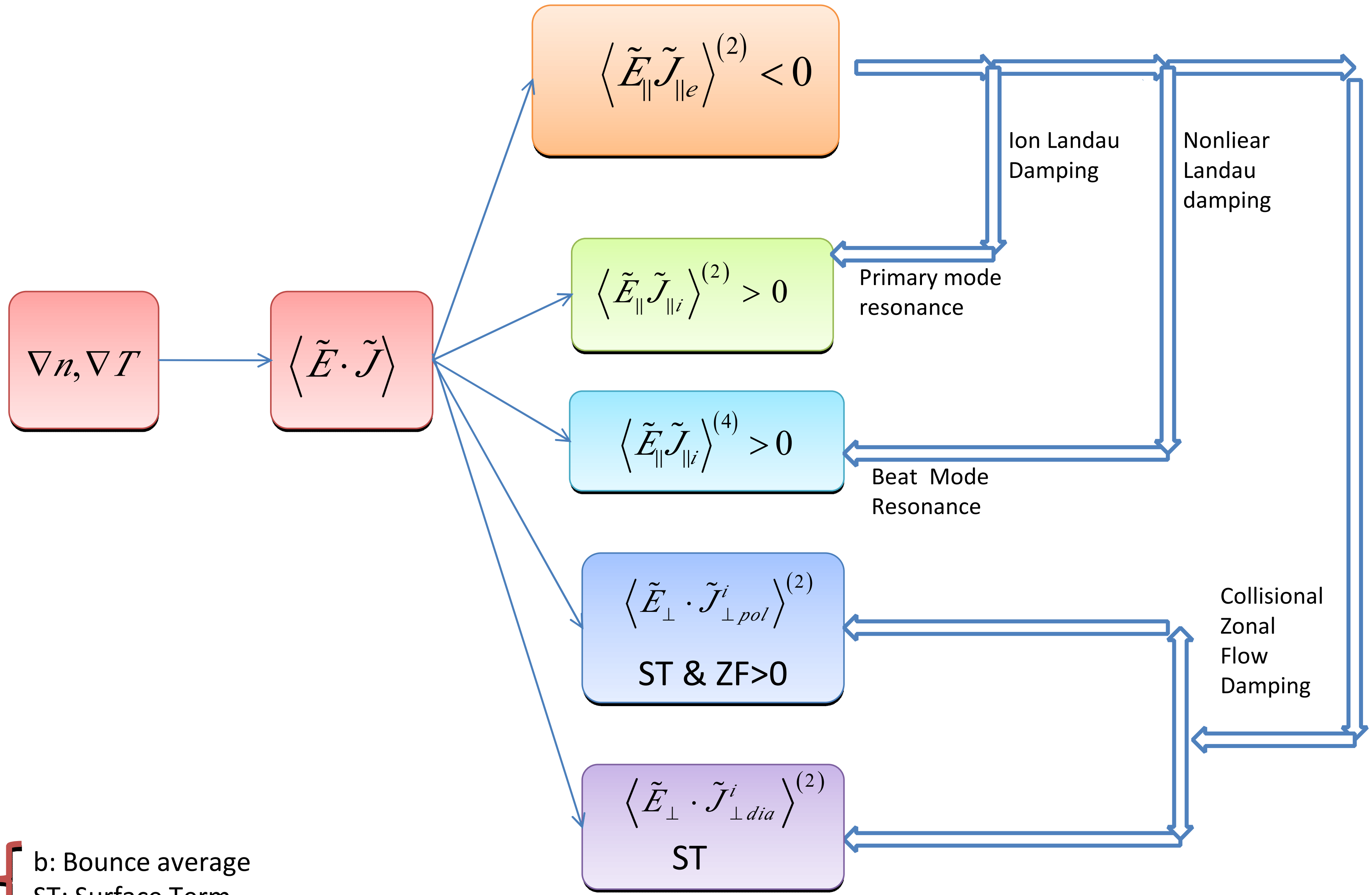
— Related to Reynolds work

★ *We need reconsider both the total turbulent heating and energy transfer chanels in an annular region!*

- Collisionless, inter-species energy transfer
  - Where does the net energy transfer go?
  - How is energy transferred from electrons to ions (**turbulent transfer channels**)?
  - How relate to saturation mechanisms?
  - Role of ZF in heating?

  - **ZF is important to saturation, so must enter energy transfer as well!?**
    - **Zonal flow damping by friction is an energy sink**
    - **Nonlinear wave-particle interaction (considered in future) is another possibility**

Turbulent Energy flow Channels



b: Bounce average
ST: Surface Term

- **Necessary Correspondence:** Nonlinear Saturation and Energy Transfer
  - Nonlinear saturation in turbulent state implies energy transfer from source $(\nabla T_e, \nabla n)$ to sink
  - Schematically, saturation implies some balance condition must be satisfied

i.e. $$0 = \gamma = \underset{>0}{\gamma_{\substack{Linear\\electron}}} + \underset{<0}{\gamma_{\substack{Linear\\ion}}} + \underset{<0}{\gamma_{\substack{Zonal\\Flow}}} + \underset{<0}{\gamma_{NLLD}} + \ldots$$

  - Channels for electron → ion energy transfer **must** be consistent with saturation balance

In particular:

- If zonal flows control saturation, they **must** contribute to energy transfer and dissipation.
- As zonal flows are nonlinearly generated (Reynolds stress), we should consider other nonlinear heating channels.

Quasilinear Turbulent Heating in Electron Drift Wave

(Prototype; CTEM- specific later)

- Calculate $\left\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel e}\right\rangle^{(2)}$ in quasilinear theory
  - ➢ DKE for electron
  - ➢ Take non-adiabatic electron distribution function

$$\tilde{g}_k = \frac{(\omega_* - \omega)}{\omega - k_z v_z}\frac{e\tilde{\varphi}_k}{T_e}\langle f_e\rangle, \quad \omega_{*e} = \frac{k_y\rho_s c_s}{L_n}, \quad \langle f_e\rangle \quad \text{is Maxwellian}$$

- $$\left\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel e}\right\rangle^{(2)} = e\int dv v_z \tilde{E}_z \tilde{g}_k = \sum_k \pi n T_e \left|\frac{e\tilde{\varphi}_k}{T_e}\right|^2 \frac{\omega}{|k_z| V_{the}}(\omega - \omega_{*e})\langle f_e\rangle_{\frac{\omega}{k_z}}$$

  - ➢ $\omega = \dfrac{\omega_{*e}}{1+k_\perp^2\rho_s^2}, \quad \left\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel e}\right\rangle^{(2)} < 0$ **the electrons cool via inverse electron Landau damping**

- Similarly, calculate $\left\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel i}\right\rangle^{(2)}$ for ion

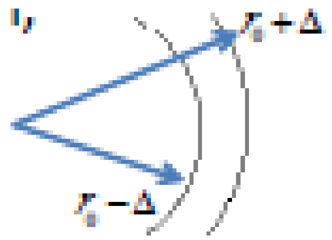
- $$\left\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel i}\right\rangle^{(2)} = \sum_k \pi n T_i \left|\frac{e\tilde{\varphi}_k}{T_i}\right|^2 \frac{\omega}{|k_z| V_{the}}\left(\omega + \frac{T_i}{T_e}\omega_{*e}\right)\langle f_i\rangle_{\frac{\omega}{k_z}}$$

  - ➢ $\left\langle \tilde{E}_{\parallel}\tilde{J}_{\parallel i}\right\rangle^{(2)} > 0$, **the ions gain energy via ion Landau damping**

Perpendicular Current Induced Turbulent Heating

- The turbulent heating induced by ion polarization current

— $\left\langle \tilde{E}_\perp \cdot \tilde{J}^{pol}_{\perp i} \right\rangle = -\left\langle \vec{\nabla}_\perp \cdot \left(\tilde{\varphi} \tilde{J}^{pol}_{\perp i} \right) \right\rangle + \left\langle \tilde{\varphi} \vec{\nabla}_\perp \cdot \tilde{J}^{pol}_{\perp i} \right\rangle$



—Defining a annular region $\langle \ldots \rangle = \int_0^{2\pi R} dz \int_0^{2\pi} r d\theta \int_{r_0-\Delta}^{r_0+\Delta} (\ldots) dr$

- Perpendicular heating ⟷ Reynolds work on zonal flow

$$\left\langle \tilde{E}_\perp \cdot \tilde{J}^{pol}_{\perp i} \right\rangle = nm_i A \left(\underbrace{\left\langle V_\theta \right\rangle \left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle \Big]_{r-\Delta}^{r+\Delta}}_{\bullet\ \text{wave energy flux}} - \underbrace{\int_{r-\Delta}^{r+\Delta} dr \left\langle V_\theta \right\rangle \frac{\partial}{\partial r} \left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle}_{\bullet\ \text{Directly linked to zonal flow drive}} \right)$$

- At steady state

$$\left\langle \tilde{E}_\perp \cdot \tilde{J}^{pol}_{\perp i} \right\rangle = \int_{r-\Delta}^{r+\Delta} dr \upsilon_{col} \left\langle V_\theta \right\rangle^2 > 0,$$

⟹ Zonal flow frictional damping is the final fate of net electron-ion energy transfer

- other damping possible

- Diamagnetic current induced turbulent heating

$$\left\langle \tilde{E}_\perp \cdot \tilde{J}^{Dia}_{\perp i} \right\rangle = -nc\tilde{\varphi} \frac{B \times \nabla \tilde{p}}{B^2} \Big]_{r-\Delta}^{r+\Delta}$$

⟹ Heat flux differential

Overview of Results

☆ Estimation of the turbulent heating contributions:

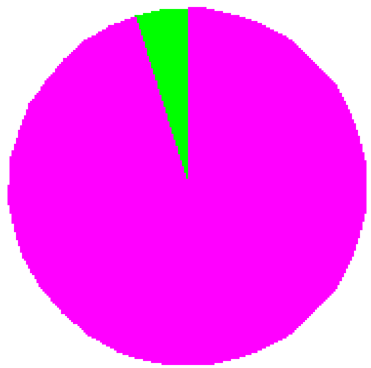
Turbulent heating	**analytical**	**Using mixing length approximation** $\frac{e\tilde{\varphi}}{T_e} \sim \rho_*$ **for fluctuation levels**
$\left\lvert \left\langle \tilde{E}\cdot\tilde{J} \right\rangle_e^{(2)} \right\rvert$	$\sum \pi n T_e \left\lvert \frac{e\tilde{\varphi}}{T_e} \right\rvert^2 \frac{(\omega - \omega_{*e})\omega}{\lvert k_z \rvert V_{the}}$	$\rho_*^2 \frac{Rq\omega_*^2}{V_{the}} F_1(k_\perp \rho_s)$
$\left\langle \tilde{E}\cdot\tilde{J} \right\rangle_i^{(2)}$	$\sum \pi n T_i \left\lvert \frac{e\tilde{\varphi}}{T_i} \right\rvert^2 \frac{(\omega - \omega_{*i})\omega}{\lvert k_z \rvert V_{thi}} \exp - \left(\frac{\omega}{k_z V_{thi}} \right)^2$	$\rho_*^2 \frac{Rq\omega_*^2}{V_{thi}} F_2(k_\perp \rho_s)$
$\left\langle \tilde{E}\cdot\tilde{J} \right\rangle_{pol}^{(2)}$	$n m_i \nu_{col} \left\langle V_\theta \right\rangle^2$	$\rho_*^2 \nu_* \varepsilon^{3/2} m_i C_s^2 \frac{V_{thi}}{Rq}$

Basic comparision of channels

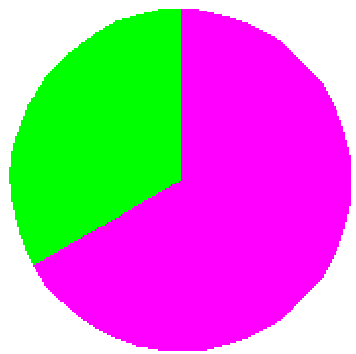
ITER Parameters R=6.2m, a=2m,q=2	
$Ratio = \frac{\left\langle \tilde{E}\cdot\tilde{J}_i \right\rangle}{\left\langle \tilde{E}\cdot\tilde{J}_e \right\rangle}$	Short wavelength $k_\perp \rho_s \sim 1$
$\left\langle \tilde{E}\cdot\tilde{J} \right\rangle_i^{(2)}$	1.56×10^{-2}
$\left\langle \tilde{E}\cdot\tilde{J} \right\rangle_{pol}^{(2)}$	$0.8\nu_*$

★ *Ratios of energy dissipation channels at differernt collisionality*

Ion Landau Damping
Zonal flow friction



$\nu_* = 10^{-3}, \rho^* = 10^{-3}$



$\nu_* = 10^{-2}, \rho^* = 10^{-3}$

☆ Zonal flow frictional damping can be a significant dissipation channel

☆ "Collisionless drift wave" $\omega \gg \nu_* > 0$

Turbulent Heating ➡ NL wave-particle Interaction

- ZF coupling to $o\left(\left|\frac{e\tilde{\varphi}}{T}\right|^4\right)$, so need calculate parallel heating to $o\left(\left|\frac{e\tilde{\varphi}}{T}\right|^4\right)$
- The ion diffusion equation in electron drift wave turbulence:

$$\frac{\partial\langle f_i\rangle}{\partial t}=\frac{\partial}{\partial v}D_{vv}\frac{\partial}{\partial v}\langle f_i\rangle+\frac{\partial}{\partial v}D_{vx}\frac{\partial}{\partial x}\langle f_i\rangle+\frac{\partial}{\partial x}D_{xv}\frac{\partial}{\partial v}\langle f_i\rangle+\frac{\partial}{\partial x}D_{xx}\frac{\partial}{\partial x}\langle f_i\rangle$$

Diffusion coefficient in quasilinear and nonlinear order

$$D_{vv}=D_{vv}^{(2)}+D_{vv}^{(4)}+\ldots \qquad D_{vx}=D_{xv}=D_{vx}^{(2)}+D_{vx}^{(4)}+\ldots \qquad D_{xx}=D_{xx}^{(2)}+D_{xx}^{(4)}+\ldots$$

The resonant ion kinetic energy evolution :

$$\frac{\partial E_{res}}{\partial t}=\int dv\frac{1}{2}mv^2\frac{\partial}{\partial t}\langle f_i\rangle$$

$$=-\int dvmvD_{vv}\frac{\partial}{\partial v}\langle f_i\rangle-\int dvmvD_{vx}\frac{\partial}{\partial x}\langle f_i\rangle+\frac{\partial}{\partial x}\int dv\frac{1}{2}mv^2(D_{xv}\frac{\partial}{\partial v}\langle f_i\rangle+D_{xx}\frac{\partial}{\partial x}\langle f_i\rangle)$$

$$=(\langle\tilde{E}\cdot\tilde{J}\rangle_{vv}^{(2)}+\langle\tilde{E}\cdot\tilde{J}\rangle_{vv}^{(4)}+\ldots)+(\langle\tilde{E}\cdot\tilde{J}\rangle_{vx}^{(2)}+\langle\tilde{E}\cdot\tilde{J}\rangle_{vx}^{(4)}+\ldots)+(\nabla\cdot q^{(2)}+\nabla\cdot q^{(4)}+\ldots)$$

- The nonlinear ion turbulent heating up to $o\left(\left|\frac{e\tilde{\varphi}}{T}\right|^4\right)$ → q is $o\left(\left|\frac{e\tilde{\varphi}}{T}\right|\right)^4$ energy flux

➡ $$\langle\tilde{E}\cdot\tilde{J}\rangle_i^{(4)}=\langle\tilde{E}\cdot\tilde{J}\rangle_{vv}^{(4)}+\langle\tilde{E}\cdot\tilde{J}\rangle_{vx}^{(4)}$$

- The forth order nonlinear diffusion coefficient

$$D_{vv}^{(4)} = \int_{-\infty}^{\infty} \frac{\left\langle \tilde{F}_2(t)\tilde{F}_2(t+\tau)\right\rangle}{2} d\tau \longrightarrow$$ perturbation theory (Dupree 68)

- The particle orbit is expanded as : $x(t) = x_0 + v_0 t + \varepsilon x_1(t) + \varepsilon^2 x_2(t) + \ldots,$

- The force in perturbative electric field

$$D_{vv}^{(4)} = D_{v_{zx}v_{zx}}^{(4)} + D_{v_{zy}v_{zy}}^{(4)} + D_{v_{zz}v_{zz}}^{(4)}$$

$$= \sum_{k,k',-k,-k'} \left(\frac{ec}{mB}\right)^2 \left|\tilde{\varphi}_k\right|^2 \left|\tilde{\varphi}_{k'}\right|^2 \left(\frac{k_\theta k_x' k_z'}{\omega - k_z v_z} \overset{v}{+} \frac{k_x k_\theta' k_z'}{\omega' - k_z' v_z}\right)^2 \mathrm{Re}\frac{i}{\omega'' - k_z'' v}$$

$$+ \sum_{k,k',-k,-k'} \left(\frac{ec}{mB}\right)^2 \left|\tilde{\varphi}_k\right|^2 \left|\tilde{\varphi}_{k'}\right|^2 \left(\frac{k_x k_\theta' k_z'}{\omega - k_z v_z} + \frac{k_\theta k_x' k_z'}{\omega' - k_z' v_z}\right)^2 \mathrm{Re}\frac{i}{\omega'' - k_z'' v}$$

Nonlinear diffuion in velocity space corrected by E×B drift motion

$$+ \sum_{k,k',-k,-k'} \left(\frac{e}{m}\right)^4 \left|\tilde{E}_z\right|^2 \left|\tilde{E}_{z'}\right|^2 \left(\frac{k_z - k_z'}{(\omega - k_z v_z)(\omega' - k_z' v_z)}\right)^2 \mathrm{Re}\frac{i}{\omega'' - k_z'' v} \longrightarrow$$

Nonlinear diffuion in Vlasov plasma, corrected by $v_{||}$ scattering (Dupree 68)

$$\Rightarrow D_{v_{zx}v_{zx}}^{(4)} \approx D_{v_{zy}v_{zy}}^{(4)} \gg D_{v_{zz}v_{zz}}^{(4)} \approx 1/\rho_*^2$$

Nonlinear diffusion correction by E×B scattering is bigger than the one by parallel acceration

- Similarly, the cross term of nonlinear diffusion coefficient

$$D_{vx}^{(4)} = \int_{-\infty}^{\infty} \frac{\left\langle \tilde{F}_2(t)\tilde{V}_2(t+\tau)\right\rangle}{2} d\tau \quad \text{and} \quad D_{v_{zz}x_{xx}}^{(4)} \approx D_{v_{zz}x_{xy}}^{(4)} \gg D_{v_{zz}x_{xz}}^{(4)} \approx 1/\rho_*^2$$

- The nonlinear turbulent heating for ions $\rightarrow$ due to Ion Compton Scattering

$$\left\langle \tilde{E}\cdot\tilde{J}\right\rangle_i^{(4)} = \left\langle \tilde{E}\cdot\tilde{J}\right\rangle_{vv}^{(4)} + \left\langle \tilde{E}\cdot\tilde{J}\right\rangle_{vx}^{(4)}$$

$$\approx \sum_{k,-k,k',-k'} \pi n T_i \frac{V_{thi}^3}{\omega_{ci}^2} \left|\frac{e\tilde{\varphi}_k}{T_i}\right|^2 \left|\frac{e\tilde{\varphi}_{k'}}{T_i}\right|^2 \frac{\omega'' k_z}{k_z''\left|k_z''\right|} \left(\frac{k_\theta k_x'}{\omega - k_z v_z} + \frac{k_x k_\theta'}{\omega' - k_z' v_z}\right)^2 \left(\frac{\omega''}{k_z''} k_z + \frac{T_i}{T_e}\omega_{*e}\right) \langle f_i \rangle \rrbracket_{\frac{\omega''}{k''}} > 0$$

Beat mode resonance : $\omega'' = \omega \pm \omega', k'' = k \pm k'$

Turbulent energy transfer : Electron $\rightarrow$ wave $\xrightarrow{\text{NLLD}}$ Ion

- Estimate $\left\langle \tilde{E}\cdot\tilde{J}\right\rangle_i^{(4)}$ using the mixing length approximation

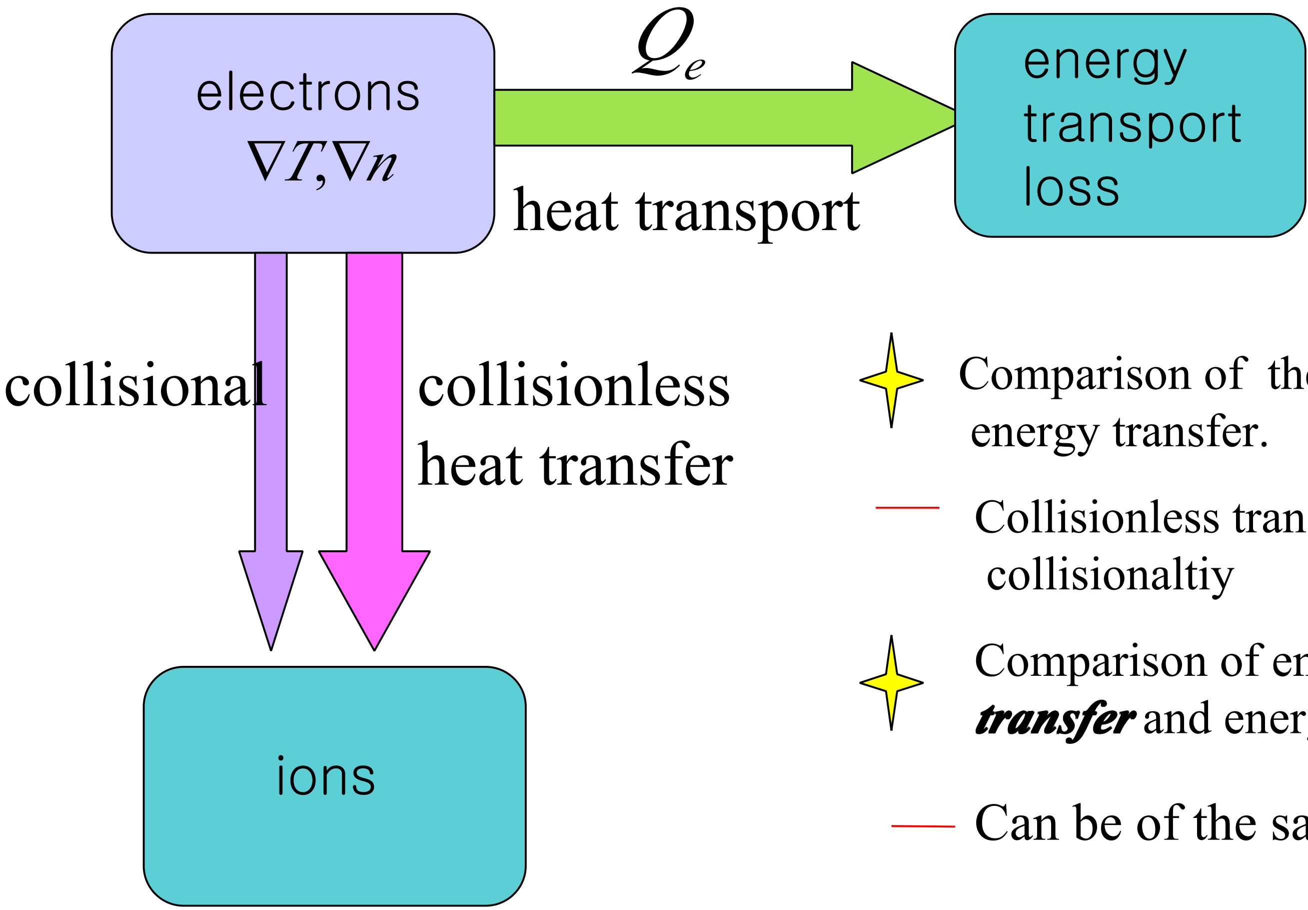
$\Rightarrow$ $\left\langle \tilde{E}\cdot\tilde{J}\right\rangle_i^{(4)} > \left\langle \tilde{E}\cdot\tilde{J}\right\rangle_i^{(2)}$ Mixing length approximation ***overestimates*** the turbulence intensity in the weak turbulence theory. (T.S. Hahm, 1991)

$\Rightarrow$ $\gamma_L N + \gamma_{NL} N^2 + \gamma_{ZF} N = 0$ N has to be ***self-consistent*** (Diamond, 2005)

Implication ➡ Bottom Line

- Electon turbulent energy transport

$$\frac{3}{2} n \frac{\partial T_e}{\partial t} + \nabla \cdot Q_e = \left\langle \tilde{E} \cdot \tilde{J}_e \right\rangle - n\nu \frac{m_e}{m_i}\left(T_e - T_i\right) \longrightarrow \text{Electron heat balance}$$



✦ Comparison of the collisonal and collisionless energy transfer.

— Collisionless transfer can dominate at low collisionaltiy

✦ Comparison of energy transfer in collisonless ***transfer*** and energy ***transport*** by heat flux Q

— Can be of the same order!

Collisionality

- Collisonality ν_* in ITER
  - dimensionless $$\nu_* = \frac{\varepsilon^{-3/2} R q \nu_e}{V_{the}} \Rightarrow \boxed{\nu_* \sim 10^{-3}}$$
- Collisionality at crossover of collisional and collisionless coupling
  - Energy transfer in collision : $Q_i \approx \dfrac{n m_e \nu_e}{m_i} T_e$
  - Quasilinear trapped electron cooling in CTEM
$$\left\langle \tilde{\bar{E}} \cdot \tilde{\bar{J}}_e \right\rangle_b^{(2)} \simeq 4\pi^{1/2} \varepsilon^{1/2} n T_e \left(\frac{R}{2a} \right)^{3/2} \rho_*^2 \left(\omega - \omega_* \right) \langle f_e \rangle]]_{E=\frac{\omega}{k_\theta} \frac{R T_e}{\rho_s C_s}}$$
  - **At crossover** : $Q_i \approx \left\langle \tilde{\bar{E}} \cdot \tilde{\bar{J}} \right\rangle_b^{(2)} \Rightarrow \boxed{\nu_* \sim 10^{-2}}$

☆ The collisonless turbulent energy transfer then beats collisional inter-species coupling process!

☆ <u>Collisionless</u> process will control electron-ion transfer in ITER

Transfer vs Transport

- The transfer and transport energy loss in CTEM
  - Compare the volume integral of the electron cooling to the surface integrated of the electron heat flux

$$A\tilde{Q}_e\rrbracket_{boundary} = \int d^3r\left\langle \tilde{E}\cdot\tilde{J}\right\rangle$$

  - The heat flux for electrons : $\tilde{Q}_e = \left\langle \tilde{v}_r \tilde{P}_e \right\rangle = -\frac{c}{B}\sum_k k_\theta \operatorname{Im}\tilde{P}_e^{(1)}\tilde{\varphi}$
  - The pressure fluctuation $\tilde{p}_e^{(1)} = \int d^3v \frac{1}{2} m v^2 \bar{\bar{g}}_b$

$$\tilde{Q}_e = \sum 4\pi^{\frac{1}{2}}\varepsilon^{\frac{1}{2}}\left(\frac{R}{L_n}\right)^{\frac{5}{2}}\left|\frac{e\bar{\tilde{\varphi}}}{T_e}\right|^2 \frac{V_{the}^2 k_\theta n T_e}{\Omega_e}\left(\omega-\omega_{*n}\right)\left\langle f_e\right\rangle\rrbracket_{E=\frac{\bar{\omega}_{de}RT_e}{\omega_* L_n}}$$

☆ The ratio

$$\frac{\Delta r\left\langle \tilde{E}\cdot\tilde{J}\right\rangle}{\tilde{Q}_e\rrbracket_{boundary}} \approx 2\frac{a}{R} \sim o(1)$$

The rate of electron energy lost by collisonless energy transfer is comparable to turbulent transport by CTEM !

Result and Discussion

- Net heating
  - Quasilinear turbulent energy transfer in drift wave
  - Nonlinear ion heating by beat wave resonance
  - Energy flux differential gives rise to the net heating ➡ Zonal flow
- Energy transfer channels
  - Identify important energy transfer channels
  - Zonal flow frictional damping can be comparable to LD
- For low collisionality ITER plasma, collisionless energy transfer is a critical element of transport model.
  - it is same order as transport

☆ In the future, an important task for ITER transport modelling

- Develope a tractable representation of the *turbulent heating* and *collisionless energy transfer*

Some details for CTEM

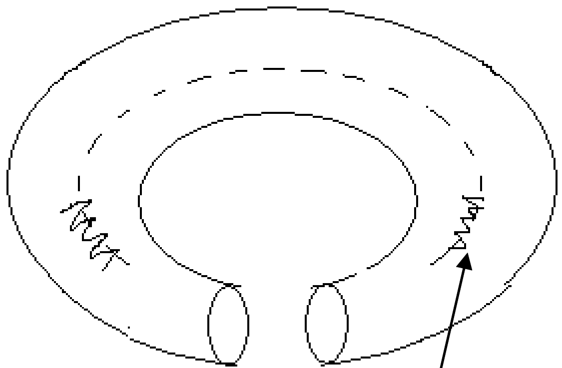
Realistic application: details of turbulent energy transfer in CTEM

- Trapped electron precession frequency:

$$\bar{\omega}_d \approx \frac{k_\theta \rho_s c_s}{R}\frac{E}{T_e}$$

- Bounce everaged kinetic equation for CTEM

$$\bar{\tilde{g}}_{k,\omega} = -\frac{e}{T_e}\langle f_e\rangle \frac{\omega-\omega_*}{\omega-\omega_d+\cancel{i\nu}}\left\langle e^{-inq\theta}\tilde{\varphi}_{k,\omega}\right\rangle_b$$



Toroidal procession of trapped particles

- turbulent heating for quasilinear trapped electron

$$\left\langle \bar{\tilde{E}}\cdot\bar{\tilde{J}}_e\right\rangle_b^{(2)} = e\int d^3v\,\bar{V}_d\,\bar{\tilde{E}}\bar{\tilde{g}}_{k,\omega} = \sum 4\pi^{1/2}\varepsilon^{1/2} n T_e\left(\frac{R}{2a}\right)^{3/2}\rho_*^2(\omega-\omega_*)\langle f_e\rangle\Big]\!\Big]_{E=\frac{\omega}{k_\theta}\frac{RT_e}{\rho_s C_s}}$$

wave-trapped particle resonance: $\omega = \bar{\omega}_d$

$$\omega = \frac{\omega_*}{1+k_\perp^2\rho_s^2} \Rightarrow \left\langle \bar{\tilde{E}}\cdot\bar{\tilde{J}}_e\right\rangle_b^{(2)} < 0$$

Trapped electron cooling via trapped electron precession resonance

Nonlinear trapped electron cooling

● The beat mode resonance effect for trapped electrons (L.Chen'77) (Gang'90)

- The 3rd order nonlinear trapped electron response function

$$\hat{h}_n^{e(3)} = -\left(\frac{nq}{r}\right)^2 d_{\theta\theta}^e \left\langle e^{-inq\theta}\tilde{\varphi}_n\right\rangle_b + d_{rr}^e \frac{\partial^2}{\partial r^2}\left\langle e^{-inq\theta}\tilde{\varphi}_n\right\rangle_b$$

$$d_{\theta\theta}^e = \left(\frac{c}{B}\right)^2 \frac{1}{\omega}\sum_{n'}\frac{1}{\omega'' - \omega_{de}''}\left|\frac{\partial}{\partial r}\left\langle e^{-in'q\theta}\tilde{\varphi}_{n'}\right\rangle_b\right|^2 \left(\frac{\omega_e^{*'}}{\omega'} - \frac{\omega_e^*}{\omega}\right)\frac{e}{T_e}\langle f_e\rangle$$

$$d_{rr}^e = \left(\frac{c}{B}\right)^2 \frac{1}{\omega}\sum_{n'}\frac{1}{\omega'' - \omega_{de}''}\left(\frac{n'q}{r}\right)^2 \left|\left\langle e^{-in'q\theta}\tilde{\varphi}_{n'}\right\rangle_b\right|^2 \left(\frac{\omega_e^{*'}}{\omega'} - \frac{\omega_e^*}{\omega}\right)\frac{e}{T_e}\langle f_e\rangle$$

- $1/\omega'' - \omega_{de}''$ $\rightarrow$ the nonlinear trapped electron-wave interaction

● The nonlinear turbulent heating for trapped electrons

$$\left\langle \bar{\tilde{E}} \cdot \bar{\tilde{J}}_e \right\rangle_b^{(4)} = e\int d^3 v \bar{V}_d \bar{\tilde{E}}_d \hat{h}_n^{e(3)}$$

$$\rightarrow -\pi^2 \left(\frac{\varepsilon}{2}\right)^{\frac{1}{2}} \sum_{n,n'} n_0 T_e \left|\frac{e\bar{\tilde{\varphi}}_{n,\omega}}{T_e}\right|^2 \left|\frac{e\bar{\tilde{\varphi}}_{n',\omega'}}{T_e}\right|^2 \frac{V_{the}^4 \rho_s^4}{\Omega_e^2 \left|k_\theta''\right|}\left(k_\theta^2 - k_\theta'^2\right)^2 \left(k_\theta^2 k_r'^2 + k_\theta'^2 k_r^2\right)\left(\frac{\omega'' R T_e}{k'' \rho_s c_s}\right)^{\frac{3}{2}} \langle f_e \rangle]\!]_{E=\frac{\omega'' R T_e}{k'' \rho_s c_s}} < 0$$

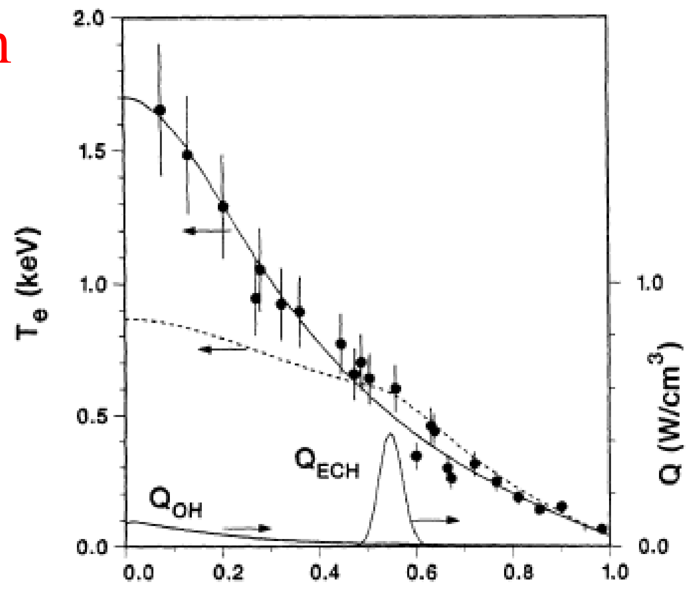
➡ **In CTEM, trapped electron can have quasilinear and nonlinear cooling. Nonlinear cooling can be significant.**

Related experimental phenomenon

- Electron temperature profile "stiffness"
  - temperature profile react weakly to changes of auxiliary heating deposition

C.C . Petty 94'

Possible dynamical cause
- Heat pinch : inward flow
  Nondiffusive term in heat flux
- Electron- ion energy transfer in the core: " Sink"



Experimental electron temperature profile measured in DIII-D tokamak.

- They are two different and independent effects . *which one is more efficient? Both must be examined..*

$$\frac{\partial T_e}{\partial t} + \nabla \cdot Q_e = \left\langle \tilde{E} \cdot \tilde{J}_e \right\rangle$$

$$Q_e = -\chi_e n_e \nabla T_e + \underbrace{V_e n_e T_e}_{\text{heat pinch}}$$

(Weiland ' 89), (L. Wang '2011)

Conclusion

- ITER plasma is low collisionality, electron heated plasma
- Turbulent heating and Turbulent energy transfer channels
  - Net heating occurs!
  - Zonal flow (& frictional damping) can be significant energy transfer channel (and sink) for CTEM turbulence
- Collisonless energy transfer likely dominant in energy coupling and a critial element in transport analysis
  - Does this process excite ITG?
- Future work extend to :
  - Realistic model: CTEM
  - Representation for energy transfer in ITER modelling
  - Future experiment :electron temperature profile "stiffness"
  - $o\left(\left|\frac{e\tilde{\varphi}}{T}\right|\right)^4$ contributions to Residual stress, in momentum flux