Turbulent Particle transport in H-mode pedestal of Tokamak Plasma

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Acknowledgements: H. Nordman, P. Kaw and X. Garbet

PPPL, December 17, 2013

High confinement (H-mode) discharges are identified:

- Steep density and temperature profiles in edge region – form pedestal
- Reduction in H_α (^{1}H Plasma), D_α (D-plasma) signals
- H – factor: $H = \frac{\tau_E}{\tau_E{}^L} > 1$

Energy confinement time is defined by

$$\tau_E = \frac{\int 1.5n(\mathrm{T}_e + \mathrm{T}_i)d^3x}{P_{input}}$$

Why Particle Transport?

Power balance:

$$P_H^{ext} + P_{alfa} = \frac{3nT}{\tau_E}; \quad P_{alfa} = \frac{1}{4} n^2 < \sigma v > \mathrm{E}_{alfa}$$

- Thermonuclear Power

$$P_{th} = n_D n_T < \sigma v > \mathrm{E} \quad = \quad \frac{1}{4} n^2 < \sigma v > \mathrm{E}$$

- Particle and thermal Transport – they are correlated

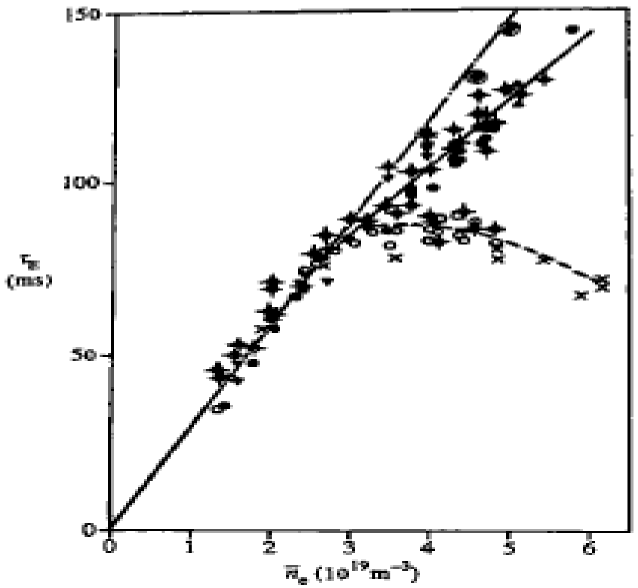
- **Peaked density profile:**

- yields high fusion power - $P_{th} \propto n^2$

- stabilizes micro-instabilities (Drift modes - ITG, ETG) and reduces heat transport
- generates a large bootstrap fraction ($J_b \propto \beta_{pol}$) required for continuous operation ($J_b \propto (1/B_P)(\mathrm{dP/dr})$)
- deep penetration of low Z , high Z impurities and H_e ashes accumulation in reactor phase (disadvantages)

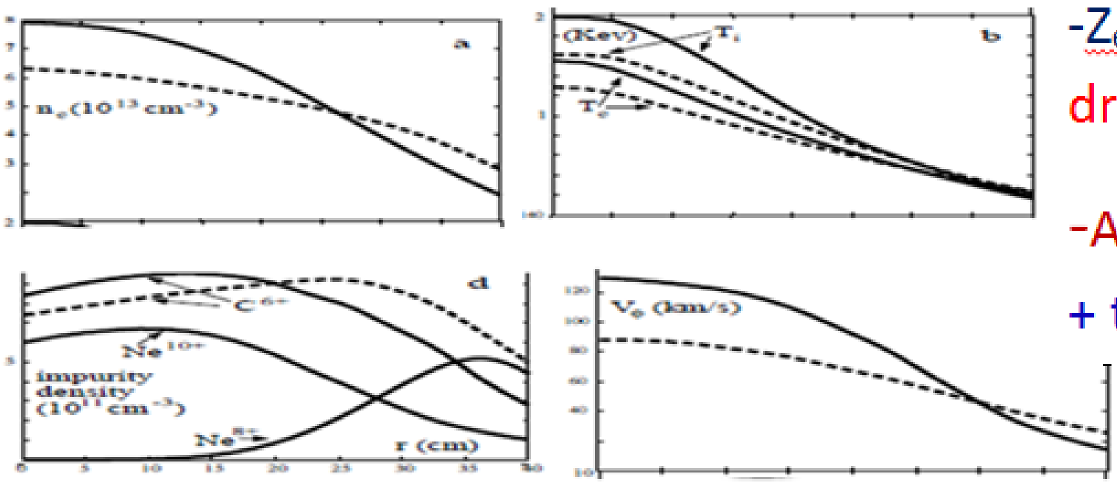
• Variants of operating modes exit by density peaking

- Improved Ohmic Confinement Mode (IOC) - $\tau_E \propto n$



R. Aratari et al., ASDEX - 88

- Super shot with solid deuterium pallets showed more peaked density profiles (due to ITG turbulence suppression)- energy confinement time was improved and $n\tau_E \sim 10^{20} m^{-3} s$ achieved
- Radiative Improved moved: Energy transport reduced with impurities seeding (TEXTOR, Ongena et al 1995)



-Z_{eff}: reduces the interchange drive in ITG dynamic

-Asymmetric radiation: MARFE + toroidal rotation

Particle versus thermal Transport

- Particle transport is different from heat transport
- Heat source is almost always located in the core

  → Distinction between pinch and diffusive terms difficult

- Particle source is often located only in outer edge region, while showing peaked density profile

  → Distinction between pinch and diffusive terms easier

- **Traditional gradient and flux relation:**

$$\Gamma = -D\nabla n + V n; \quad V = V^{an} + V^{neo} + V^{ware}$$

$$\frac{\Delta n}{n} = \frac{V R}{D}$$

-> Peaked density parameter

- **Relation between gradient and flux is more complex**

- **The vague form turbulent flux as**

$$\Gamma = -D\left(\nabla n, \nabla T, \nabla B, \cdots\right)$$

❖ Gradient and Flux Matrix

- **General form of transport matrix**

$$\begin{pmatrix} \Gamma \\ Q \\ \pi_\phi \\ \cdots \end{pmatrix} = \begin{bmatrix} D & D_{Tn} & D_{nV} & V_{Dn} \\ D_{nT} & \chi_T & D_{TV} & V_{DT} \\ D_{Vn} & D_{VT} & \chi_\phi & V_{DV} \\ \cdots & \cdots & \cdots & \end{bmatrix} \begin{pmatrix} \nabla n \\ \nabla T \\ \nabla V_\phi \\ \cdots \end{pmatrix} + D_J \nabla F_j$$

❖ Outline

- **Neoclassical particle transport and limitations**
- **Turbulent particle transport**
- **Transport in pedestal**
- **Summary and open issues**

•Neoclassical Transport and Limitations

- **Ware Pinch:** conservation of canonical moment in the presence of induced toroidal electric field (E_ϕ), all trapped particles drift towards the magnetic axis

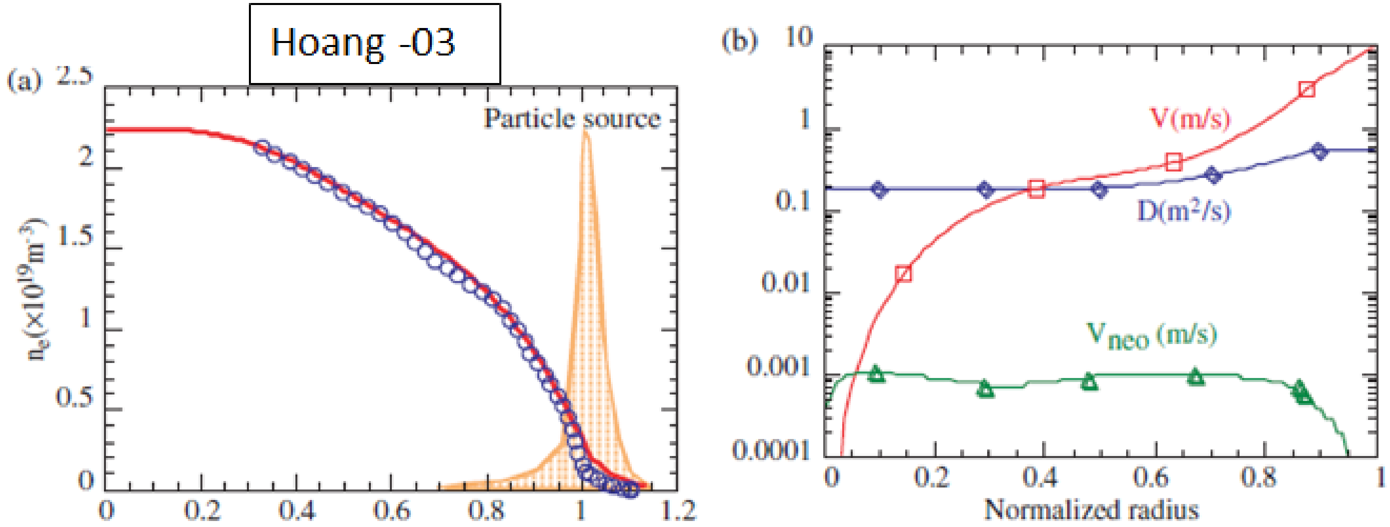
$$V^{ware} \sim 2.44\,\varepsilon^{1/2} E_\phi / B_\theta$$

- Usually dominant in core at low power- Wagner 93
- ITB (EDA H-mode) in Alcator C-Mod could be understood by ware pinch- Ernst 04 (??)
- Peaked density is observed in no-inductive discharge i.e., $V^{ware} = 0$

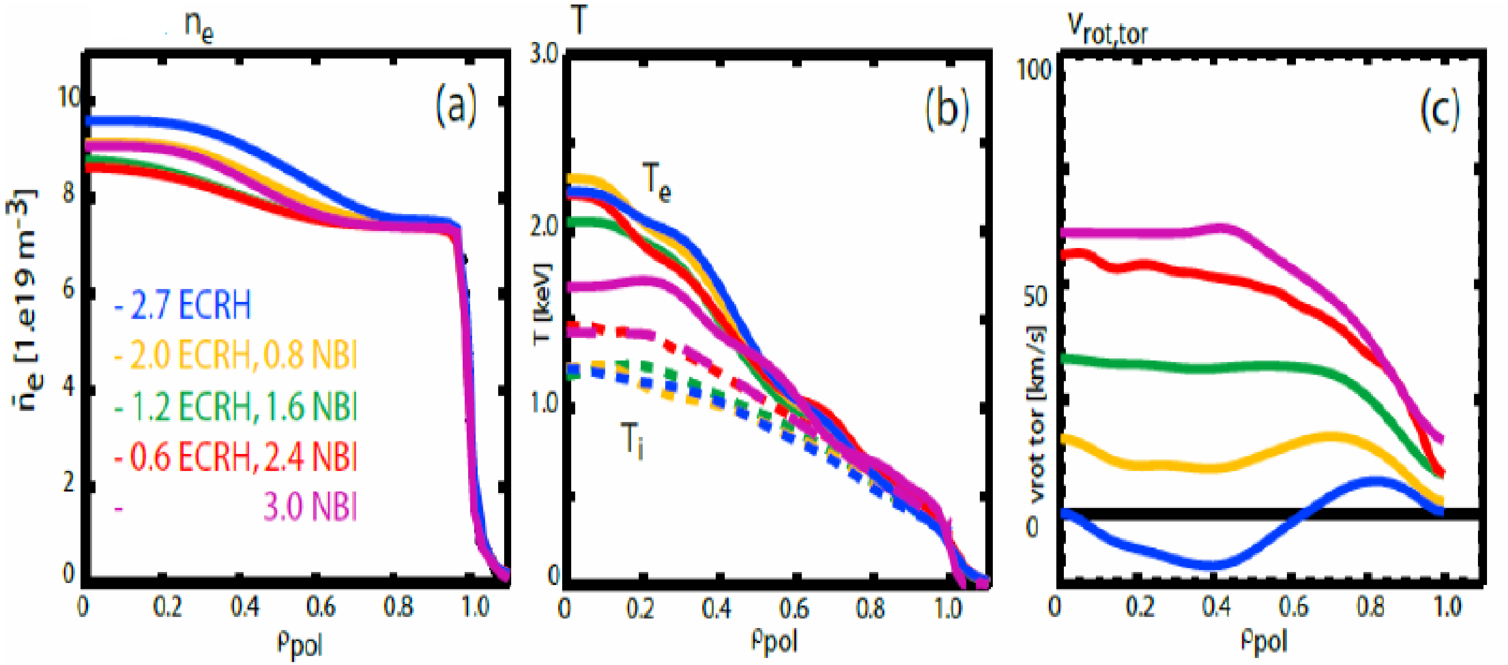
- Some cases [high density H-mode in JET, ASDEX-UP] observed pinch found to be

$$V_{pinch} \geq V^{neo}; \qquad D \propto \chi_e$$!! Sign of ETG Turbulence (discuss later)

- Ware pinch cannot explain all experiments [L-mode in JET, D-IIID, TEXTOR, TCV, Tore-supra results] and no-inductive discharge (Tore-supra) i.e., $V^{ware} = 0$



- NBI fuelling is not essential element for peaked density
- Actions of toroidal rotation also of interest



Core Particle Transport C. Angioni, ITPA T&C, Hefei, 2-5.04.2012

❖ Particle Turbulent transport

- Quasi-linear particle flux results from linear phase shift between density and potential perturbation $\tilde{n} = (1 + i\delta)\tilde{\phi}$ - transport by $\omega < \Omega_i$ micro-turbulence. Drift KE – Horton-83:

Fluctuation spectrum

$$\Gamma_n = \sum_k \left\langle (k_y \rho_s)^2 \int d^3v F_M \left[\frac{\gamma_k J_0(k_\perp \rho_s)^2 \, |\tilde{\phi}_k|^2}{(\omega_{rk} + \omega_{Dk})^2 + \gamma_k{}^2} \right] \left[R/L_n + (E/T_e - 1.5) R/L_T - \omega_{Dk} \right] \right\rangle$$

$$\propto \underbrace{\left[D(R/L_n) \right.}_{\text{Diffusive}} + \underbrace{D_T R/L_T}_{\text{Thermo diffusion}} + \underbrace{\left. RV_p \right]}_{\text{Pinch – Compressibility}}$$

$$\Gamma_n \propto \sum_k \left\langle |V_k|^2 \, \delta(\omega - kV) \left[R/L_n + (E/T_e - 1.5) R/L_T - 2\omega / R\omega_{Dk} \right] \right\rangle_V$$

❖ TEP Theory

(Yankov 94, Nycander-Rosenbluth 95, Naulin 98)

- For $\vec{B} = \hat{z}B(x,y)$ and $v_E = \hat{z}\times\nabla\phi/B$; $\vec{\nabla}\cdot\vec{v}_E \neq 0$ → Compressible
- $\partial_t n + \vec{\nabla}\cdot n\vec{v}_E = d_t(n/B) = 0$; Here n/B is a Lagrangian invariant and equivalent to advection of n/B
- Turbulence mixing → relaxation towards $\nabla_x \ln n = \nabla_x \ln B$ (equivalent to peaking factor) or canonical profile $n = B(x)$
- Extension to toroidal momentum pinch (Diamond, Hahm--) - Lagrangian invariant $nV_{\|}/B^3$ → Turbulent mixing - relaxation towards $\nabla \ln(nV_{\|}) = 3\nabla \ln B$

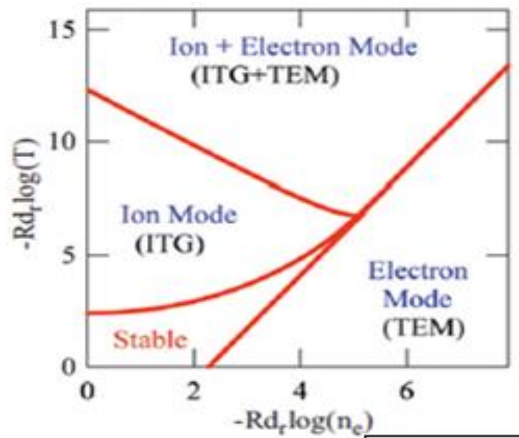
❖ Thermo-diffusion flux

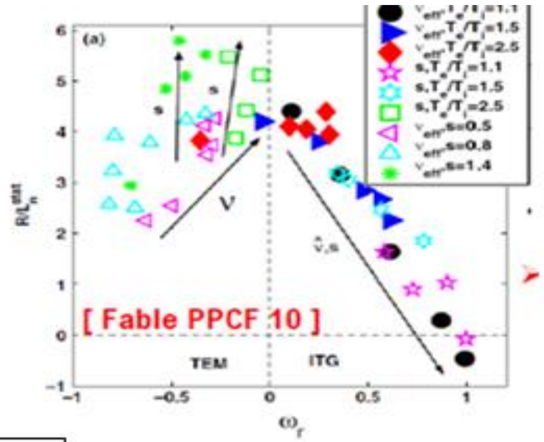
(Coppi 79, Waltz 89, Terry 89, Nordman 90----)

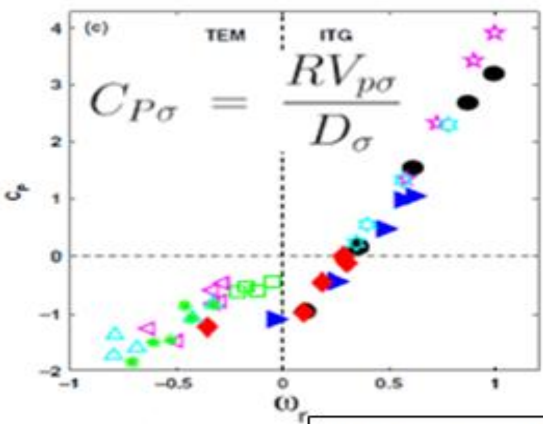
- Term proportional to $\left(-R\nabla \ln T\right)$ - Thermo-diffusion flux

$$RV_p = D_{nT}\left(\omega_{rk},\omega_d(\hat{s}),\omega_{dtr}(\hat{s}),\nu_{eff},\gamma_k\right)\left(-R\nabla \ln T\right)$$ - Trapped particles

- Interaction between toroidal momentum and particle fluxes appears – step density with toroidal flows
- D_{nT} -Complex!! and depend on the characteristic of turbulence
- ITG-TEM mode - **CORE-region**

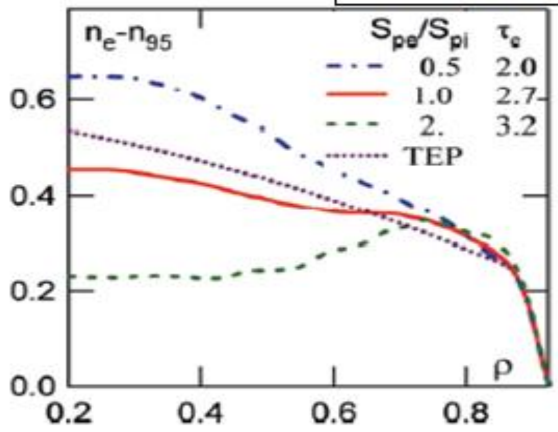


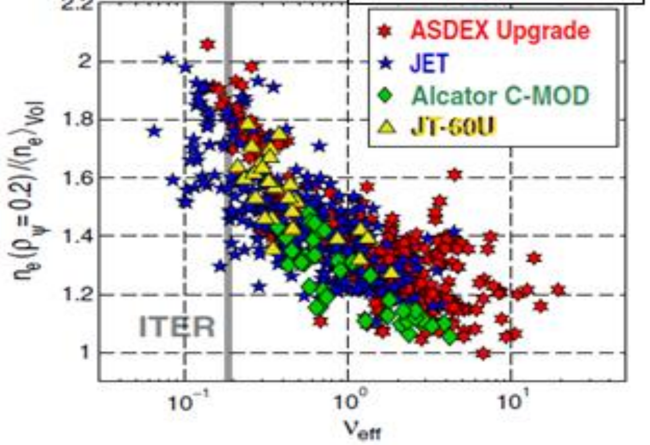




Garbet 03

Angioni 09





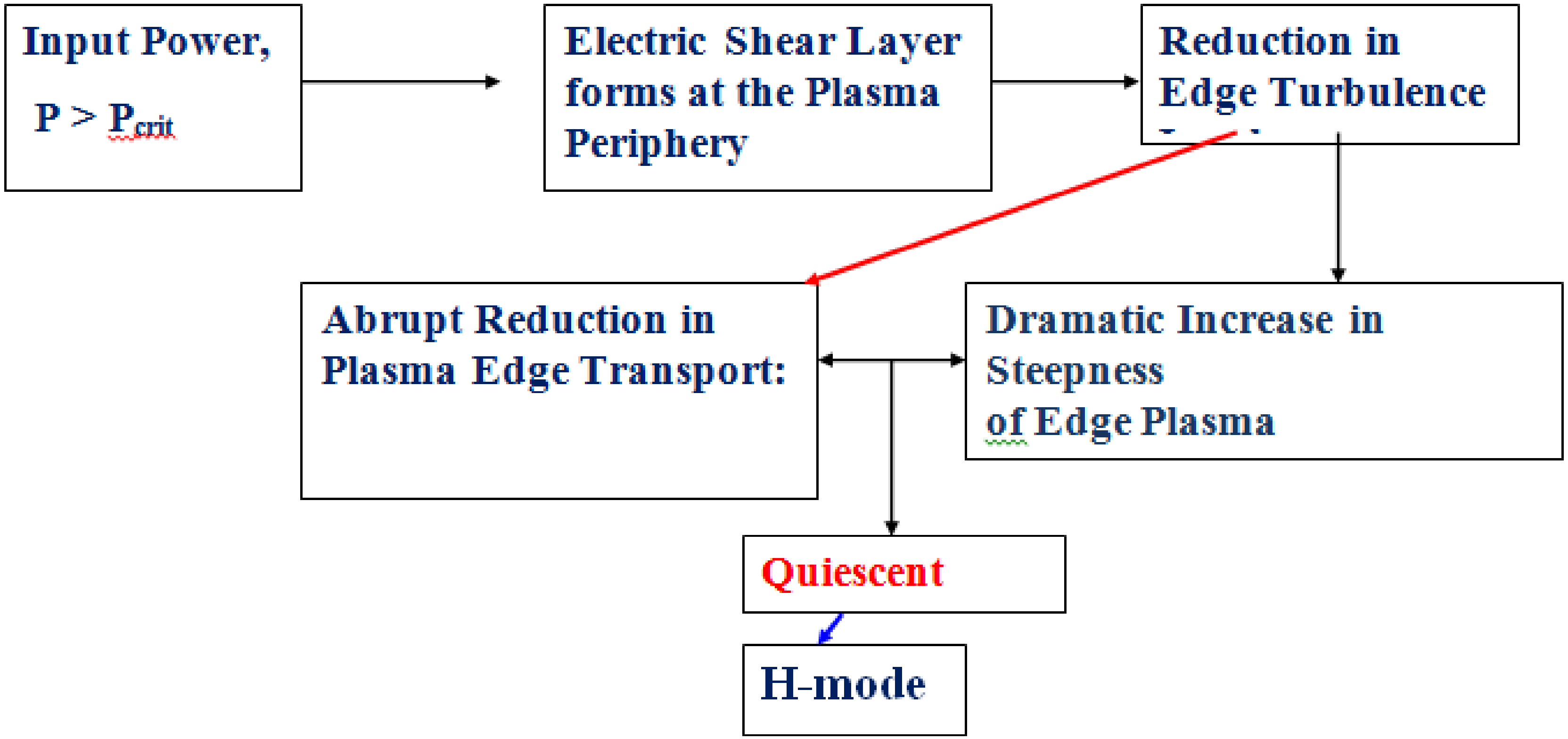
❖ QL versus Non QL - Hot topic?

- QL theory suggests a linear relation between gradient and flux and turbulent saturation - mixing length: $\nabla \delta n = \nabla n \Rightarrow \delta n / n \sim 1/k_x L_n$

  $\partial_t \sim (c/B)\hat{z} \times \vec{\nabla}\delta\phi \cdot \vec{\nabla} \Rightarrow e\delta\phi / T_e \sim (\gamma_k / \omega_*)(1/k_x L_{n,T})$
- Existence-multi-states: L-H, ITB, cold pulse expts. – suggests the relation between gradient and flux is quite intricate.
- Multi-scales interaction between particle, thermal, and momentum fluxes, mean flows, zonal flows, zonal fields etc. **– the hot topic**
- Meso-scale coherent structures and nonlocal diffusion is also vital (??) – complicated

❖ Transport in H-mode pedestal

• L-H transition and quiescent state H-mode



Questions:

- What is the underlying physics of steep density formation though the particle source is absent?

- Drift turbulence on scales $\rho_s = c_s / \Omega_i$ - ITG-TEM and DRBM, are the main drivers of transport channels are suppressed due to ExB shear /or Zonal flow rotations.
- Reduced turbulent diffusion and neo-classical diffusion are small to explain the rapid development of sharp profiles in H-mode transition.
- Transition occurs in m-sec from L - I and I - H
- Pedestal Physics, not well understood. But not ITG-TEM, DRBM turbulence → Can it be ETG?

- Propose: ETG mode may a possible candidate for particle pinch and thermal transports in barriers and pedestal confinement time $\tau_E^{Ped} \propto n / I_p$ - Ohkawa scaling

- **Streamers in local ETG simulations-** Jenko 2000

- Electron transport remains anomalous - unaffected from ExB shear and MHz fluctuations are observed in: NSTX (Smith 09), FT-2 (Gusakov 06), Tore Supra (Hennequin09)

❖ Toroidal ETG Mode

ITG versus ETG

ITG **ETG**

$$\tilde{n}_e = \tilde{\phi} \quad (\omega / k_\parallel < V_{the}); \qquad \tilde{n}_i = -\tau_i \tilde{\phi} \quad (\omega / k_\perp < V_{thi})$$

$$\gamma^{ITG} \sim \mathrm{k}_\theta \, \rho_i (V_{thi} / \sqrt{RL_n}); \qquad \gamma^{ETG} \sim \mathrm{k}_\theta \, \rho_e (V_{the} / \sqrt{RL_n})$$

$$\chi_i / \chi_e \sim \sqrt{m_i / m_e}$$

- Condition for adiabatic ion $k_\perp c_i > \omega | \sim \omega_* \Rightarrow \quad \rho_s / \mathrm{L}_n > 1$, OK in core
- Wave number and frequency ordering in pedestal: $k_\perp \rho_e \leq 1$, $k_\perp c_i \geq | \omega | \sim \omega_*$
- Both like Interchange mode- stabilize by Larmor radius
- ETG is mirror image of ITG
- Interchange mode stabilize by Larmor radius

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- For $k_\perp c_{i,I} \sim |\omega|$, ETG mode resonates with background ions, which results in deviation of ions from Boltzmann condition. Non-adiabatic response can be determined by DKE,

$$\frac{\partial \tilde{f}_j}{\partial t} + \vec{V}_\perp \cdot \frac{\partial \tilde{f}_j}{\partial \vec{x}} + \frac{Ze}{m_J} \delta E_\perp \cdot \frac{\partial f_{0j}}{\partial \vec{V}} = 0.$$

$$\tilde{n}_i = -\tau_i \tilde{\phi}\left[1 + i\pi^{1/2}\hat{\omega}\exp(-\hat{\omega}^2)\right]; \quad \tilde{n}_I = -\tau_I \tilde{\phi}\left[1 + i\pi^{1/2} A_I^{1/2} Z \hat{\omega}\exp(-A_I\hat{\omega}^2)\right]$$

Electrostatic ETG eigenmode equation in $\hat{s} - \alpha$ geometry

$$\left(A\frac{\partial^2}{\partial\theta^2} + B + C\theta^2 \right)\tilde{\phi}_k = 0$$

- Radial length of ETG mode → By balancing

Vorticity [i.e. $k_\perp^2 \rho_e^2 \omega^2$] ~ Parallel compression [i.e. $c_e^2 \, \mathrm{k}_\parallel^2 (1+5\tau^* / 3)$]

$$\gamma^2 k_y^2 \rho_e^2 (\hat{s}-\alpha)^2 \theta^2 \simeq c_e^2 / \mathrm{q}^2 \mathrm{R}^2 \, \partial^2 / \partial\theta^2$$

- Simple analysis yields inverse of mixing length

$$(k_x \rho_e)^2 \approx (k_y \rho_e)^2 \, |\hat{s}-\alpha|^2 \, (\Delta\theta)^2 = \bar{\varepsilon}_n \, |\hat{s}-\alpha| \, (1+5\tau^* / 3)^{1/2} / 2q(\bar{\varepsilon}_n \eta_e / \tau^*)^{1/2} (1-\eta_{th} / \eta_e)^{1/2}$$

- For $\hat{s} > \alpha$ and $\eta_{th} / \eta_e < 1$ (scaling similar to ITG by Biglari *et al*-89)

$$\chi_e \approx k_y \rho_e \frac{q}{\hat{s}} \frac{c_e \rho_e^{\,2}}{L_T}$$

- In the opposite limit, when $\hat{s} \leq \alpha$

$$\chi_e \approx \frac{c_e \lambda_s{}^2}{qR} \frac{(\eta_e - \eta_{th})}{2\tau^* |1 - \hat{s}/\alpha|} \quad \propto \quad I_P / na^2$$ "Ohkawa scaling in pedestal"

ETG driven electron thermal transport in pedestal has many interesting features:

1) It reproduces Ohkawa scaling that $\chi_e \propto \lambda_s^2$.
2) χ_e, proportional to *local* current $\chi_e \propto 1/q$ - this is in contrast to general believing that χ_e improves with increasing current.

3) χ_e is inversely proportional to the parameter $|1 - \hat{s}/\alpha|$, which indicates a possible blow up of electron thermal transport as α approaches to local magnetic shear

4) χ_e is the dominant energy loss channel over ion loss in plateau regime (i.e., $\chi_i^{plateau} \sim q c_i \rho_i^2 / R$) in H-mode pedestal if $\chi_e > \chi_i^{plateau}$ - which yields condition $\sqrt{m_e / m_i} > q^2 |1 - \hat{s}/\alpha| \beta / 2$.

The other implication of the pedestal confinement scaling:

- AS $\chi_e \propto 1/q$, electron confinement will deteriorate as a bootstrap current builds up - increase of χ_e implies the increase of the turbulence level - resulting in the generation of anomalous electron hyper-viscosity ($\mu_{\|e}^H$)
- $\mu_{\|e}^H$, likely to accelerate magnetic reconnection and ensuing ELM crash or may enhance ELM activities.

- Recent simulation (Xu-10) used $\mu_{\|e}^{H} \sim \chi_e$ without theoretical justification. Here, it is straightforward to obtain $\mu_{\|e}^{H} \sim \chi_e$ by calculating radial current flux and electron heat flux,

$$\mu_{e\|} = m_e < \tilde{v}_{rk}(n_0 \tilde{J}_{\|e-k} + \tilde{n}_{-k} J_{\|0}) > \quad \simeq m_e n_0 [-\mu_{\|e} dJ_{\|0} / dr + V_{pinch} J_{\|0}]$$

$$Q_e =< \tilde{v}_{rk}(n_0 \tilde{T}_{e-k} + \tilde{n}_{-k} T_{e0}) > \approx n_0 [-\chi_e dT_e / dr + V_{pinch} T_e]$$

Here $\mu_{\|e}^{H} \sim \chi_e$, as in the case of ITG turbulence (Mattor-88) and given by

$$\mu_{\|e} \sim \chi_e \approx c_e L_n \frac{k_\theta^2 \rho_e^2 \gamma_{0k}}{|\omega_{0k}|^2} \left| \frac{e\phi_k}{T_e} \right|^2 \sim \chi_e^{ohkawa} \, | k_y \rho_e | \eta_e^2 (\eta_e - \eta_{th}) / | 1 - \hat{s} / \alpha |$$

- Electron Prandtl number due to ETG turbulence is 1

•Particle pinch and pinch velocity

- The non-adiabatic ions and impurities in the edge pedestal can induce particle flux – similar to coupled ITG-TEM, $\Gamma_n \equiv \langle \tilde{v}_{rk} \tilde{n}_{-k} \rangle$,

$$\Gamma_n \approx \pi^{1/2} \tau_i n c_e k_y \rho_e \left(\frac{\omega_r}{k_\perp V_{thi}} \right) \left[\exp\left(-\frac{\omega_r^2}{k_\perp^2 V_{thi}^2} \right) + \frac{\tau_I}{\tau_i} Z_{eff} A_i^{1/2} \exp-\left(-A_i^{1/2} \frac{\tau_I}{\tau_i} \frac{\omega_r^2}{k_\perp^2 V_{thi}^2} \right) \right] |\tilde{\phi}_k|^2$$

$$\approx -\pi^{1/2} n |k_y \rho_e| \left(\frac{\chi_e^{Ohkawa}}{4L_{Te}} \right) \left(\frac{\tau_i}{\tau^*} \right)^{3/2} \left(\frac{R}{L_{Te}} \right)^{1/2} \left(\frac{\rho_s}{L_{Te}} \right) \left(\frac{1-\eta_{th}/\eta_e}{1+5\tau^*/3} \right)^{1/2} \frac{1}{|1-\hat{s}/\alpha|}$$

$$\times \left(\exp(-\hat{\omega}^2) + (T_i/T_I) Z_{eff} A_I^{1/2} \exp(-A_I \hat{\omega}^2) \right)$$

- In absence of recycled neutral flux in pedestal from wall, a steady state (i.e. $\Gamma_n = 0$) is set by the condition $\eta_e \sim \eta_{th} \sim 2$

- The density scale length L_n locked to L_{Te} which is set by ETG heat balance $< L_{Te} > \sim Q_e / \chi_e T_e$; Q_e is the heat flux entering into pedestal from the core.
- pinch time or pedestal formation time due to ETG turbulence, $\tau = n L_n / \Gamma_n$
- τ for two sets of tokamak plasma parameters: $n = 0.2, 0.7$, $T_e = 0.8, 2.5$ $B = 2, 5$, $R = 1.5, 6$, $\eta_e = 2.0$, $Z_{eff} = 2.0$, $\hat{s} = 2$, $\alpha = 2.5$, $q = 3$, $\tau_i = \tau_I = 1$, $A_I = 6$, $A_i = 2$, $< k_y \rho_e >= 0.5$, $L_n / a = 0.04$ → resulting in $\tau = 0.1, 20\, ms$ for each case
- Density pedestal formation occurs within $100 \mu s$ in medium size tokamaks whereas in large machines like ITER, the pedestal formation time will be slower and typically $\tau \leq 20 ms$.

- Acceleration of density pedestal formation can be summarized as: Ion temperature and density pedestals start to form first as ρ_i scale turbulence is quenched by $E \times B$ shear. Since ETG turbulence will still be active in this condition and drive inward particle pinch, accelerating the density pedestal formation. This pedestal formation continues until it hits the ETG threshold $\eta_e \sim \eta_{th} \sim 2$, as observed in ASDEX-U experiments (Neuhauser-02).

CONCLUSIONS

(i) The electron thermal conductivity exhibits a different scaling depending on relative values of $\hat{s}$ versus α. It exhibits gyro-Bohm-like scaling when $\hat{s} > \alpha$, while follows the Ohkawa scaling when $\hat{s} < \alpha$ - Ohkawa scaling governs χ_e in edge pedestal.

(ii) ETG turbulence can induce an inward particle pinch during the development phase, which can lead to the rapid formation of density pedestal until it hits ballooning mode limit.

(iii) Our theory predicts that the pedestal electron temperature profile must remain near the ETG threshold value $\eta_e \sim \eta_{th} \sim 2$.

(iv) ETG turbulence will prevail in pedestal (as long as $\eta_e > \eta_{th}$) no matter whether the KBM threshold condition is met or not. KBMs, on the other hand, become unstable when a pressure gradient exceeds BM threshold. Once the BM onset condition is met, ETG and KBM turbulence may co-exist in the pedestal.

(v) How this multi-scale interaction happens and what would be the consequence of this have not fully elucidated yet.

(vi) We plan to extend this analysis to include the interaction between ETG and BM to study back reaction of BM to ETG via multi-scale interaction.

Thank you