Electron Transport Stiffness and Heat Pulse Propagation on DIII-D

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Fundamental Behavior of Drift Wave Turbulent Transport is Tested Using Heat Pulse Propagation

- Carefully constructed experiment directly probes diffusive transport to test key predicted behaviors:
  - Instability threshold in $\nabla T_e$
  - Electron transport stiffness
- Off-axis ECH varies electron heat flux to scan $\nabla T_e$ over large range
  - Moved one gyrotron from outside to inside on shot-to-shot basis
- Modulated one gyrotron (outside) for measurement of heat pulse propagation

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Modulation in Electron Temperature Profile is Fitted to Linearized Energy Conservation Equation

- Fourier-transformed first-order equation:

\[-D^{HP}\nabla^2 \tilde{T}_e + V^{HP} \nabla \tilde{T}_e + \left( \frac{1}{\tau^{HP}} + i \frac{3}{2} \omega \right) \tilde{T}_e = \tilde{S}_e\]

- Multiple harmonics of $T_e$ oscillations are simultaneously fit to determine $D^{HP}, V^{HP}, \tau^{HP}$
Heat Pulse Propagation is a Good Test of Transport Stiffness Models

• This talk focuses on the relation between the “heat pulse” and “power balance” diffusivities:

\[
D_{HP} = -\frac{1}{n_e} \frac{\partial Q^{PB}}{\partial \nabla T_e} = \frac{\partial}{\partial \nabla T_e} \left( D^{PB} \nabla T_e \right)
\]

where

\[
Q^{PB} = -n_e D^{PB} \nabla T_e + n_e V^{PB} T_e
\]

• Comparing the incremental \((D_{HP})\) to equilibrium diffusivity \((D^{PB})\) relates stiffness to the shape of the heat flux curve:

\[
S = \frac{D_{HP}}{D^{PB}} = \frac{\partial \ln(Q/n)}{\partial \ln(\nabla T)}
\]
The “Heat Pulse” Diffusivity at $\rho = 0.6$ Rapidly Increases for $-\nabla T_e > 3.2$ keV/m — Critical Gradient Threshold?

- Key analysis step is to determine the “power balance” diffusivity by numerical integration of the measured “heat pulse” diffusivity:

$$D^{PB} = \frac{1}{\nabla T_e} \int_0^{\nabla T_e} D^{HP} d(\nabla T_e)$$

- This yields the purely diffusive portion of the equilibrium heat flux
Diffusive Heat Flux Falls Short of Total Heat Flux from Power Balance — Indicating Something is Missing

- Diffusive heat flux is

\[ Q_{\text{diff}} = -n_e D_{\text{PB}} \nabla T_e \]

\[ \frac{\nabla T_e}{T_e} \int_0^{\nabla T_e} D_{\text{HP}} d(-\nabla T_e) \]

- The difference between the heat fluxes can be reconciled by a non-zero “power balance” convective velocity

\[ V_{\text{PB}} = \frac{Q_{\text{PB}}}{n_e T_e} - \frac{1}{T_e} \int_0^{\nabla T_e} D_{\text{HP}} d(-\nabla T_e) \]
The “Power Balance” Diffusivity Increases Rapidly Above $-\nabla T_{\text{crit}}$ While Convection is Mainly Outwards

\[
D^{\text{PB}} = \frac{1}{\sqrt{T_e}} \int_0^{\nabla T_e} D^{\text{HP}} d(\nabla T_e)
\]

\[
V^{\text{PB}} = \frac{Q^{\text{PB}}}{n_e T_e} - \frac{1}{T_e} \int_0^{\nabla T_e} D^{\text{HP}} d(-\nabla T_e)
\]

\[
D^{\text{PB}} \quad (\text{m}^2/\text{s})
\]

\[
V^{\text{PB}} \quad (\text{m/s})
\]

- $\nabla T_{\text{crit}}$

- $\rho = 0.6$
Measured Stiffness Factor Jumps Up ~4 Times When $-\nabla T_e/T_e$ Exceeds Critical Value

$$S = \frac{D^{HP}}{D^{PB}} = \frac{\partial \ln(Q^{PB}/n_e - V^{PB}T_e)}{\partial \ln(\nabla T_e)}$$
Measured Stiffness Factor Jumps Up ~4 Times When $-\nabla T_e/T_e$ Exceeds Critical Value

$$S = \frac{D^{HP}}{D^{PB}} = \frac{\partial \ln(Q^{PB}/n_e-V^{PB}T_e)}{\partial \ln(\nabla T_e)}$$

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![Graph showing measured stiffness factor jumps up ~4 times when $-\nabla T_e/T_e$ exceeds critical value.](image)

- **ECH only**
- **ECH + NBI**

$D^{HP}/D^{PB}$

$-\nabla T_{crit}$

$\rho = 0.6$

$-\nabla T_e$ (keV/m)
Measured Stiffness Factor Jumps Up ~4 Times When \(-\nabla T_e/T_e\) Exceeds Critical Value

\[
S = \frac{D_{HP}}{D_{PB}} = \frac{\partial \ln\left(\frac{Q_{PB}}{n_e} - V_{PB}T_e\right)}{\partial \ln(\nabla T_e)}
\]

\[\begin{align*}
D_{HP}/D_{PB} & = \rho = 0.6 \\
-\nabla T_{crit} & = -\nabla T_e (\text{keV/m}) \\
-\nabla T_e/T_e (\text{m}^{-1}) & = \rho = 0.6
\end{align*}\]
Critical Gradient and Stiffness Factor from Nonlinear GYRO Simulations Agree With Experiment

- Comparison of ECH + co-NBI case
- GYRO stiffness factor determined using total heat flux

\[ S = \frac{\partial \ln Q_e}{\partial \ln \nabla T_e} \]
The “Minimal” Critical Gradient Transport Model by Garbet Can Be Tested Against DIII-D Data

- Simple transport model that preserves some basic properties of turbulent transport
- Main hypothesis is gyroBohm-like turbulent transport that is switched on above a threshold $\kappa_{\text{crit}} = -R\nabla T_{\text{crit}}/T$

$$\frac{D}{D_{gB}} = \chi_s q^{1.5} \left( - \frac{R\nabla T}{T} - \kappa_{\text{crit}} \right) H \left( - \frac{R\nabla T}{T} - \kappa_{\text{crit}} \right) + \chi_0 q^{1.5}$$

Note that there is no convective term

- $\chi_s$ and $\chi_0$ are dimensionless coefficients to be fitted to data
  - $\chi_s$ is the “effective stiffness factor”

X. Garbet et al. 2004 Plasma Phys. Control. Fusion 46 1351
Diffusion Coefficients Exhibit Expected Behavior for Transport Switched On Above a Critical Gradient

ECH only: $L_{\text{crit}}^{-1} = 3.7 \text{ m}^{-1}$

$\chi_s = 0.80$

$\chi_0 = 1.04$
TGLF Transport Model has Similar Effective Stiffness Factor as Experiment But Predicts a Lower Critical Gradient

- Comparison of ECH-only case
- TGLF diffusion coefficient determined using total heat flux

\[ D^{TGLF} = - \frac{Q_e}{n_e \nabla T_e} \]

Experiment: \( L_{\text{crit}}^{-1} = 3.7 \text{ m}^{-1} \), \( \chi_s = 0.80 \)

TGLF: \( L_{\text{crit}}^{-1} = 3.1 - 3.4 \text{ m}^{-1} \), \( \chi_s = 0.73 \)
Conclusions

- We have developed a new method to look directly at diffusive behavior by combining heat pulse propagation and power balance analysis.

- In L-mode plasmas with off-axis ECH, a critical value of $\nabla T_e$ is observed, above which there is a sudden increase ($\approx 4 \times$) in the electron transport stiffness.

- Predicted electron transport stiffness and critical $\nabla T_e$ from GYRO and TGLF are in good agreement ($\approx 10\%$) with experiment.
  - Will extend this study to H-mode plasmas.