What we learned about Electron Transport From Tore Supra

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Key Features of Tore Supra Transport Studies

- Clean electron power balance data with accurate $T_e$ profiles and centrally deposited electron power
- Power scans from Ohmic to 8MW giving $T_e$ up to 7kev [more recently higher $P$ and $T_e$ up to 9kev]
  - Flux Scaling with density & temperature
  - Integrated System Dynamics- Chronos

Fast Wave Electron Heating Database

- **DB of 26 Quasi-steady state plasmas**
  (duration ranging from 1 to 5 seconds $\approx 20 - 120 \times \tau_E$)
- No fast particles, no appreciable sawteeth.
- Electron / Ion channels are decoupled ($T_e \sim 2T_i$)
- Central localization of FW deposited power
- Up to 90% of FW power coupled to the electrons: $q_{\mathrm{rf}}^e \gg q_{\mathrm{ei}}, q_{\mathrm{ohm}}$

$\Rightarrow$ Good confidence in transport power balance value of $q_e(r,t)$
Parametric Dependence: \( q_e = \text{const.} \; n_e^\beta \; T_e^\alpha \left( \frac{1}{L_{Te}} - \frac{1}{L_c} \right) \)
Critical Gradient and Internal Magnetic Fluctuations
\( \delta B \) by Cross-Polarisation Scattering

\[ I_p = 1.3 \text{MA}, \quad B = 3.7 \text{T} \]
\[ n_e(0) = 6 \times 10^{19} \text{m}^{-3} \]
RF power = 1MW - 3.3MW
Electromagnetic drift wave turbulence driven by the ETG is Standard Model $T_e(r,t)$

- Overpredicts $T_e$ in the outer part of plasma ($r/a \geq 0.7$)
- Thermal energy $W_e$ over-estimated by 10%
Predictive Simulations with ETG Model

for $\beta_e > \beta_{e,cr}$

$$q_e = C_e^\text{em} n_e T_e q \frac{c^2}{\omega_{pe}^2} \frac{V_e}{R^2} \left( \frac{R}{L_{Te}} - \frac{R}{L_c} \right)$$

for $\beta_e < \beta_{e,cr}$

$$q_e = C_e^\text{es} n_e T_e q^2 \left( \frac{\rho_e^2 V_e}{L_{Te}^2} \right) \left( \frac{R}{L_{Te}} - \frac{R}{L_c} \right)$$

For comparison: ITG-TEM flux

$$q_e = -n_e f_{tr,e} \chi^\text{ITG} \nabla T_i = C_e^\text{ITG} f_{tr, e} n_e T_i c_s q^2 \rho_s^2 \left( \frac{R}{L_{Ti}} - \frac{R}{L_c} \right)$$
Heat Flux versus Temperature Gradient Length$^{-1}$
Model Comparisons

Similar results in 2008 preprint Asp, Horton, Kim, Sauter et al for TCV plasma with 3X ECH heating

Now use $ARV = \frac{\text{variance of model from data}}{\text{variance of data}}$

ETG model explains about 70% of the data variation ($ARV \approx 0.3$)

while the ARV for the ITG-TEM model has $ARV \approx 1.3$ ..worse than “persistence prediction”
What have we learned?

- ETG model works well – quantitatively well. Consistent with historical problem since does not depend on presence of trapped electrons.
  
- TCV analysis of four phases of a third-harmonic ECH driven plasma agrees with ETG predicted $q_e(r,t)$ & $T_e(r,t)$ versus poor results from ITG/TEM models.

- NSTX/HHFW and FTU show similar ETG results to TS data and agree with ETG predictions.

- ETG is [should be] the standard, baseline model of electron thermal transport for toroidal systems.
ETG flux for real-time prediction in NSTX discharge

Real-Time forecasts of $q_e$ and thus $T_e$ may give way to predict NTMs and disruptions.

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**NSTX Electron Transport at Low $B_T$**

Kaye et al, Chengdu, IAEA 2006 and Nucl Fusion 2007

ETG linearly unstable only at lowest $B_T$
- 0.35 T: $R/L_{Te}$ 20% above critical gradient
- 0.45, 0.55 T: $R/L_{Te}$ 20-30% below critical gradient

Non-linear simulations indicate formation of radial streamers (up to $200\rho_e$): FLR-modified fluid code [Horton et al., PoP 2005]

- Good agreement between experimental and theoretical saturated transport level at 0.35 T
- Experimental $\chi_e$ profile consistent with that predicted by e-m ETG theory [Horton et al., NF 2004] at 0.35 T

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Inverse Cascade to Large Scale Vortices + Scaling Turbulence

\[ E(k_{\text{perp}}, t) \]

\[ k_{\text{perp}} \rho_0 e \]
Diagram of Fluctuations and Mixing Length Amplitudes

Fluctuation frequency vs wavenumber

Amplitude vs wavenumber