Particle and Energy Transport in Dedicated $\rho^*$, $\beta$ and $\nu^*$ Scans in JET ELMy H-modes

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Structure of talk:

• Background
• Energy transport results
  — $\rho^*$, $\beta$, $\nu^*$ scans
• Trace tritium transport results
  — $\rho^*$, $\beta$, $\nu^*$ scans
• Theory and modelling implications
• Predictions for ITER
Background

• Kadomtsev (SJPP, 1975) and Connor and Taylor (NF, 1977) showed

\[ \omega_c \tau_E \propto B \tau_E \propto F(\rho^*, \beta, \nu^*) \]

\( \rho^* \) = dimensionless Larmor radius, \( \beta \) = kinetic to magnetic pressure ratio, \( \nu^* \) = normalised collisionality.

• IPB98(y,2) scaling from the Multi-machine database has dimensionless form

\[ B \tau_E \propto \rho^{*-2.70} \beta^{-0.9} \nu^{*-0.01} \]

• 2-point scans of \( \rho^* \), \( \beta \) and \( \nu^* \) on JET (and JET/DIII-D for \( \beta \)) in 1996 gave

\[ B \tau_E \propto \rho^{*-3.0} \beta^{-0.0} \nu^{*-0.3} \]

• Particle transport is less well studied, He experiments indicate

\[ \tau_{p,He} = 5 \times \tau_E \]
Energy: $\beta$ scan results

- Extensive $\beta$ scans ($\rho^*$, $\beta$ and $q$ fixed) by JET and DIII-D in 2003
  [D C McDonald et al (PPCF, 2004) and C C Petty et al (PoP, 2004)]

- $B \tau_E$ had only a weak dependence on $\beta$, even within Type I ELMs

As $\beta$ increases, performance increases more favourably than the conventional prediction

$B \tau_E \propto \beta^{0.0 \pm 0.1}$

- Hence, provided steady stable high $\beta$ operation can be maintained the performance of ITER will be significantly improved
Energy: $\nu^*$ scaling

- Part of a collaboration with CMOD, so a high triangularity shape was used
- The current was varied in the range $I_p = 0.68 - 1.17$ MA
- To keep $\rho^*$, $\beta$ and $q$ fixed: $B \propto I$; $n \propto I^0$; $T \propto I^2$

\[
B \tau_E \propto \nu^* \quad -0.35 \pm 0.04
\]

RMSE = 6%

Similar to 2 point scan of 1996

$(B \tau_E \propto \nu^* \quad -0.28)$
Energy: $\rho^*$ scaling with Type III ELMs

• Low triangularity shape. Current varied in the range $I_p = 1.3 - 4.3\,\text{MA}$

• To keep $\beta$, $\nu^*$ and $q$ fixed: $B \propto I$; $n \propto I^{4/3}$; $T \propto I^{2/3}$

$B \tau_E \propto \rho^*^{2.9\pm0.5}$

close to gyro-Bohm

• The $\nu^*$ and $\beta$ match was not perfect for the extremes (open points)

• Introducing a $\nu^*0.35$ brings them closer to the scaling
Energy: $\rho^*$ scan with Type I ELMs

- So for the full scan, $I_p = 1.4 - 4\text{MA}$, we take $\chi$’s at $x = 0.5$

- Compare thermal diffusivities

- Here $\chi \propto 1 / B$, consistent with a gyro-Bohm scaling

$$\chi / B \propto \rho^* + 3.2 \pm 0.4$$

again, close to gyro-Bohm
Trace tritium: non-dimensional ($\rho^*, \beta, \nu^*$) experiments

• Set of 5 discharges prepared in D-D
  — 3 point $\rho^*$ scan
  — 2 point $\beta$ scan
  — 2 point $\nu^*$ scan

• Reran with a T puff (2.5-5mg over 80ms)

• Line integrated D-T and D-D neutrons measured with 10 horizontal and 9 vertical cameras
Trace tritium: fitting diffusivity and advection

- Take $\mathbf{V} + \mathbf{D}$ with 3 basis functions each
- SANCO forward models $n_T +$ neutrons
- UTC finds best fit with error bars

$$\frac{\partial n_T}{\partial t} = \nabla \cdot \left( n_T \mathbf{v} - D \nabla n_T \right) + s$$
Trace tritium: $\rho^*$ scan in Type I ELMs

- Low triangularity shape. Current varied in the range $I_p = 2 - 2.75$ MA
- 3 point scan with inner ($x=0-0.45$) and outer ($x=0.65-0.85$) measurements

$D_{\text{inner}} / B_0 \propto \rho^{*3.22\pm0.62}$

$D_{\text{outer}} / B_0 \propto \rho^{*1.90\pm0.38}$

- Gyro-Bohm like behaviour
- Bohm like behaviour
- Both results are consistent with the 1997 discharges
Trace tritium: $\beta$ and $\nu^*$ scan results

- Two point $\beta$ scan
  
  \[D_{\text{inner}} \propto D_{g-\text{Bohm}} \beta^{-0.34 \pm 0.08}\]
  
  \[D_{\text{outer}} \propto D_{\text{Bohm}} \beta^{-0.55 \pm 0.09}\]

- Two point $\nu^*$ scan
  
  \[D_{\text{inner}} / B_0 \propto \nu^*^{-0.51 \pm 0.17}\]
  
  \[D_{\text{outer}} / B_0 \propto \nu^*^{-0.40 \pm 0.15}\]

- Fit to outer data for 9 shots gives
  
  \[D_{\text{ELMy}} / B_0 \propto \rho^{2.4} \beta^{-1.06} \nu^*^{-0.13} q^{1.81}\]

- The $\nu^*$ results is more ambiguous, but $\beta \uparrow \Rightarrow D_T \downarrow \Rightarrow \tau_T \uparrow$

- Across whole database \[D_T / \chi = 0.3 - 1.5\]
Summary of experimental results

- The $\rho^*$, $\beta$ and $\nu^*$ results for thermal transport may be summarised as:

  \[ B \tau_E \propto \rho^* -3.1 \pm 0.5 \quad \beta^{0.0 \pm 0.1} \quad \nu^* -0.35 \pm 0.05 \]

  - gyro-Bohm
  - Electrostatic
  - Collisional

- The $\rho^*$, $\beta$ and $\nu^*$ results for trace T transport may be summarised as:

  \[ B/D_T \propto \rho^* -3.2 \pm 0.62 \quad \beta^{+0.5 \pm 0.1} \quad \nu^* +0.5 \pm 0.1 \]

  - gyro-Bohm
  - Electromagnetic
  - Collisional

- With a weaker, Bohm like $\rho^*$ scaling in the outer region $x=0.65-0.85$

- Positive effect of $\beta$ on trace T confinement. Similar behaviour seen for trace helium \[\text{[C C Petty et al (2004)]}\]
Transport modelling for trace tritium discharges

- gyro-Bohm like, ES bhvr. of thermal transport shots well described by ES models like MMM

- non ES bhvr. of trace T transport requires a EM model

- A model based on neo-classical orbits in stochastic EM fields fits with the data

D. C. McDonald et al, Particle and Energy Transport in Dedicated $\rho^*$, $\beta$ and $\nu^*$ Scans in JET ELMy H-modes, IAEA - 20th Fusion Energy Conference, Vilamoura, Portugal, 4th Nov 2004
Re-analysis of the Multi-machine Database

- PCA “Errors in variables methods” now being used to determine scaling

- $\beta$ dependence found to be strongly dependent on errors in $P$ and $W$

- The exponent of $\beta$, $\alpha_\beta$, lies in the range $-0.7 < \alpha_\beta < 0$

- $\nu^*$ correlates with $\beta$ dependence

See Cordey et al, P3-32
Consequences for ITER

- For ES model, at operating point, $+2\% \tau_E$ at $\beta_N = 1.8$
- However, scaling gives $+50\% \tau_E$ at $\beta_N = 3.0$
- Other ES models give even higher $\tau_E$
- POPCON plots show access to very high $Q$ for $\beta_N = 3.0$
- Impact of higher particle confinement, particularly for He ash, at $\beta_N = 3.0$ remains to be assessed
Summary of theory and modelling implications

• results of scans

\[ B \tau_E \propto \rho^{-3.1} \beta^{-0.0} \nu^{-0.35} \]
\[ B/D_T \propto \rho^{-3.2} \beta^{0.5} \nu^{+0.5} \]

• ES, g-Bohm
• EM, g-Bohm

• ES models, such as MMM, describe energy confinement

• Particle model based on neo-classical transport in stochastic EM fields does describe the EM beta dependence

• Candidates exist (ITG...), but describing the different particle/energy transport (\(\beta\) and \(D_T/\chi=0.3-1.5\)) in one model remains a challenge for theory.

• Improvement in the predicted \(\tau_E\) for ITER would be substantial at \(\beta_N \geq 3.0\). Particle effects to be assessed.