Modeling Of Anomalous Transport in ECRH Plasmas At HSX

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Acknowledgements: Travel Support from NIFS & ITC17/ISHW2007 - Thank You!!

ITC17/ISHW2007 Ceratopia Toki, Gifu, Japan October 17, 2007
Outline

• Transport in HSX plasma
  – Mostly anomalous

• Modeling stellarator turbulent transport – stealing from tokamaks (Weiland ITG/TEM model)
  – Using 3D linear gyrokinetics (GS2) to justify approximations using tokamak model

• 1-D predictive transport modeling of HSX profiles and confinement

• Conclusions
HSX is Helically Symmetric in |B|

- Quasihelical symmetry (QHS) reduces direct loss orbits (IAEA 2002), flow damping (PRL, 2005), and neoclassical transport (PRL, 2007)

Typical plasma parameters

- \( <n_e> \leq 6 \times 10^{12} \text{ cm}^{-3} \)
- \( T_e \sim 0.5 - 2.5 \text{ keV} \gg T_i \sim 20-100 \text{ eV} \)

\[ B = B_0 \left[ 1 - \varepsilon_H \cos(N - m\ell) \right] \]

\[ B = B_0 \left[ 1 - \varepsilon_H \cos(N - m\ell) + \varepsilon_M \cos(N\phi) \right] \]

\[ \varepsilon_{\text{eff}} = |N - m\ell| \approx 3 \]

\[ \ell = 1 \]

\[ N = 4, m = 1 \]

\[ <R> = 1.2 \text{ m} \]

\[ <a> = 0.12 \text{ m} \]

\[ \ell = 1.05 \rightarrow 1.12 \]

\[ B_0 = 0.5 - 1.0 \text{ T} \]

ECRH

- 28 GHz
- 100 kW

\[ \nu_{\ast e} = \frac{\nu_e / \varepsilon_H^{1/2}}{\varepsilon_H^{1/2} \frac{\nu_{Te}}{q_{\text{eff}}R}} \leq 0.1 \]

→ Opportunity to study electron heat transport in LMFP
Reduction of Core Neoclassical Transport is Observed with Quasihelical Symmetry

• Similar $T_e$ achieved in QHS with **half the power** of Mirror
  → Neoclassical $\chi_e$ reduced in core via quasihelical symmetry (reduced $1/\nu$ ripple transport)

• Transport is anomalous over most of minor radius
Modeling Anomalous Transport

• “State of the art” drift wave turbulent transport models (ITG/TEM/ETG) exist for tokamaks (MMM / Weiland, IFS-PPPL, GLF23, TGLF)

• These are quasi-linear transport models \( (\gamma_{\text{lin}}/k_{\perp}^2) \) that have been tweaked to best match non-linear simulations
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- A number of 3D linear & non-linear stability calculations (ITG/TEM/ETG) now exist (Rewoldt et al.; Kendl & Wobig; Jost et al.; Belli et al.; Jenko, Kendl, Merz; Rafiq, Nadeem, et al.; Kuroda et al.; Sugama et al.; Yamagishi et al.; + others)

- However, no anomalous (ITG/TEM/ETG) transport models (usable for predictive simulations) have been formally developed for generic 3D stellarator configurations

→ No non-linear simulations for HSX (previous linear calculations by Jost; Rafiq; Rewoldt)
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REMAINDER OF THIS TALK

• Test of the axisymmetric Weiland ITG/TEM anomalous transport model for dominant electron heated HSX stellarator plasmas

• Beginning tests of the validity of the Weiland ITG/TEM model against 3D gyrokinetic linear stability calculations (GS2)
GS2 Is Used For Stellarator Microstability

- Flux tube gyrokinetic code in ballooning coordinates (Kotchenreuther et al., 1995; Dorland et al., 2000)
  - Initial value (can do non-linear)
  - 3D equilibrium input (shaped tokamak or stellarator, Belli et al., 2001)
  - Electromagnetic ($\beta$)
  - Momentum conserving collision operator
  - No assumptions on $k_{\perp}$ (ITG/TEM/ETG)

- Used for 12+ years by 30+ users for analysis on numerous tokamaks
- Benchmarked in numerous scenarios, including stellarator configurations (NCSX, HSX)
- We are using GS2 electrostatically for linear calculations → compare to Weiland model

NCSX linear stability (Belli et al., APS 2001)

QHS 3D microstability

QHS linear stability

Rewoldt et al. (2005)
What is the Weiland Model?

• A linear fluid model for toroidal ITG and TEM instabilities, including:
  • Multiple ion ITG
  • Collisionless TEM
  • Collisional stabilization of TEM
  • Electromagnetic (finite $\beta$)
  • Parallel ion dynamics (momentum transport)

• Heat and particle transport predictions come from quasi-linear mixing length estimates which compare well to limited non-linear simulations (Nordman et al., 1990; Dimits et al., 2000)

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• For HSX, using collisionless electrostatic form including particle, and ion and electron heat transport

• Geometry parameters required are trapped electron fraction ($f_i$) and “appropriate” toroidal drift scale length ($L_B = R$ for a tokamak)

\[
\begin{bmatrix}
\omega_r, \gamma \\
\kappa_e, \kappa_i, D
\end{bmatrix} = \rho_s^2 c_s \cdot F \left( \frac{a}{L_{Te}}, \frac{a}{L_{Ti}}, \frac{a}{L_n}, \frac{a}{L_B}, \frac{T_e}{T_i}, f_i, k_{\perp}\rho_s \right)
\]

• What are the “appropriate” geometry parameters for HSX?
Microstability Estimates Can Be Made Using Axisymmetric Models With “Quasisymmetric” Approximation

- 3D stability calculations find most unstable eigenmodes (ITG/TEM) ballooning in the low field, bad curvature region in HSX (also seen in Rewoldt 2005; Rafiq 2006)

- Dominant particle trapping comes from helical ripple, $\varepsilon_H (0.14 \cdot r/a = 1.4 \cdot r/R)$

- Reduced connection length, $L_c = q_{\text{eff}} R = R/|N-m_1| \approx R/3$, leads to very low collisionality electrons across the minor radius $\rightarrow$ CTEM ($T_e >> T_i$)

  $$v_{*e} = \frac{v_e / \varepsilon_H}{\varepsilon_H^{1/2} \frac{v_{Te}}{q_{\text{eff}} R}} \leq 0.1$$

- Normal curvature rotates helically, with bad curvature following the location of low field strength

  - $\kappa_{N,\text{max}} \sim 1/45 \, \text{cm}^{-1} \neq 1/R$ (R=120 cm)

  - To account for toroidal drifts in drift wave models, $R \rightarrow R/3$
Comparison Of Linear Growth Rates Between Weiland Model And 3D Gyrokinetics

- Weiland ITG/TEM model is used with approximations:
  \[ f_i \approx \sqrt{2\varepsilon_T} \rightarrow \sqrt{2\varepsilon_H}, \quad \kappa_N \& |\nabla B|/B \sim 1/R \rightarrow 3/R \]

- Linear growth rates from Weiland and 3D GS2 are in agreement near experimental gradients \((a/L_n, a/L_{Te} = 2 \rightarrow 5, \text{largest difference } \sim 30\%)\)
- Larger deviations exist near marginal stability
- Weiland growth rates \(2\times\) smaller without “quasisymmetric” approximation
Predictive 1D Transport Modeling Is Performed Using “Multi-Mode” Approach

- \((\chi, D) = (\chi, D)_{\text{neoclassical}} + (\chi, D)_{\text{anomalous}}\)
  - Neoclassical from DKES (Hirshman et al., 1986)

- Electron energy source from ECRH
  - Profile from ray tracing
  - Total absorbed power from measurement

- Particle source adjusted to minimize difference in \(n_e\) (within factor of ~2 of DEGAS calculations)

- Radiation, electron-ion coupling negligibly small
- Boundary conditions from experiment

- 1D flux-surface averaged transport equations integrated

\[
\frac{\partial}{\partial t} n + \frac{1}{V'} \frac{\partial}{\partial \rho} V' \left( - D \frac{\partial n}{\partial \rho} \left\langle |\nabla \rho|^2 \right\rangle + V^{(n)} n \left\langle |\nabla \rho| \right\rangle \right) = \sum S(\rho)
\]

\[
\frac{3}{2} \frac{n}{\partial t} T + \frac{1}{V'} \frac{\partial}{\partial \rho} V' \left( - n \chi \frac{\partial T}{\partial \rho} \left\langle |\nabla \rho|^2 \right\rangle + V^{(nT)} n T \left\langle |\nabla \rho| \right\rangle \right) = \sum \frac{1}{e} P(\rho)
\]
Density Profiles In Good Agreement

• Core $T_e$ underpredicted in QHS

![Graph showing density and temperature profiles in QHS, with $P_{ECRH} = 44$ kW]
Density Profiles In Good Agreement

• Core $T_e$ underpredicted in QHS
• Global confinement predicted within 10%

![Graph showing density profiles and temperature profiles for QHS and Experiment with PECRH = 44 kW.](image)

**ITER Physics Basis Figures of Merit (1999)**

$$\text{STD} (n_e) = \sqrt{\frac{1}{N} \sum_j (n_e^{\text{sim}}(\rho_j) - n_e^{\exp})^2}$$

= 9.1%

$$\text{STD} (T_e) = \sqrt{\frac{1}{N} \sum_j (T_e^{\text{sim}}(\rho_j) - T_e^{\exp})^2}$$

= 40%

<table>
<thead>
<tr>
<th>$P_{ECRH}$ (kW)</th>
<th>$\tau^{\exp}$ (ms)</th>
<th>$\tau^{\text{sim}}$ (ms)</th>
<th>$\Delta\tau/\tau^{\exp}$</th>
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Predicted Confinement Time Scaling Close To Experiment

- Experimental power scaling slightly weaker than simulation
  \[ \tau_{E,\text{exp, diamagnetic}} \sim P^{-0.36} \]
  \[ \tau_{E,\text{sim}} \sim P^{-0.57} \]

QHS
\[ B = 1 \text{T} \]
\[ <n> \sim 4 \times 10^{12} \text{ cm}^{-3} \]
3D Linear Stability Similar Between QHS & Mirror

- |B| no longer symmetric
- Local geometry similar in ballooning region

→ Results in similar growth rates
- Similar to results with approximate DTEM response in HSX (Rafiq & Hegna, Phys. Plasmas 2006)
Profiles In Reasonable Agreement for Mirror

- Overall confinement overpredicted at low power

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STD ($n_e$) = 11%

STD ($T_e$) = 30%
Summary

• Anomalous transport is significant in both quasisymmetric (QHS) and non-symmetric (Mirror) configurations
  – With low collisionality electrons, CTEM expected to be dominant instability

• First test of Weiland ITG/TEM model for dominant electron heated stellarator plasmas
  – With “quasisymmetric” approximations, linear growth rates from Weiland model agree within ~30% of 3D gyrokinetic (GS2) linear stability calculations (near experimental gradients)
  – Density profiles and QHS energy confinement times predicted within ~10%
  – Electron temperature profiles further off (~40%)

\[ \Delta \gamma_{\text{lin}} < 30\% \]
\[ \sigma_{n_e}, \sigma_{\tau} < 10\% \]
\[ \sigma_{T_e} < 40\% \]