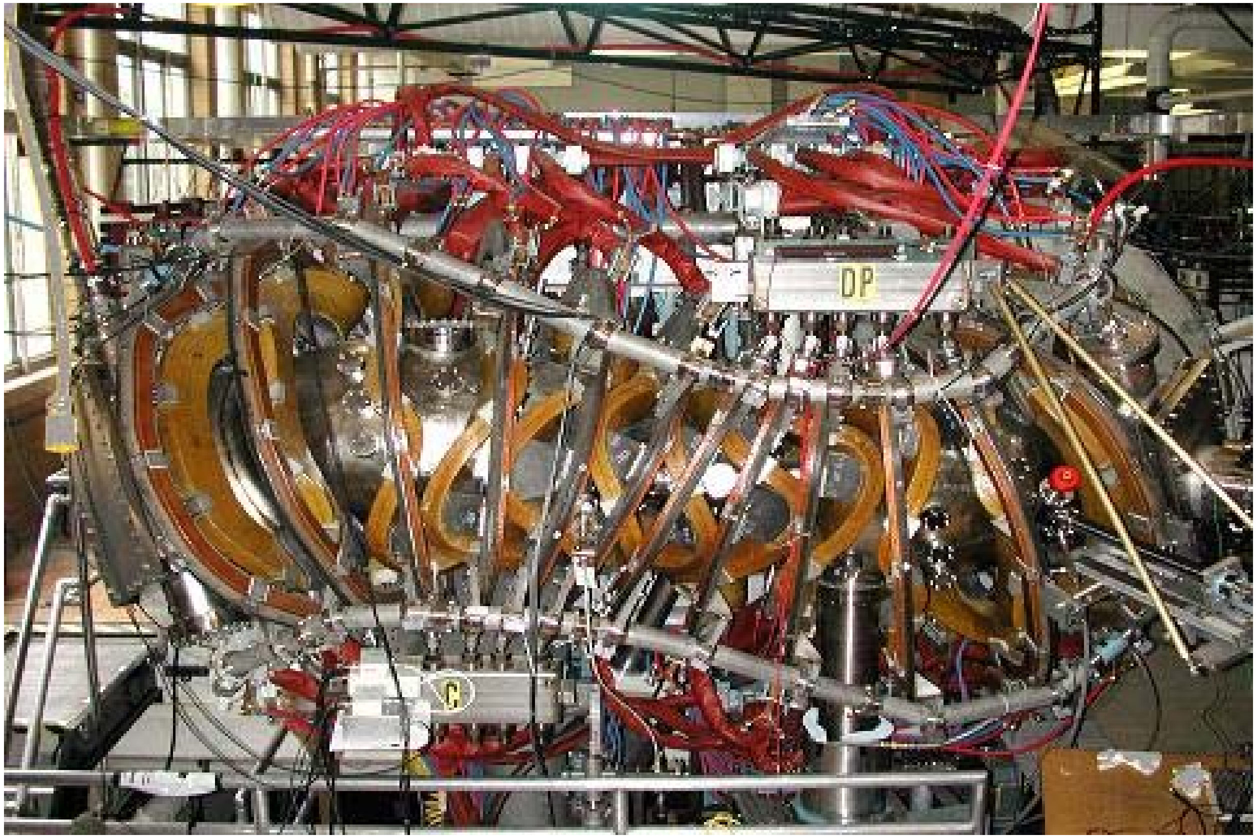
Modeling Of Anomalous Transport in ECRH Plasmas At HSX



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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

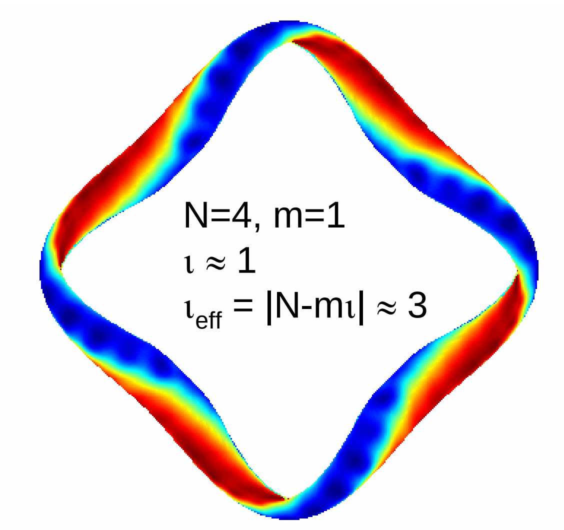
- 1-D predictive transport modeling of HSX profiles and confinement

- 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)

QHS



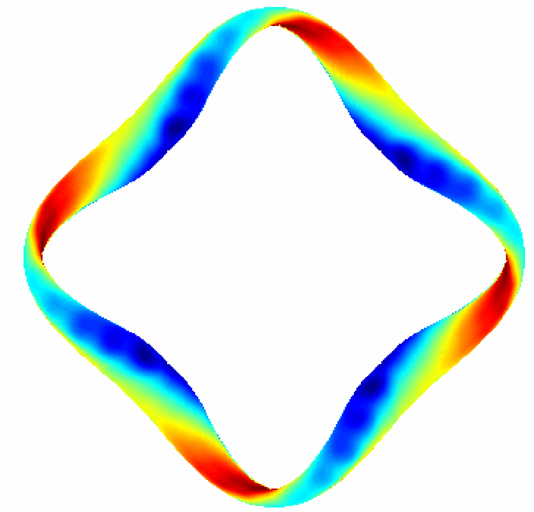
N=4, m=1

$\iota \approx 1$

$\iota_{eff} = |N - m\iota| \approx 3$

$$B = B_0\left[1 - \underline{\varepsilon_h} \cos(N - m\iota)\phi\right]$$

Mirror



$$B = B_0\left[1 - \underline{\varepsilon_h} \cos(N - m\iota)\phi + \underline{\varepsilon_M} \cos(N\phi)\right]$$

<R>	1.2 m
<a>	0.12 m
ι	1.05 →1.12
B_0	0.5 -1.0 T
ECRH 28 GHz	100 kW

Typical plasma parameters

- $\langle n_e \rangle \leq 6 \times 10^{12}$ cm^{-3}
- T_e ~ 0.5 - 2.5 keV $>>$ T_i ~ 20-100 eV

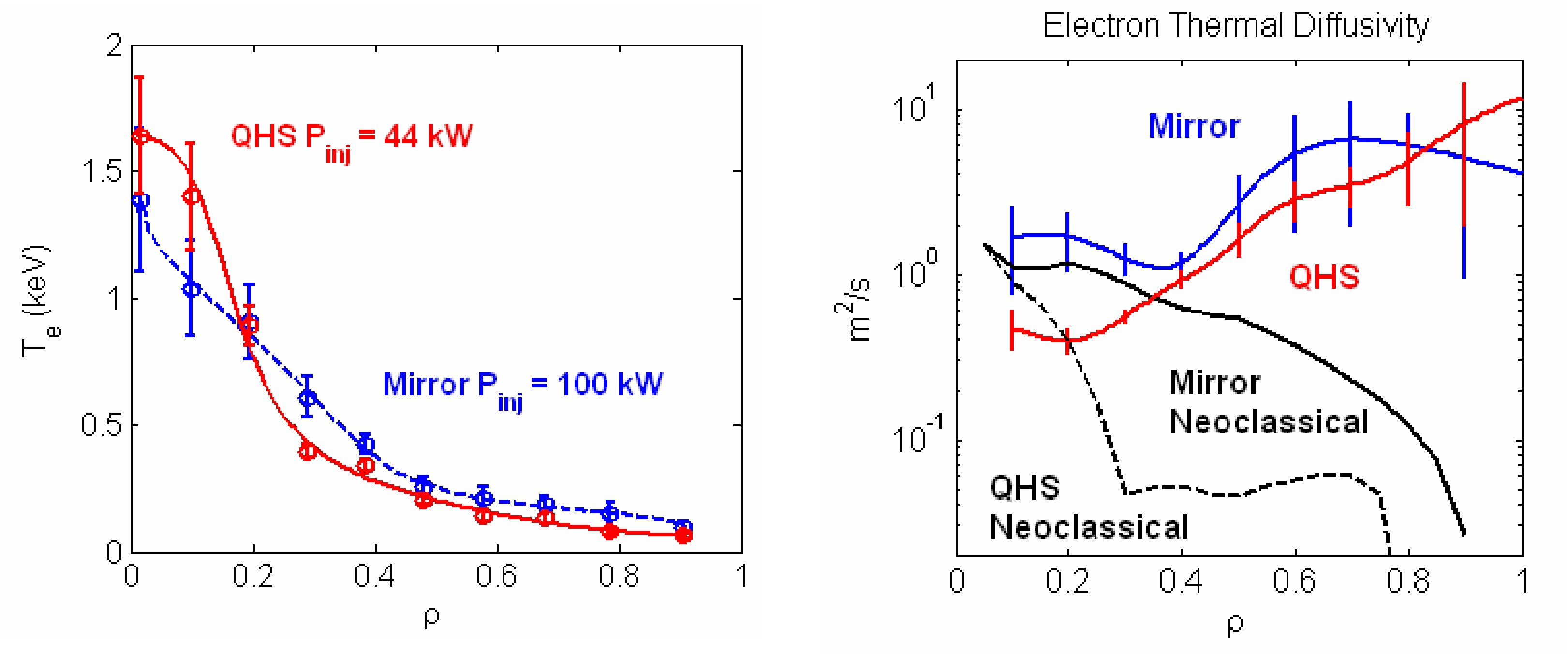
→ Opportunity to study electron heat transport in LMFP

$$\nu_{*e} = \frac{\nu_e / \varepsilon_H}{\varepsilon_H^{1/2} \dfrac{v_{T_e}}{q_{eff} R}} \leq 0.1$$

Reduction of Core Neoclassical Transport is Observed with Quasihelical Symmetry

- Similar T_e achieved in QHS with **half the power** of Mirror

→ Neoclassical χ_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 ($\gamma_{lin}/k_\perp^2$) that have been tweaked to best match non-linear simulations

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- These are quasi-<u>linear</u> transport models ($\gamma_{lin}/k_{\perp}^{2}$) that have been tweaked to best match non-linear simulations
- 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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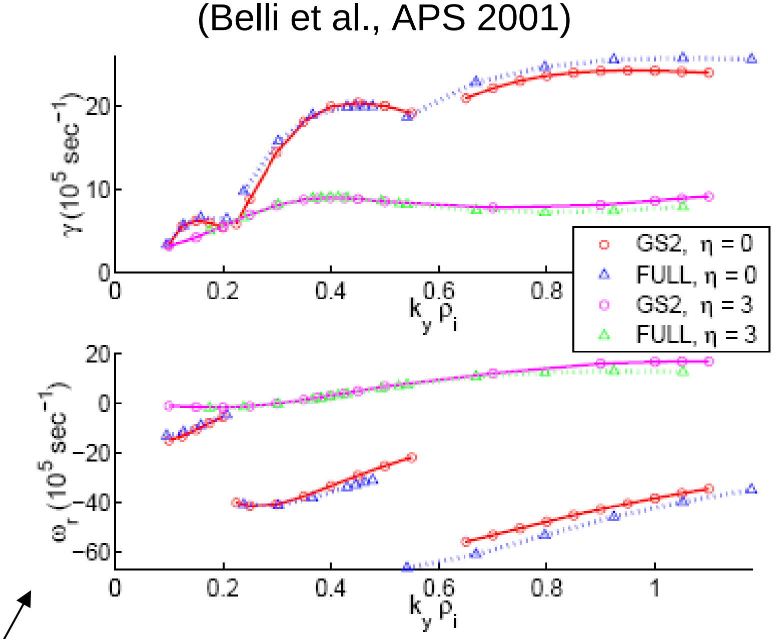
REMAINDER OF THIS TALK

- 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)

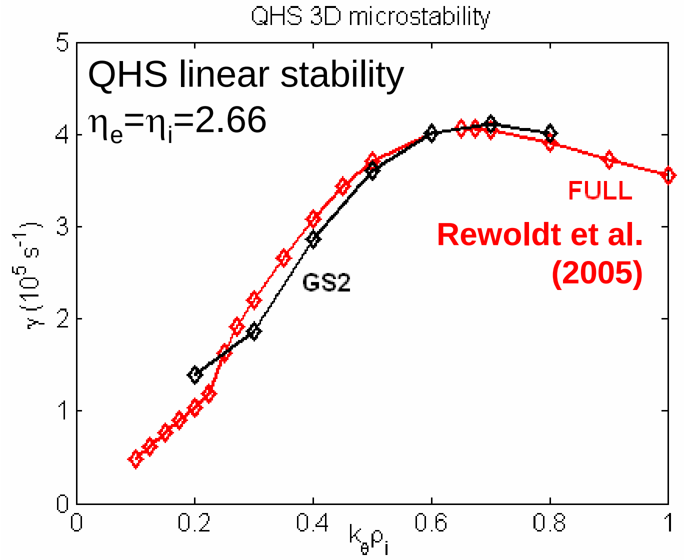
GS2 Is Used For Stellarator Microstability

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

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



- 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**



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 β)
  - 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)

- Easy to solve (quick) – useful for predictive transport modeling

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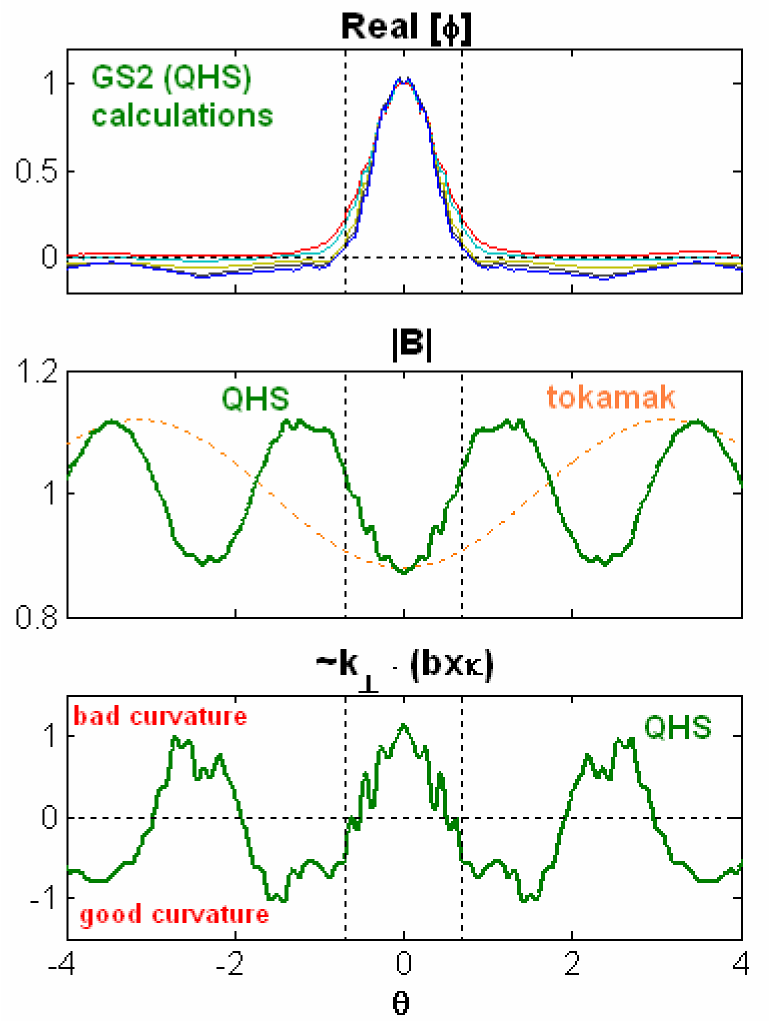
- For HSX, using collisionless electrostatic form including particle, and ion and electron heat transport
- Geometry parameters required are trapped electron fraction (f_t) and “appropriate” toroidal drift scale length ($L_B = R$ for a tokamak)

$$\begin{bmatrix} \omega_r, \gamma \\ \chi_e, \chi_i, D \end{bmatrix} = \frac{\rho_s^2 c_s}{L_n} \cdot F\left(\frac{a}{L_{Te}}, \frac{a}{L_{Ti}}, \frac{a}{L_n}, \frac{a}{L_B}, \frac{T_e}{T_i}, f_t, k_\perp \rho_s \right)$$

- 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, ε_H ($0.14 \cdot r/a = 1.4 \cdot r/R$)
- Reduced connection length, $L_c = q_{eff}R = R/|N-m\iota| \approx R/3$, leads to very low collisionality electrons across the minor radius → CTEM ($T_e >> T_i$)

$$\nu_{*e} = \frac{\nu_e / \varepsilon_H}{\varepsilon_H^{1/2} \dfrac{v_{T_e}}{q_{eff}R}} \le 0.1$$

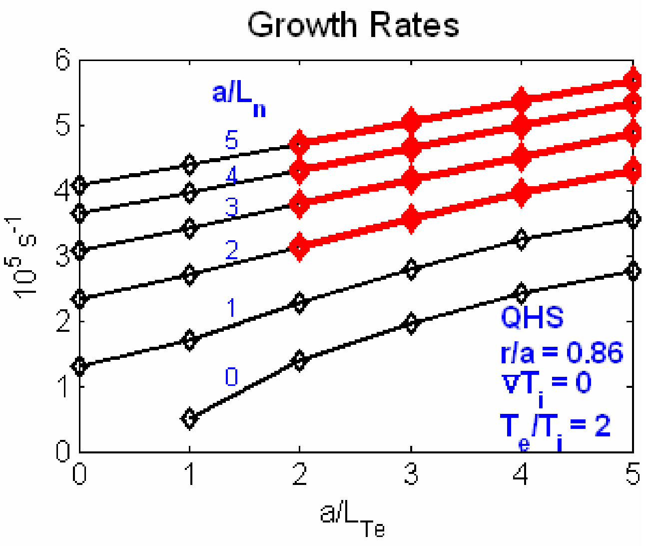
- Normal curvature rotates helically, with bad curvature following the location of low field strength
- $\kappa_{N,max} \sim 1/45\ \mathrm{cm}^{-1} \neq 1/R$ (R=120 cm)
- To account for toroidal drifts in drift wave models, R → R/3

Comparison Of Linear Growth Rates Between Weiland Model And 3D Gyrokinetics

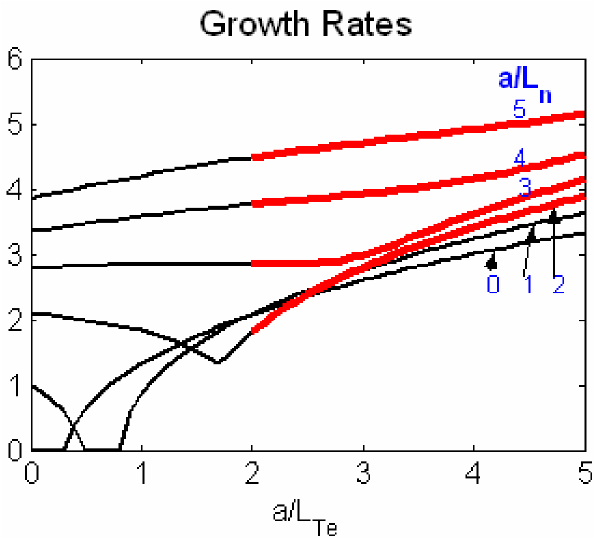
- Weiland ITG/TEM model is used with approximations:
  $f_t \approx \sqrt{2\varepsilon_T} \rightarrow \sqrt{2\varepsilon_H}$, κ_N & $|\nabla B|/B \sim 1/R \rightarrow 3/R$

- Linear growth rates from Weiland and 3D GS2 are in agreement near experimental gradients (a/L_n, $a/L_{Te} = 2 \rightarrow 5$, largest difference ~30%)
- Larger deviations exist near marginal stability
- Weiland growth rates 2× smaller without “quasisymmetric” approximation

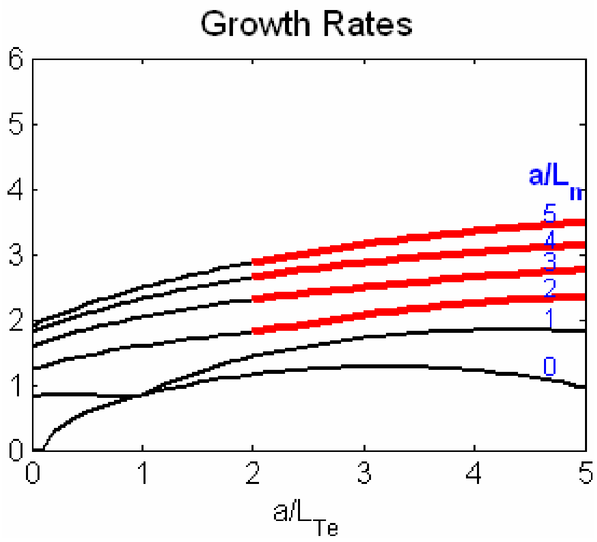
GS2 - HSX



Weiland - HSX



Weiland - TOK



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)
  - Anomalous from Weiland ITG/TEM and RBM (MMM, Bateman et al., Phys. Plasmas, 1998)

- 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

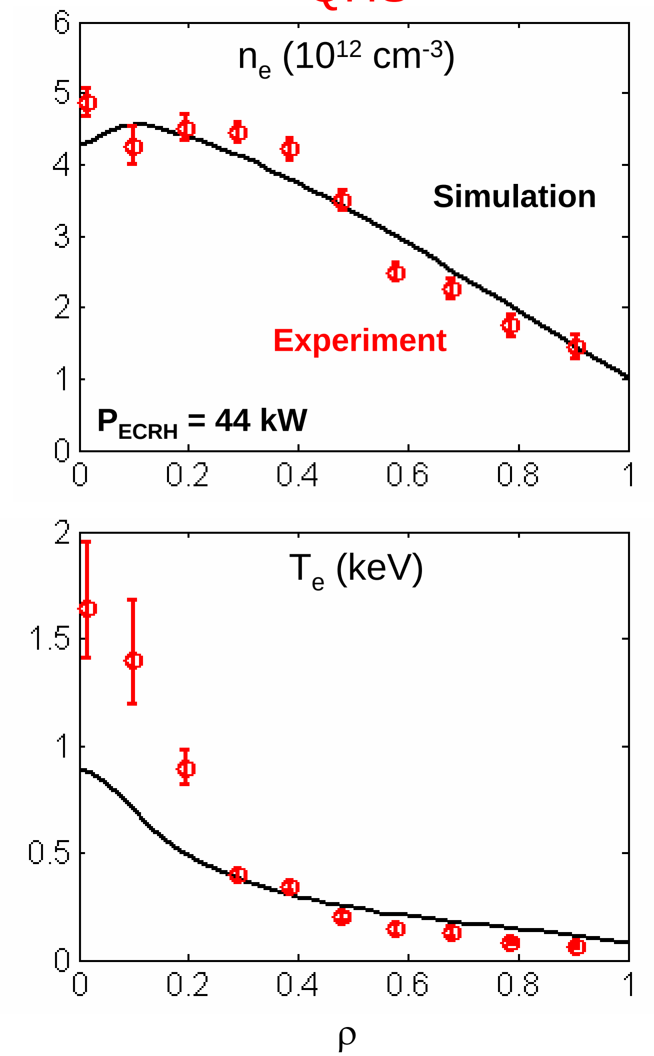
$$\frac{\partial}{\partial t} n + \frac{1}{V'}\frac{\partial}{\partial \rho} V'\left(- D\frac{\partial n}{\partial \rho}\left\langle \left|\nabla\rho\right|^2\right\rangle + V^{(n)} n\left\langle \left|\nabla\rho\right|\right\rangle\right) = \sum S(\rho)$$

$$\frac{3}{2} n \frac{\partial}{\partial t} T + \frac{1}{V'}\frac{\partial}{\partial \rho} V'\left(- n\chi\frac{\partial T}{\partial \rho}\left\langle \left|\nabla\rho\right|^2\right\rangle + V^{(nT)} nT\left\langle \left|\nabla\rho\right|\right\rangle\right) = \sum \frac{1}{e} P(\rho)$$

Density Profiles In Good Agreement

- Core T_e underpredicted in QHS

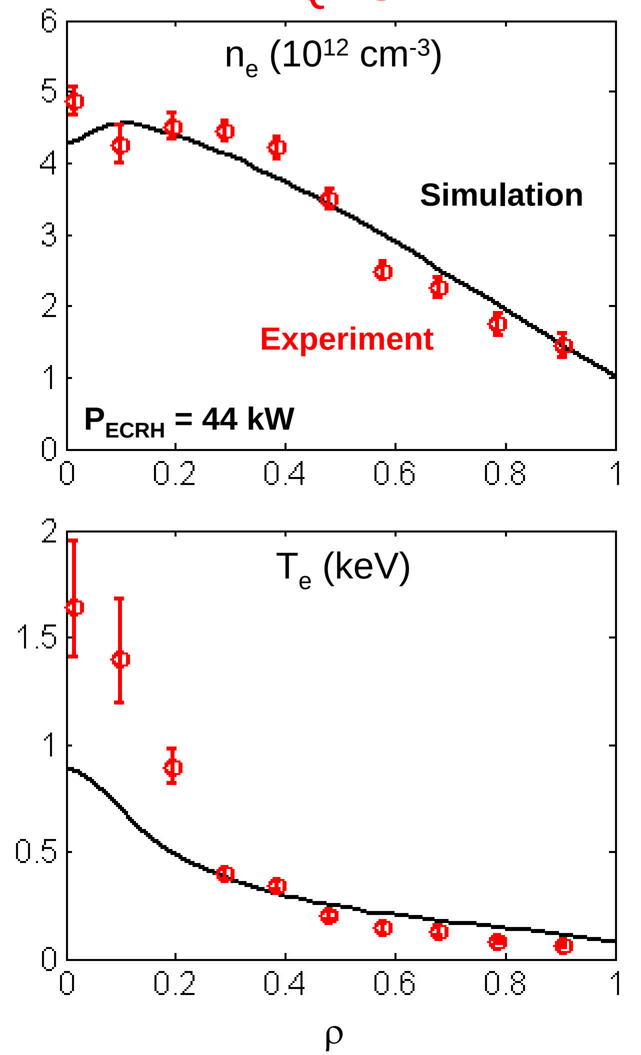
QHS



Density Profiles In Good Agreement

- Core T_e underpredicted in QHS
- Global confinement predicted within 10%

QHS



ITER Physics Basis Figures of Merit (1999)

$$\mathrm{STD}(n_e) = \frac{\sqrt{\frac{1}{N}\sum_j \left(n_e^{sim}(\rho_j) - n_{e,j}^{exp}\right)^2}}{\sqrt{\frac{1}{N}\sum_j \left(n_{e,j}^{exp}\right)^2}} = 9.1\%$$

$$\mathrm{STD}(T_e) = \frac{\sqrt{\frac{1}{N}\sum_j \left(T_e^{sim}(\rho_j) - T_{e,j}^{exp}\right)^2}}{\sqrt{\frac{1}{N}\sum_j \left(T_{e,j}^{exp}\right)^2}} = 40\%$$

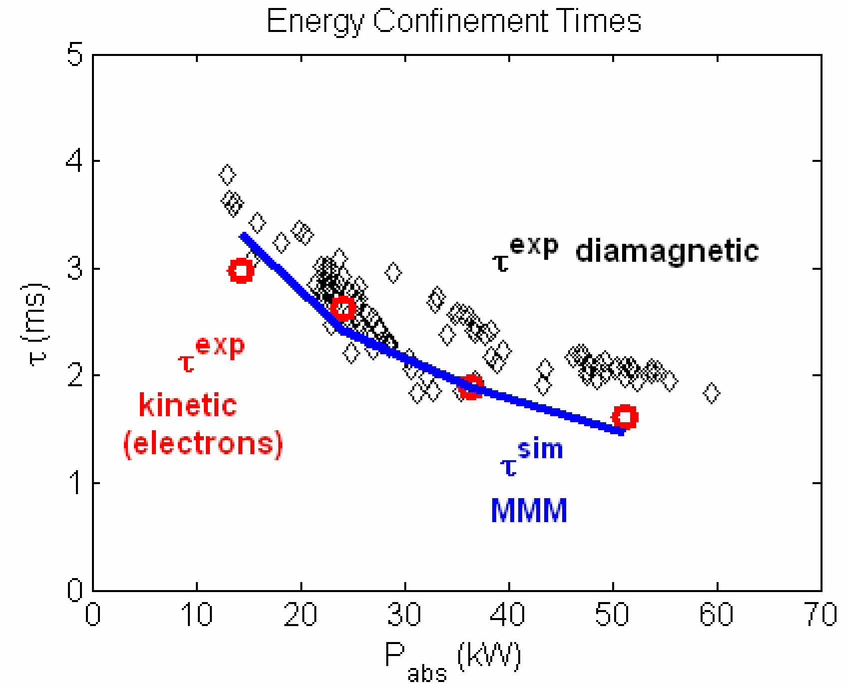
P_{ECRH} (kW)	τ^{exp} (ms)	τ^{sim} (ms)	$\Delta\tau/\tau^{exp}$
26	3.0	3.3	10%
44	2.6	2.4	-8%
70	1.9	1.9	0%
100	1.6	1.5	-6%

Predicted Confinement Time Scaling Close To Experiment

- Experimental power scaling slightly weaker than simulation

$\tau_E^{\mathrm{exp,diamagnetic}} \sim P^{-0.36}$

$\tau_E^{\mathrm{sim}} \sim P^{-0.57}$

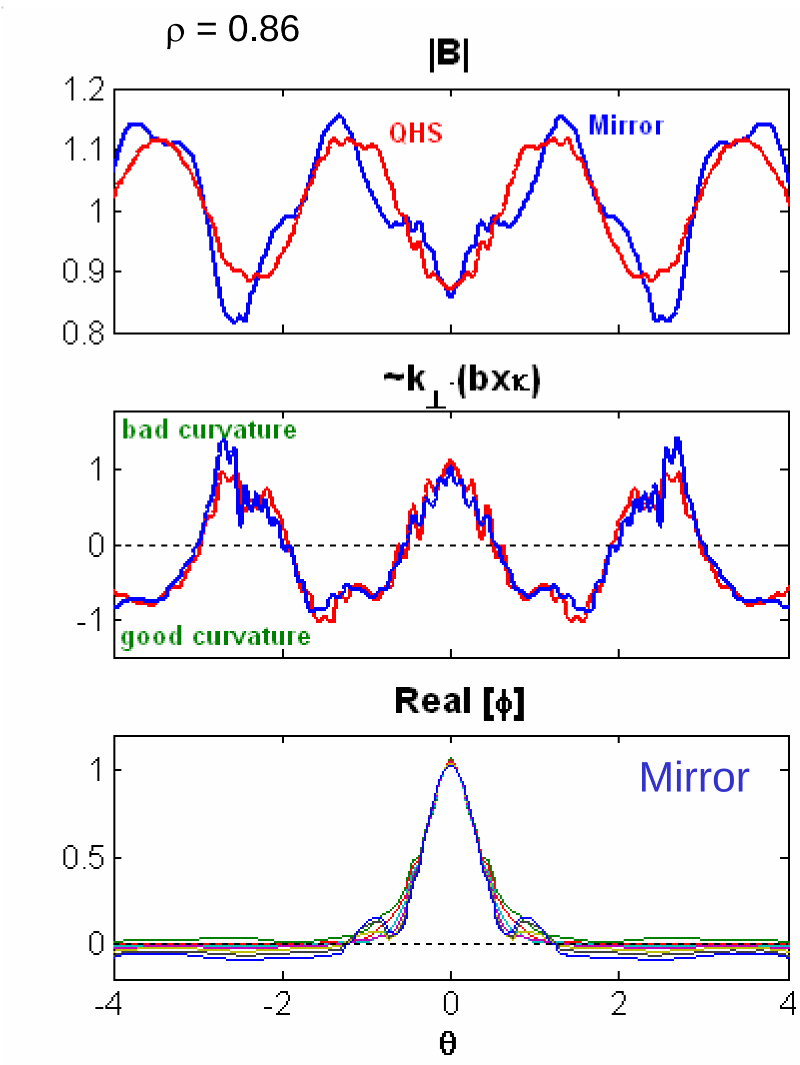


QHS

B = 1 T

$\langle n \rangle \sim 4 \times 10^{12}$ cm^{-3}

3D Linear Stability Similar Between QHS & Mirror

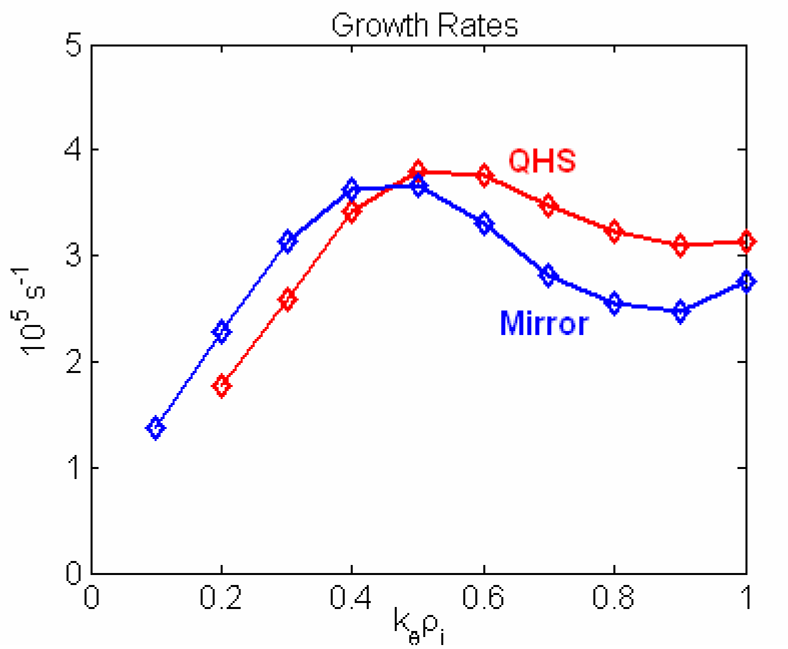


- |B| no longer symmetric
- Local geometry similar in ballooning region

→ Results in similar growth rates

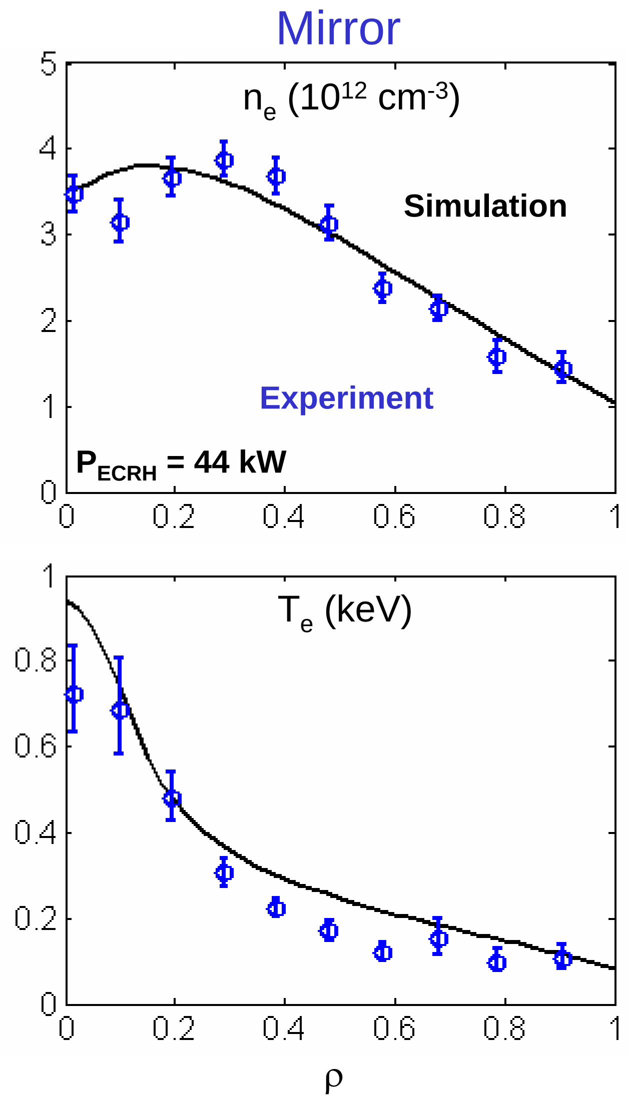
- Similar to results with approximate DTEM response in HSX (Rafiq & Hegna, Phys. Plasmas 2006)

GS2 (3D)



Profiles In Reasonable Agreement for Mirror

- Overall confinement overpredicted at low power



STD (n_e) = 11%

STD (T_e) = 30%

P_{ECRH} (kW)	τ^{exp} (ms)	τ^{sim} (ms)	$\Delta\tau/\tau^{exp}$
26	1.9	3.1	63%
44	1.9	2.4	26%
70	1.6	1.8	13%
100	1.6	1.6	0%

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, <u>linear growth rates</u> 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%)

$\Delta\gamma_{lin} < 30\%$

$\sigma_{ne},\sigma_{\tau} < 10\%$

$\sigma_{Te} < 40\%$