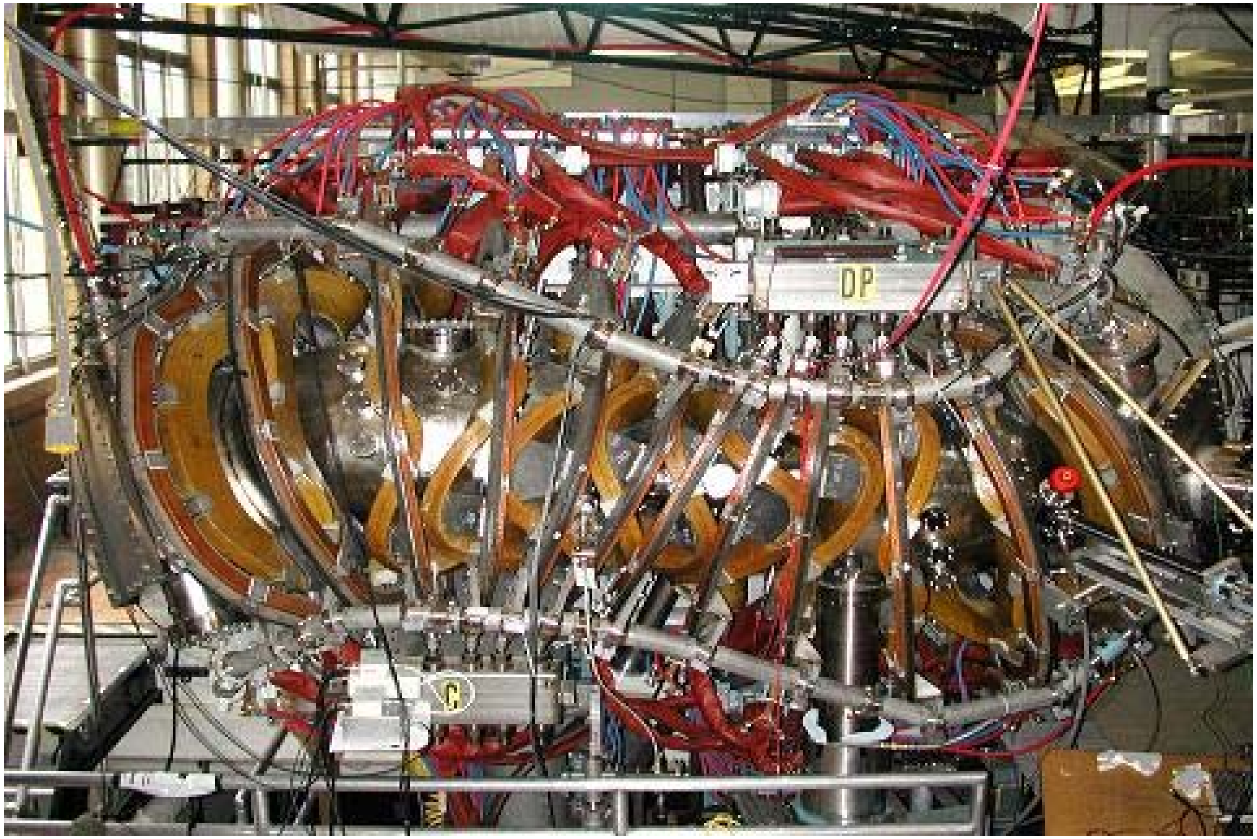
Turbulence Measurements and Theory Based Transport Modeling of ECRH Plasmas in HSX



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Acknowledgements
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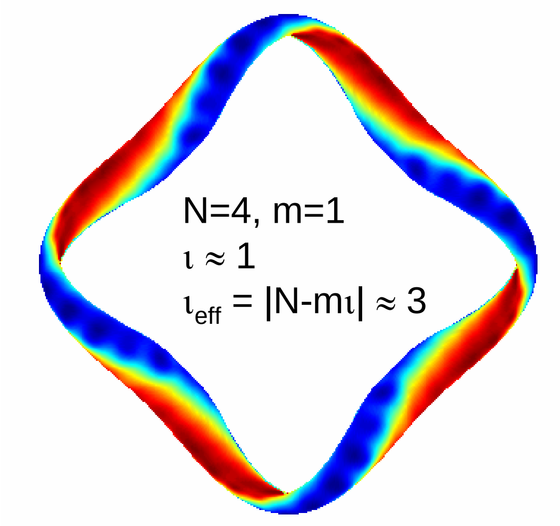
Nuclear Engineering/Engineering Physics, UW-Madison

US/Japan Workshop, Auburn, AL 2006

HSX is Helically Symmetric in |B|

QHS



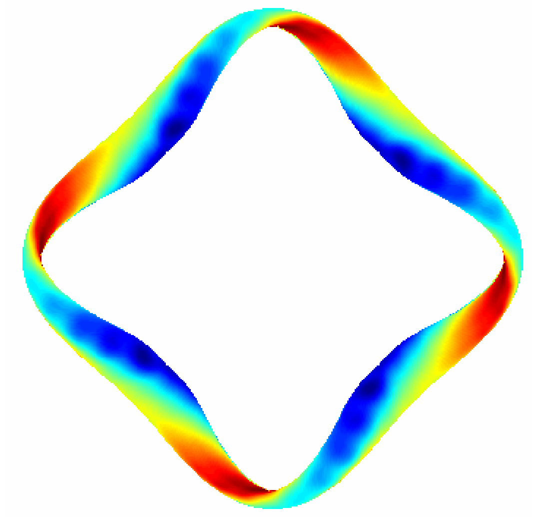
N=4, m=1

$\iota \approx 1$

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

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

Mirror



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

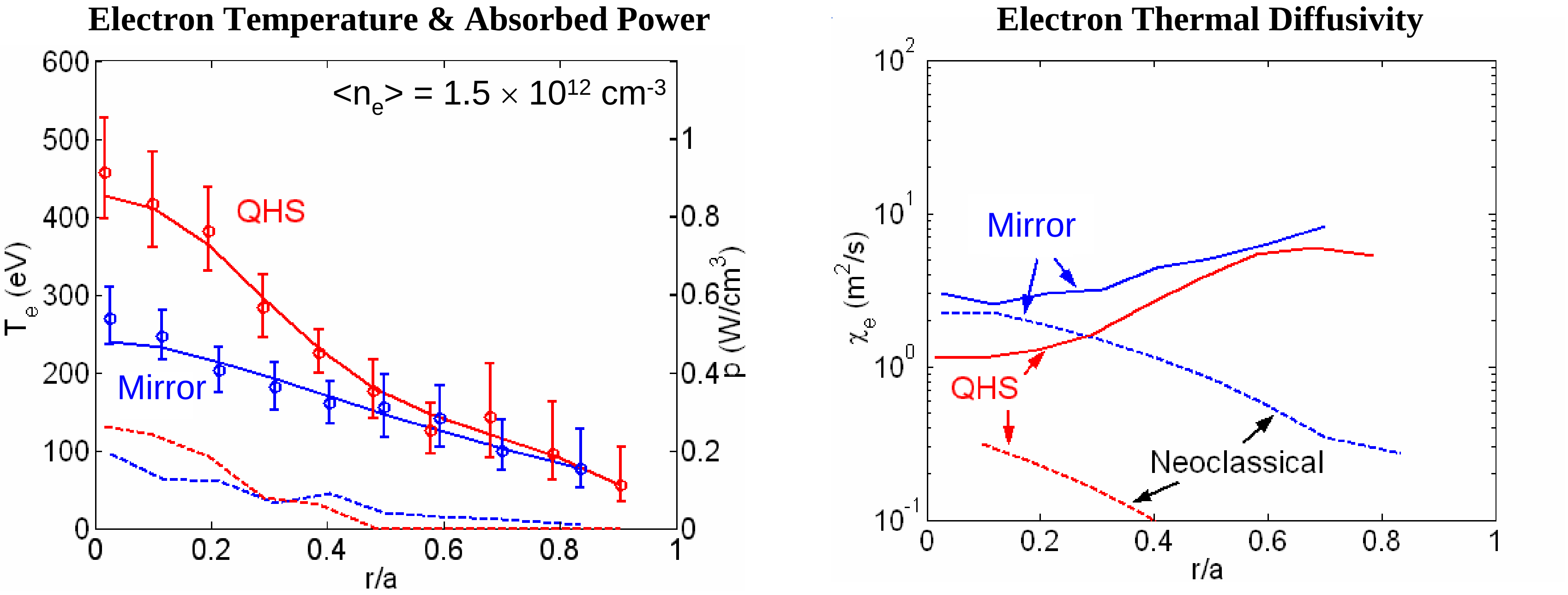
<R>	1.2 m
<a>	0.12 m
ι	1.05 →1.12
B_0	0.5 T
X2 ECRH	100 kW

TRANSPORT GOALS OF HSX

- Demonstrate reduced transport via quasisymmetry
  - Demonstrate reduction of neoclassical transport
  - Is anomalous transport also reduced?

Reduction of Core Neoclassical Transport is Observed with Quasisymmetry

- B=0.5 T, P_{inj} = 50 kW
- Central electron temperature is ~200 eV hotter with same absorbed power
- Anomalous transport is significant in both configurations → similar at the edge



(J.M. Canik, ISW 2005)

This Talk

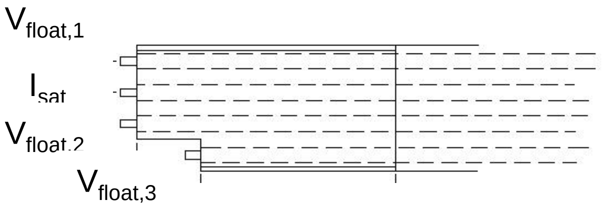
→ Investigate turbulence characteristics in both QHS & Mirror

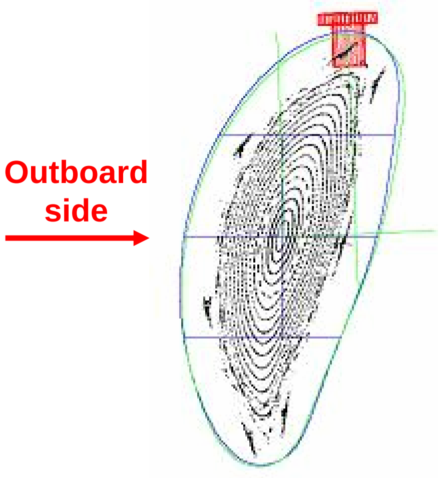
→ Compare to linear instability estimates

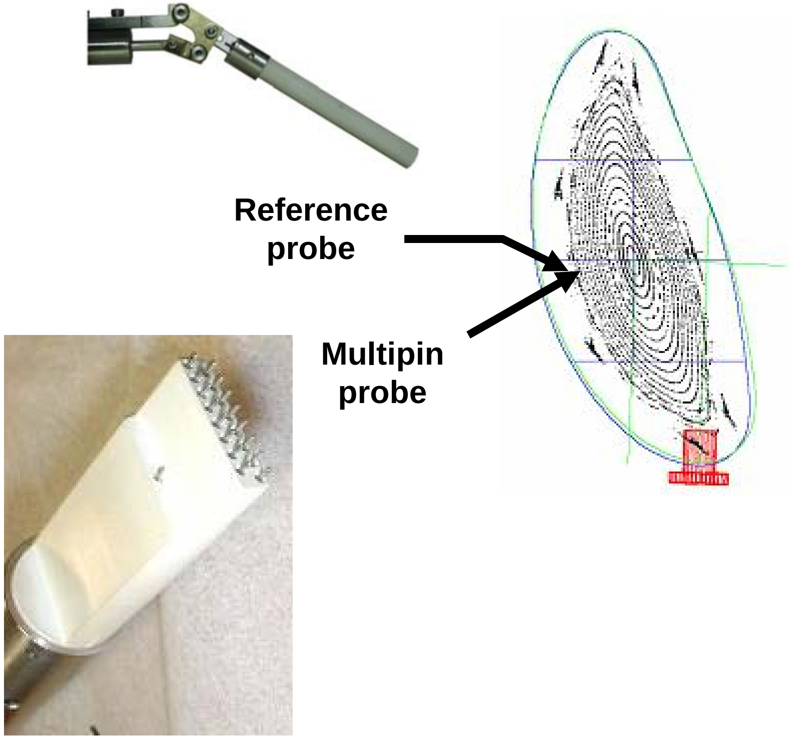
→ Test theory based TEM transport model

Langmuir Probes Used for Edge Measurements

- Two probe configurations for measuring turbulence characteristics
  - 4 pin probe to measure wavenumber, cross-phase, transport, radial electric field
  - 16 pin probe to measure 2D correlation functions

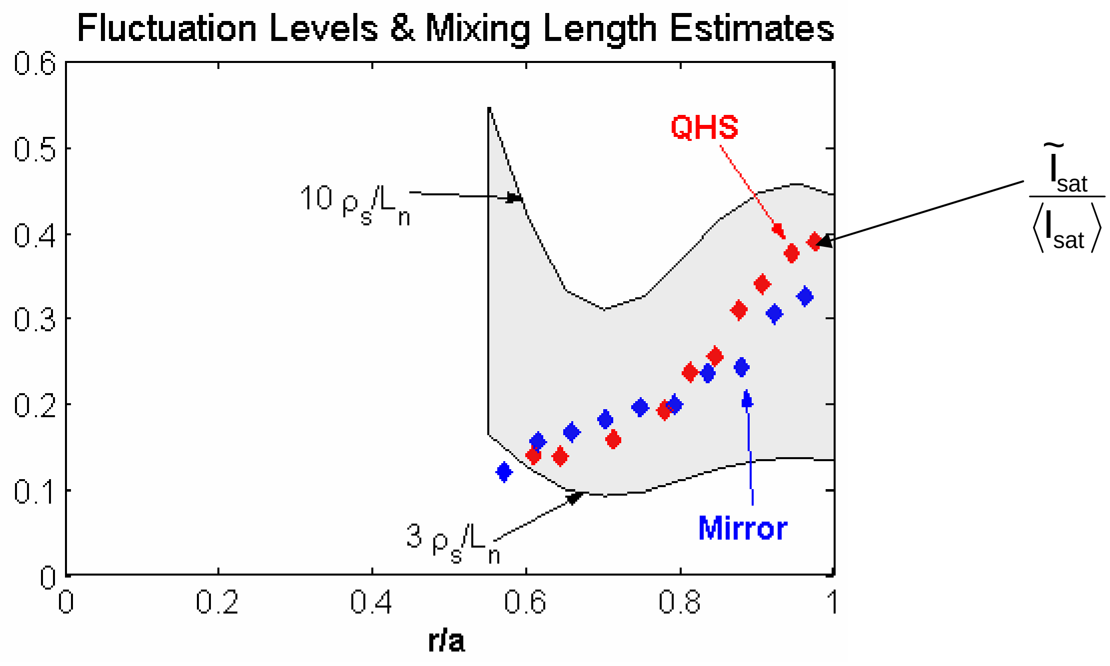






- Following turbulence data acquired at same injected power (50 kW)

Fluctuation Levels are Similar in QHS & Mirror Edge Plasmas



$\frac{\tilde{I}_{sat}}{\langle I_{sat} \rangle}$

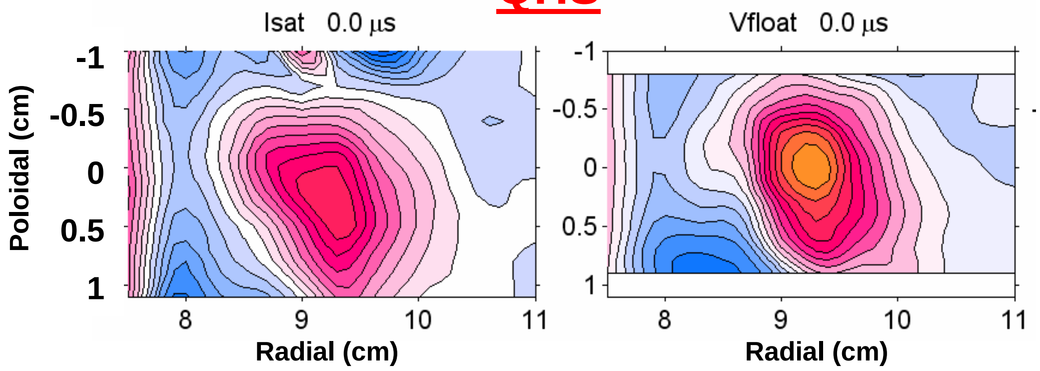
- Fluctuation levels fall within standard mixing-length estimates $\frac{\tilde{I}_{sat}}{\langle I_{sat} \rangle} \sim 3 - 10 \frac{\rho_s}{L_n}$

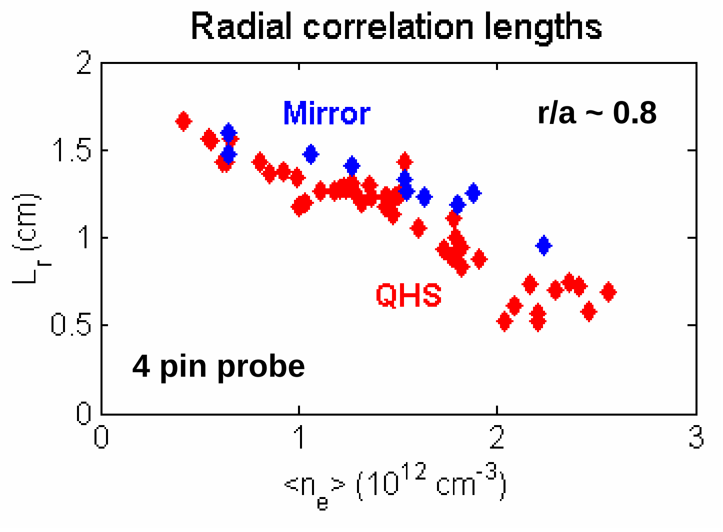
- Normalized potential and density fluctuations are similar $\left| \frac{\tilde{\varphi}}{T_e} \right| \sim \left| \frac{\tilde{n}}{n_0} \right|$

Correlation Lengths and Times are Similar in QHS and Mirror Edge Plasmas

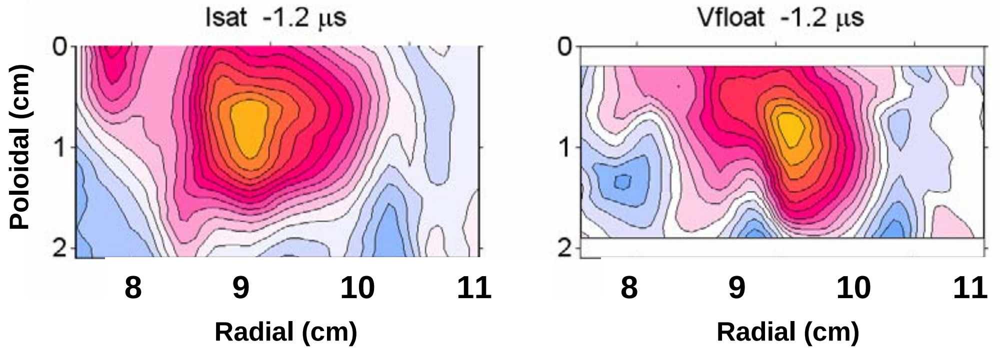
- 2D correlation functions are ~ isotropic
- $L_r \approx \langle k_\theta \rangle^{-1}$ and decreases with density (decreasing edge temperature)
- Some evidence for $\langle k_\perp \rangle \rho_s \sim$ const ($\approx$0.15)

QHS



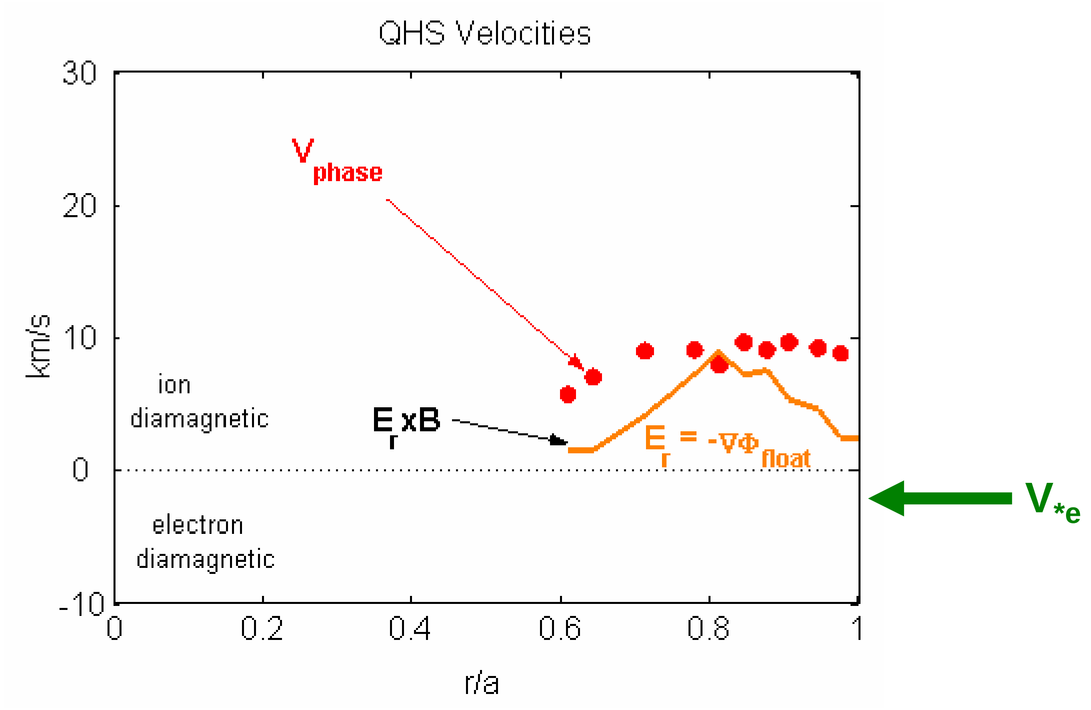


Mirror



Measured Phase Velocities are in the Ion Diamagnetic Direction

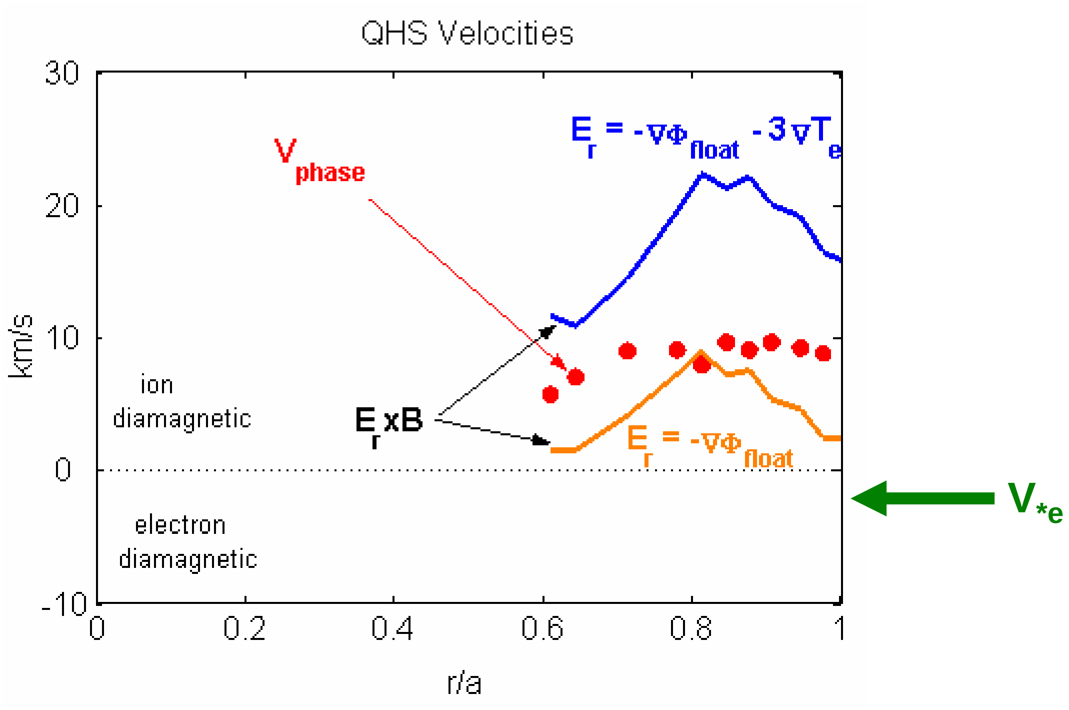
- Mode velocity (V_{phase} - $V_{E\times B}$) in ion diamagnetic direction with E×B velocity calculated from floating potential profile ($E_r = -\nabla\Phi_f$)



Mode Velocities are in the Electron Diamagnetic Direction

- Mode velocity (V_{phase} - $V_{E\times B}$) in ion diamagnetic direction with E×B velocity calculated from floating potential profile ($E_r = -\nabla\Phi_f$)

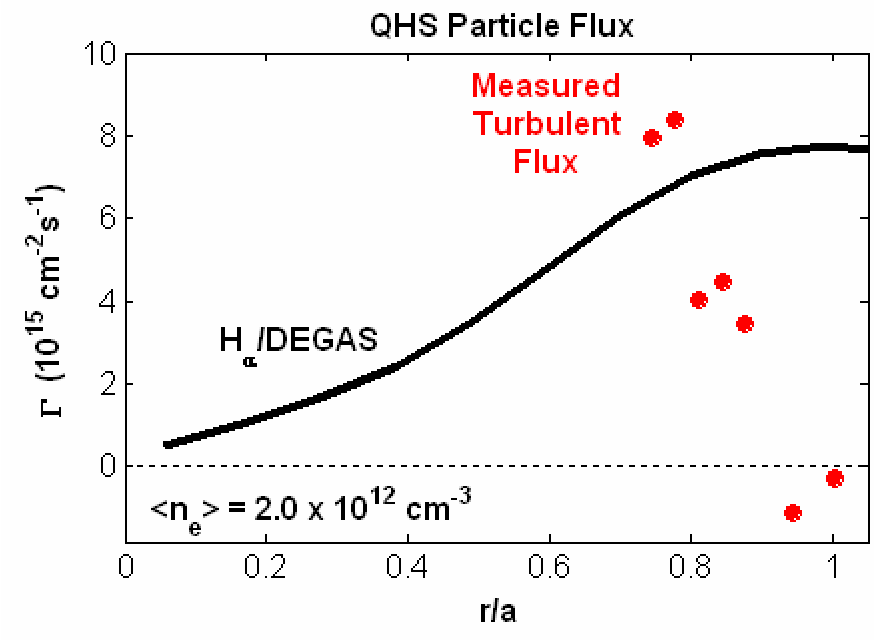
- If an estimated ∇T_e accounted for ($E_r = -\nabla\Phi_p = -\nabla\Phi_f - 3\nabla T_e$), mode velocity in electron diamagnetic direction



Profile of Turbulent Particle Flux is Different than Neutral Modeling

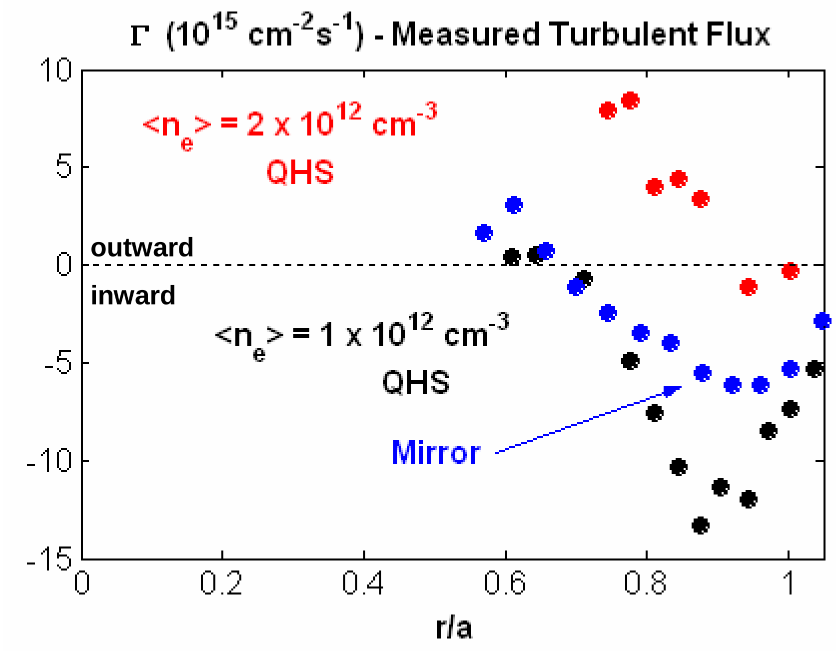
- Particle flux found from H_α measurements and 3D DEGAS neutral gas modeling

- Measured turbulent flux ($\Gamma = \tilde{n}\tilde{\Phi}k_y \sin(\alpha_{n\varphi})/B$) similar in magnitude (~10^{15} $cm^{-2}s^{-1}$) but profile shape different – common with probe measurements



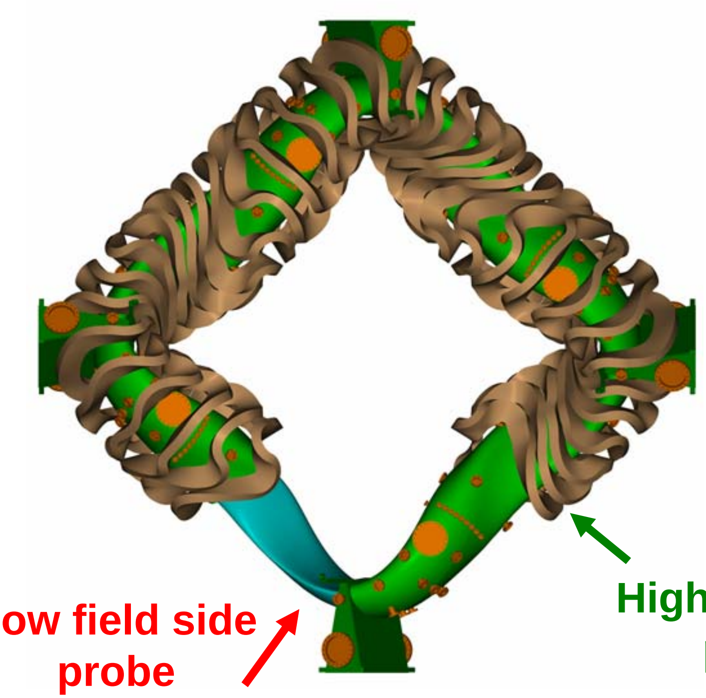
Measured Turbulent Particle Transport is Inward at Low Density for Both QHS & Mirror

- Measured turbulent driven flux reverses direction at low density owing to relative sign change in k_y-$\alpha_{n\varphi}$



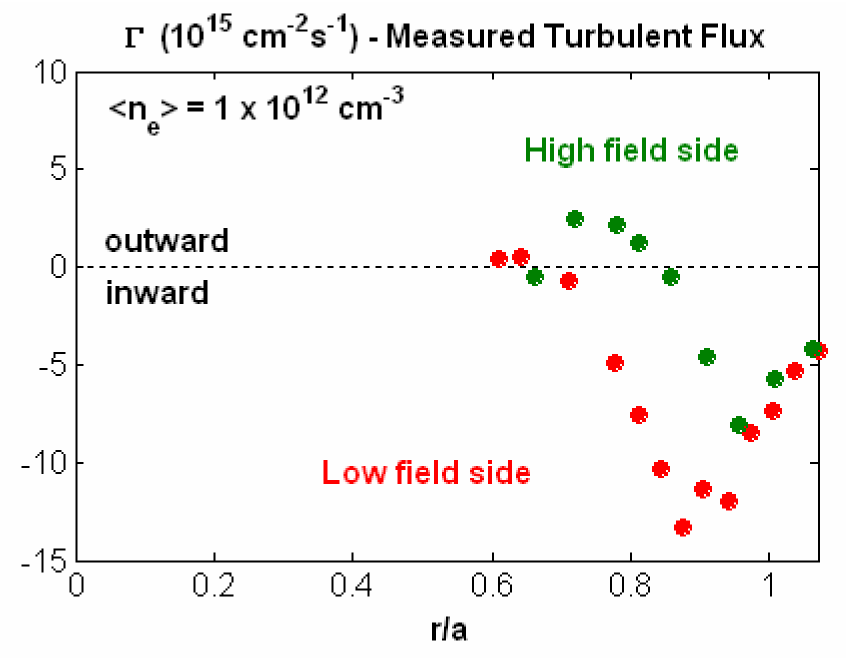
- Possible sources of measurement error
  - Neglect of T_e fluctuations
  - Physical perturbation of probe
  - Suprathermal electrons
- Is the measured turbulent flux asymmetric on a flux surface?

Measured Transport is Inward Directed at a Separate Location



Low field side probe

High field side probe



Measured E×B Rates are Larger at Lower Density When Inward Transport is Measured

- Inward edge transport measured in CHS and H-1 with significant E_r shear $\omega_E > V_{phase}/L_r$ (Shats, 2000)

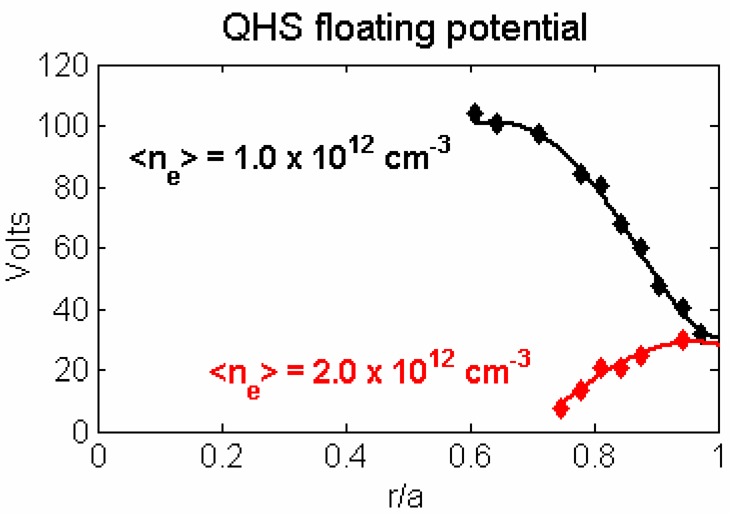
- Floating potential profiles change significantly with density

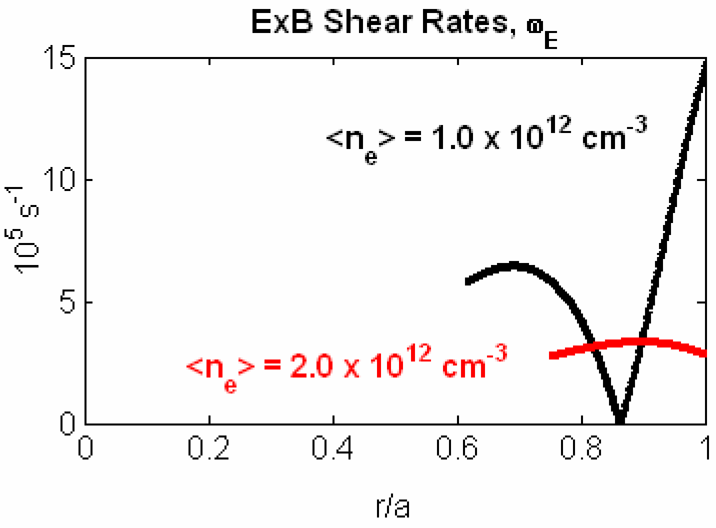
Assume Isotropic

$$\omega_E = \overset{1}{\cancel{\frac{k_\perp}{k_\psi}}} \frac{|\nabla\psi||\mathbf{B}\times\nabla\psi|}{B^2} \left| (\iota - N) \frac{\partial}{\partial\psi} \left[\frac{1}{(\iota - N)} \frac{\partial}{\partial\psi} \Phi_0(\psi) \right] \right|$$

(Hahm, 1997)

	Γ out	Γ in
$\langle n_e \rangle$ (10^{12} cm^{-3})	2.0	1.0
ω_E (10^5 s^{-1})	3	5
V_{phase}/L_r (10^5 s^{-1})	8	5





Geometry Approximations Required for Linear Stability Estimates

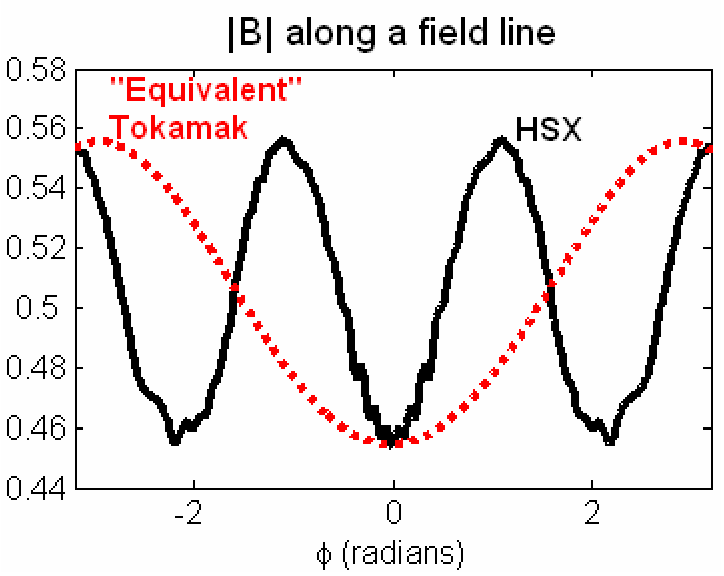
- 3D stability calculations find most unstable eigenmodes (ITG/TEM) ballooning in the low field, bad curvature region in HSX (Rewoldt 2005; Rafiq 2006)

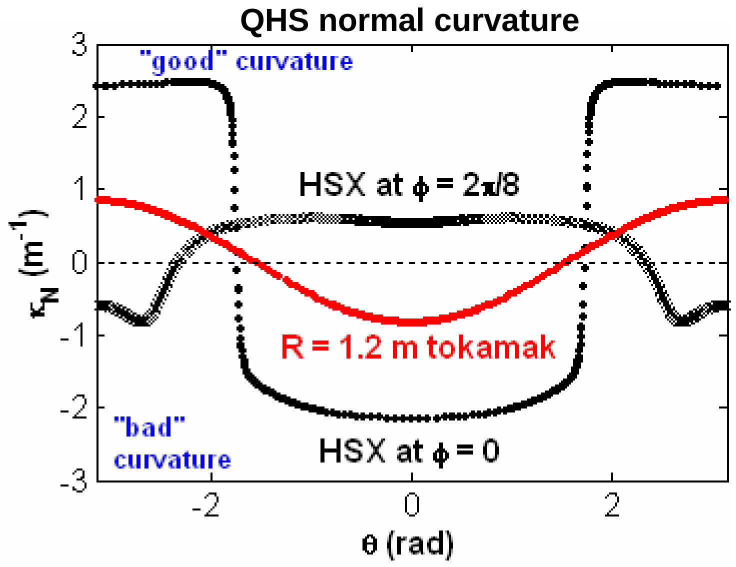
- Dominant particle trapping comes from helical ripple, ε_H (0.14 at r/a=1)

- 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 → TEM

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

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

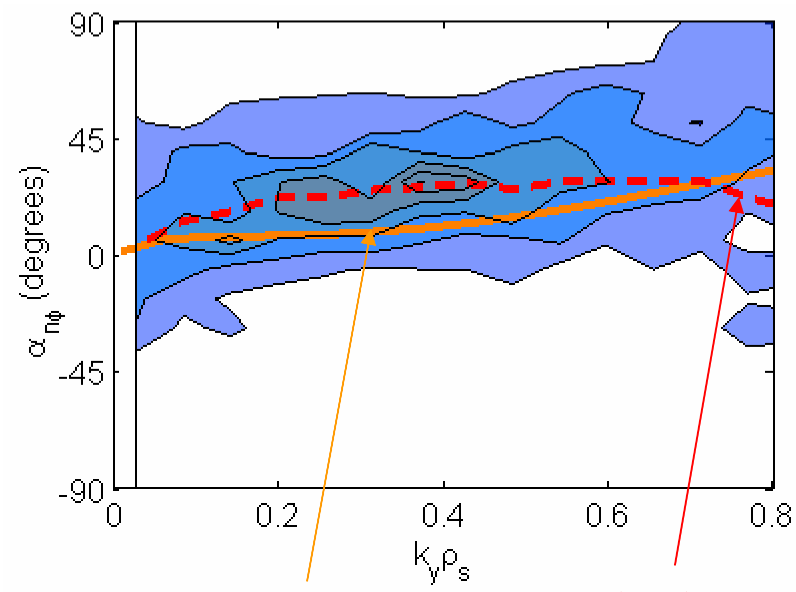




n-φ Cross Phase Similar to Linear Drift Wave Prediction

- Linear stability estimates with geometry approximations
  - Electron drift wave stability (trapped electron mode, TEM)

$P(k_y, \alpha_{n\varphi} \,|\, \omega) S(k_y, \alpha_{n\varphi} \,|\, \omega)$



Electron DW
n-φ phase

$\langle \alpha_{n\varphi} \rangle$ - experiment

r/a ≈ 0.8

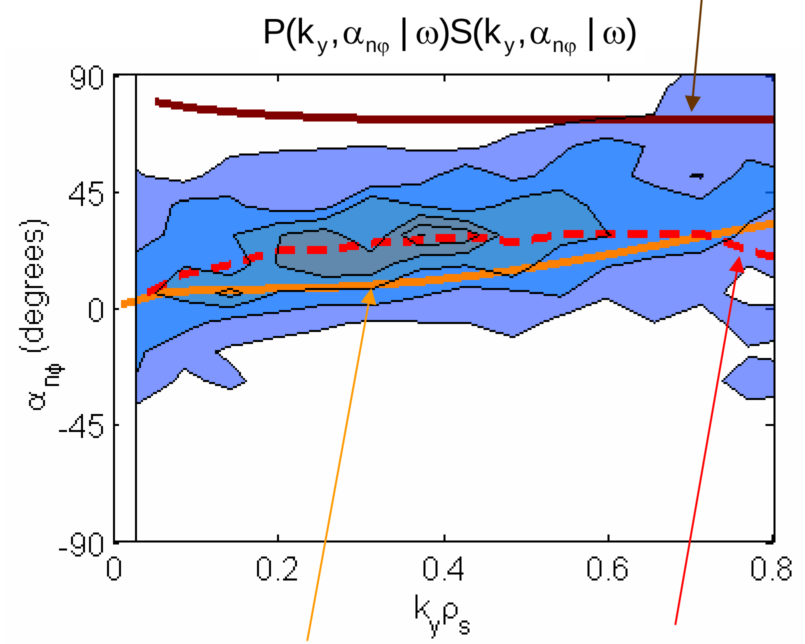
TEM (Kadomtsev & Pogutse, 1971; Horton, 1976)
dominant DW instability (ν_{*e} ~ 0.1 out to edge)

$$\frac{\tilde{n}_e}{n} \approx \frac{\tilde{\varphi}}{T_e}\left(1 - f_t\left\langle \frac{\omega - \omega_{*e}\left(E/T_e - 3/2\right)}{\omega - \omega_{De} + i\nu_{eff}} \right\rangle\right)$$

n-φ Cross Phase Similar to Linear Drift Wave Prediction

- Linear stability estimates with geometry approximations
  - Electron drift wave stability (trapped electron mode, TEM)
  - Resistive ballooning mode (RBM)

RBM
p-φ phase



Electron DW
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$$\frac{\tilde{n}_e}{n} \approx \frac{\tilde{\varphi}}{T_e}\left(1 - f_t\left\langle \frac{\omega - \omega_{*e}(E/T_e - 3/2)}{\omega - \omega_{De} + i\nu_{eff}} \right\rangle\right)$$

RBM (Carreras, Diamond et al., 1983; Callen, 2005)
estimate using ***local*** shear and curvature

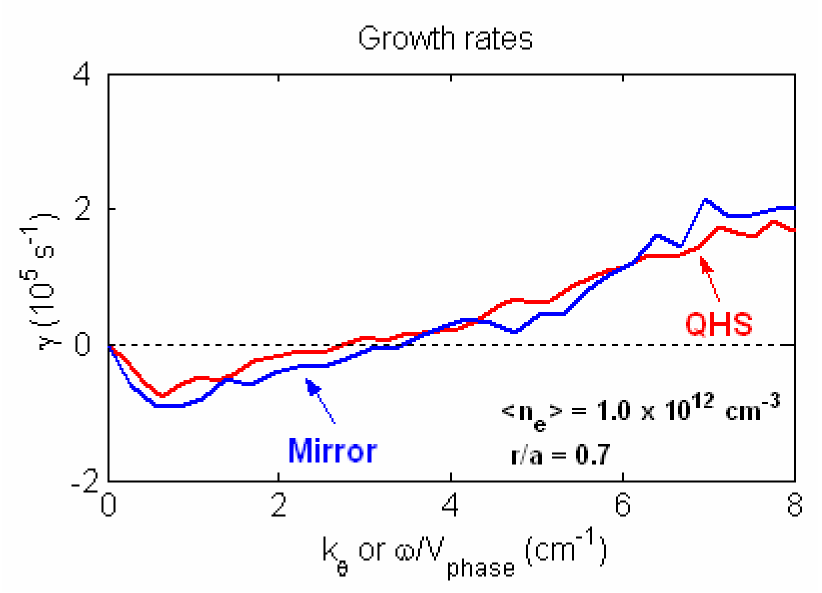
$$\omega(\omega + \tau\omega_{*ep})(\omega - \omega_{*ep}) + i\nu_\eta \omega_A^2 (D_I^\ell)^2 = 0$$

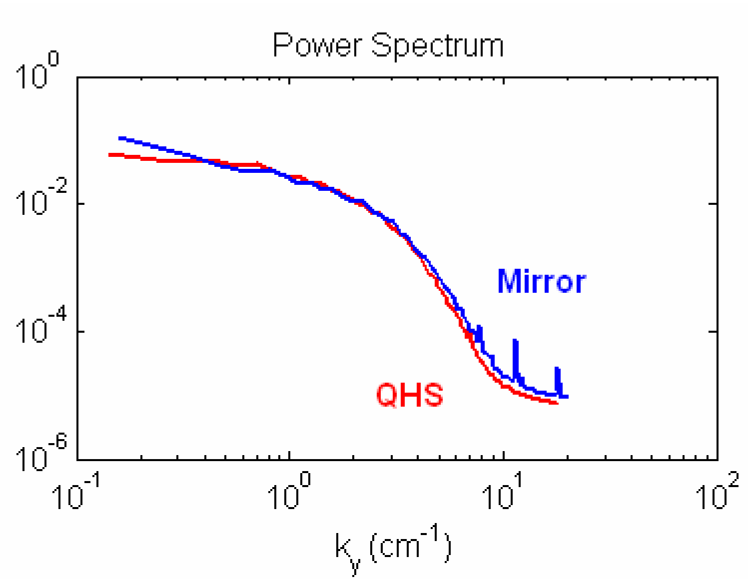
$$D_I^\ell = \frac{(L_s^\ell)^2 \beta}{R_c^\ell L_P}$$

(see talk by Rafiq)

Experimental Growth Rates are Determined Using Bispectral Analysis

- Experimental growth rates determined from bispectral analysis & single field model equation (Kim et al., 1996)
- QHS & Mirror inferred growth rates are the same
- Region of damping where spectra peak



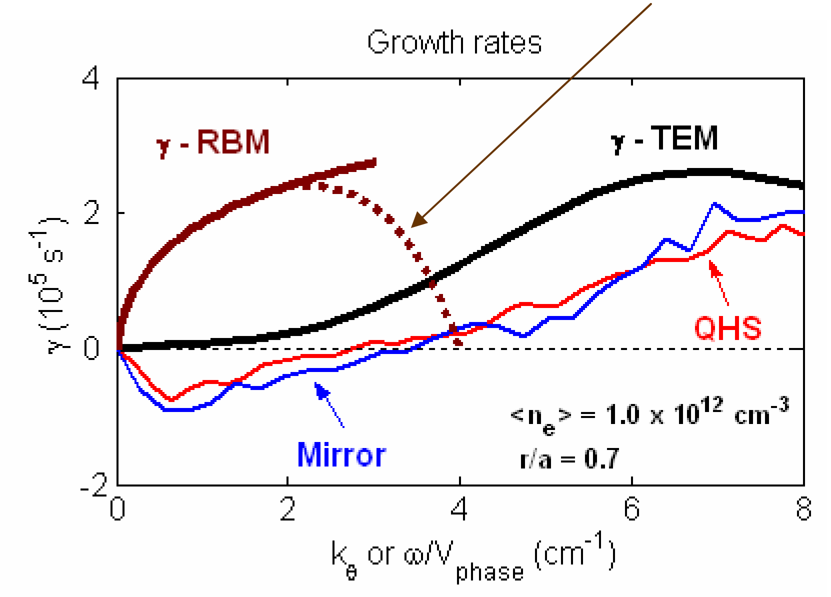


(ρ_s ~ 1.6 mm)

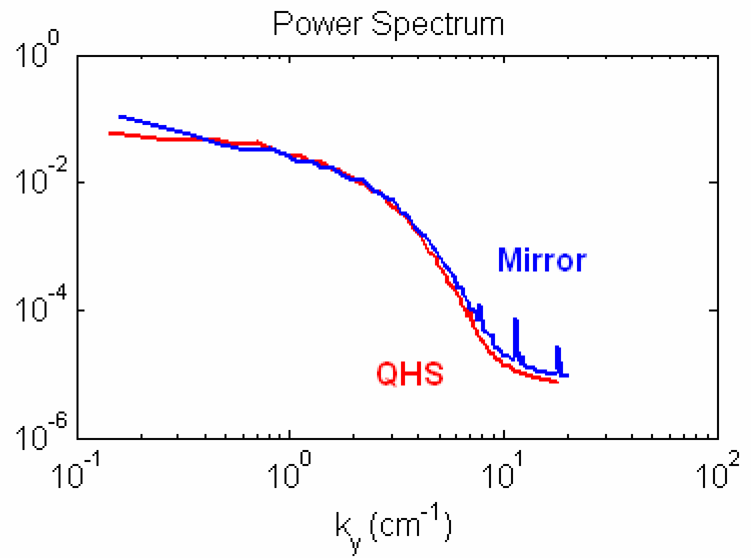
Experimentally Inferred Growth Rates are Comparable to TEM Growth Rates

- Experimental growth rates determined from bispectral analysis & single field model equation (Kim et al., 1996)
- QHS & Mirror inferred growth rates are the same

Dashed line is a schematic approximation of $\mu_\perp$, $D_\perp$ effects



(ρ_s ~ 1.6 mm)



Summary of Turbulence Measurements

- Edge turbulence measurements in both QHS and Mirror configurations at the same injected power are very similar
  - Fluctuation levels
  - Correlation lengths
  - Transport
- Turbulent fluxes are large enough to account for anomalously large transport, but directed inward at low density
- Cross phases and inferred growth rates are similar to TEM (linear) predictions

Can theory based TEM transport models reasonably predict anomalously large transport in ECRH plasmas in HSX?

Predictive Simulations of n_e, T_e, T_i

- Electron energy source from ECRH
  - Total absorbed power from measurements
  - Profile from ray tracing
- Particle source from gas puff and recycling
  - Profile based on 3D neutral gas simulations
  - Magnitude allowed to adjust in simulation to match $\langle n_e \rangle_{sim}$ to $\langle n_e \rangle_{exp}$
- Collisional coupling to ions ($T_i \sim$ 15-30 eV)
- Ion energy sink from i-n charge exchange
- Radiation neglected

- Transport coefficients are modeled as sum of neoclassical and anomalous, $\chi = \chi_{e,NC} + \chi_{e,an}$
- Neoclassical from fit to Monte Carlo mono-energetic diffusion coefficients (Talmadge et al, 2004)
- Anomalous from Weiland ITG/TEM model (Nordman et al., 1990)

- Updating ambipolar E_r every 50 μs ($\tau_E \sim 1$ ms)
- Boundary conditions taken from experiment
- Integrated with Matlab PDE solver
- *No free fit parameters have been used*

Theory Based Weiland ITG/TEM Model

- Axisymmetric fluid model for both toroidal ITG and TEM instabilities
- Simplest version includes single ion species, trapped electrons

$$\left[\chi_e,\chi_i,D,\omega_r,\gamma\right]=F\left(\frac{R}{L_{Te}},\frac{R}{L_{Ti}},\frac{R}{L_n},\frac{T_i}{T_e},f_t,k_\perp\rho_s\right)$$

- With geometry approximation, provides reasonable comparison to 3D gyrokinetic FULL code calculations in scaled HSX (Rewoldt et al., 2005)

Parameters

B = 1.5 T

R = 3.6 m, a = .36 m

r/a = 0.86

$n_i=n_e = 1.9 \times 10^{13}$ cm^{-3}

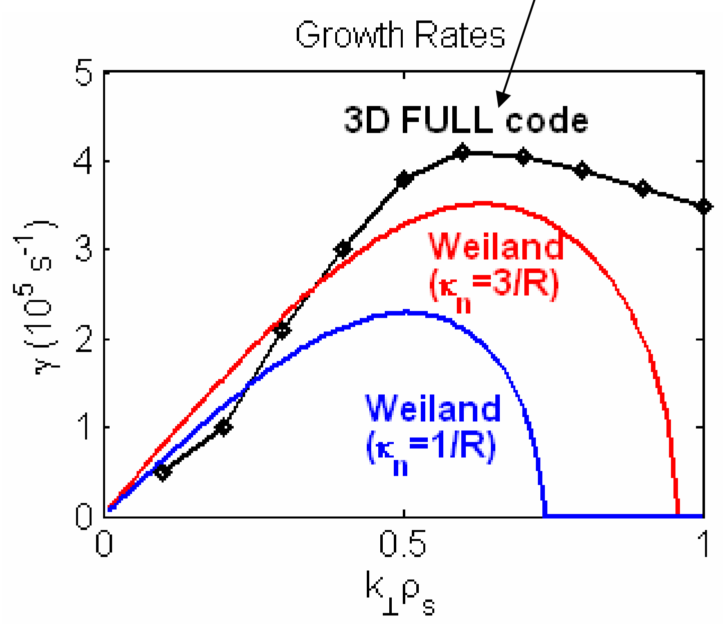
$T_e = T_i = 300$ eV

$R/L_n = 13.3$

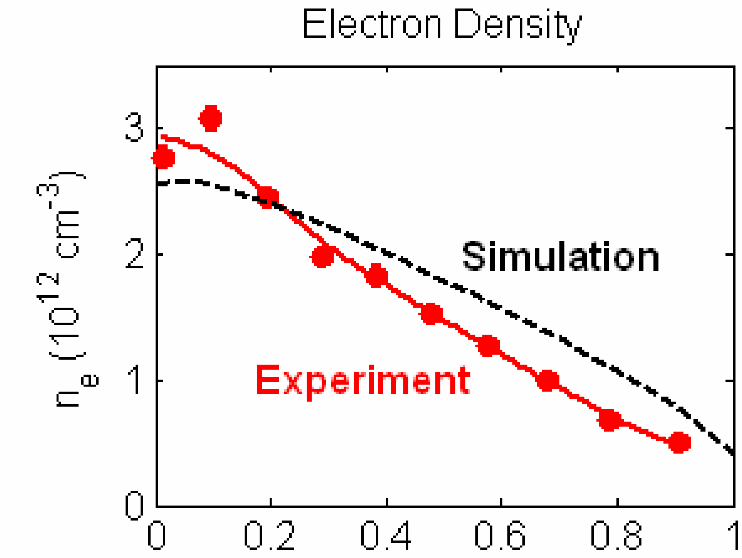
$\eta_e = \eta_i = 2.66$

$Z_{eff} = 1$

$\beta=0$, $\nu_e = 0$, $\omega_{E\times B} = 0$

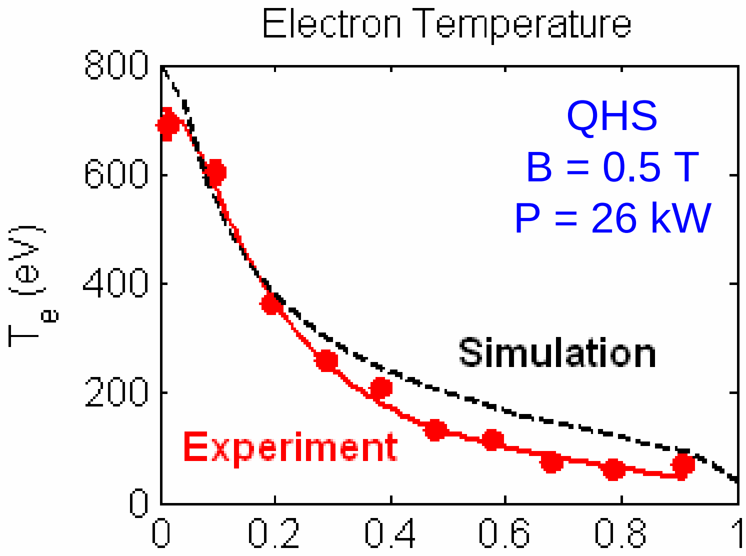


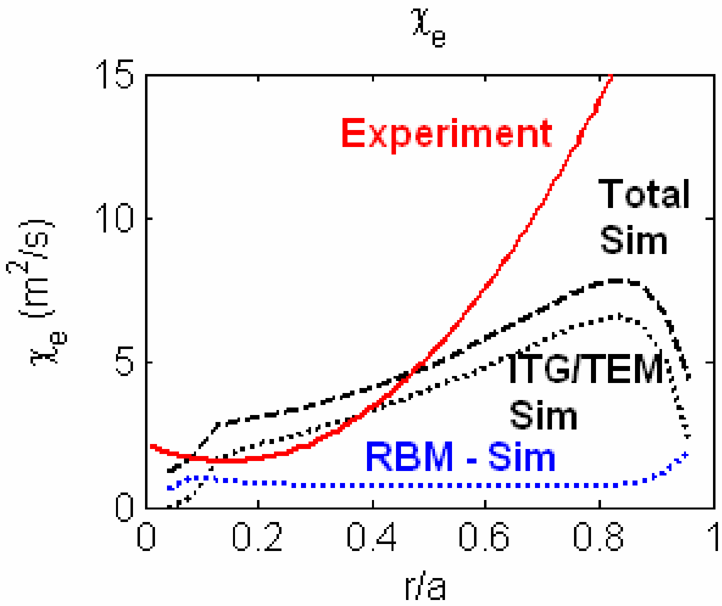
Weiland ITG/TEM Model Predicts Central n_e and T_e in QHS Plasmas


Electron Density

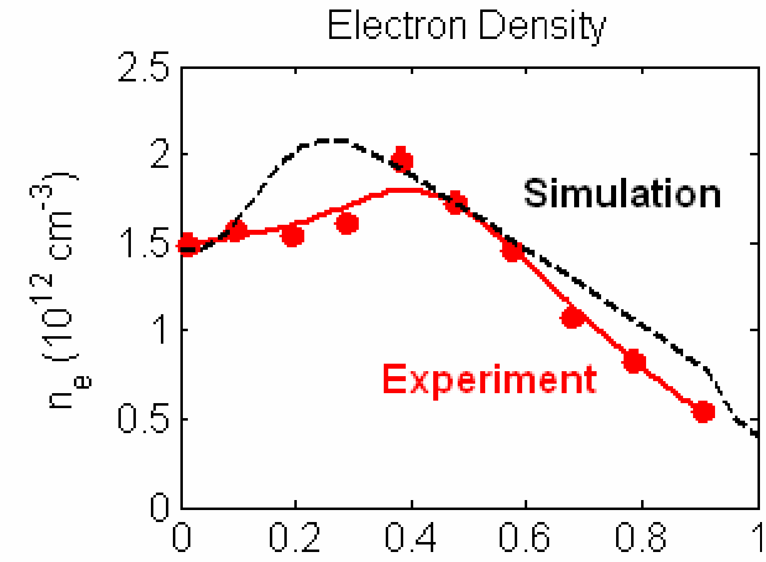
- Predicted TEM instability decreases towards edge

→ Also including resistive ballooning mode contribution, as used in the Multi Mode Model (Bateman et al, 1998)

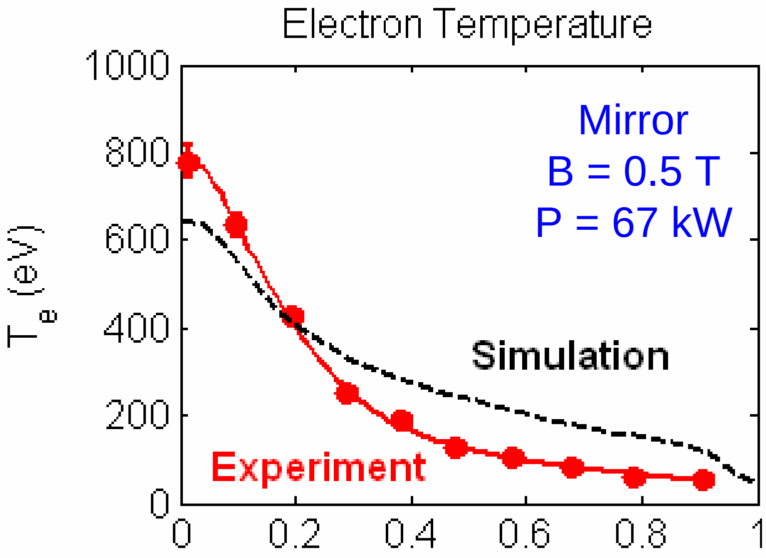

Electron Temperature

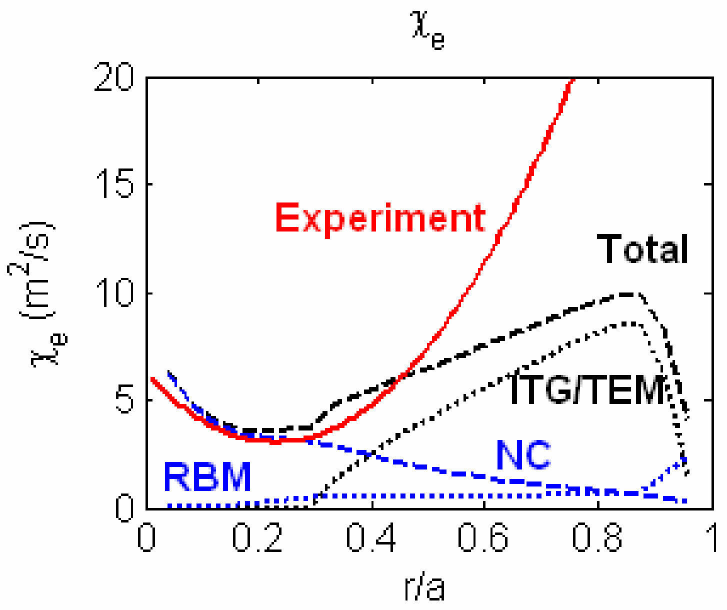

χ_e

Weiland Model Reasonably Predicts Profiles in Mirror Plasmas


Electron Density

- Using the same anomalous model
- Predictive modeling captures the central hollowing of the density profile
- Inverse density gradient stabilizes TEM in the core


Electron Temperature


χ_e

Summary

- Anomalous transport is significant in both quasisymmetric (QHS) and non-symmetric (Mirror) configurations

- Measured **edge** turbulence characteristics in QHS & Mirror configurations are very similar at <u>same injected power</u> (fluctuation levels, correlation lengths, cross phases, transport, inferred growth rates)

- Although turbulent flux is large enough to account for anomalous transport, measured direction is still being investigated

- With low collisionality electrons, TEM expected to be dominant instability
  - Experimental cross phases and growth rates similar to approximate linear TEM predictions

- The Weiland ITG/TEM anomalous transport model provides reasonable prediction of profiles in both the QHS and Mirror configurations