HSX: STATUS, PLANS AND OPPORTUNITIES FOR THEORY RESEARCH

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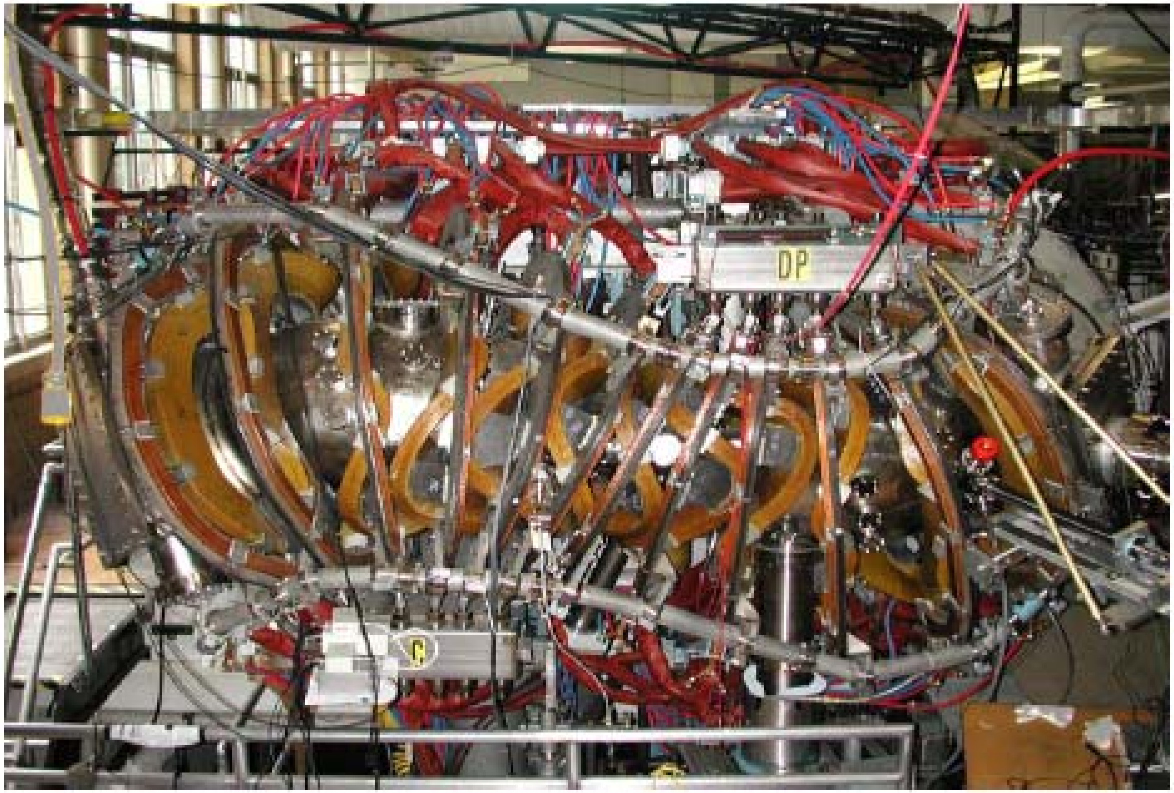
Stellarator Theory Teleconference

March 9, 2006

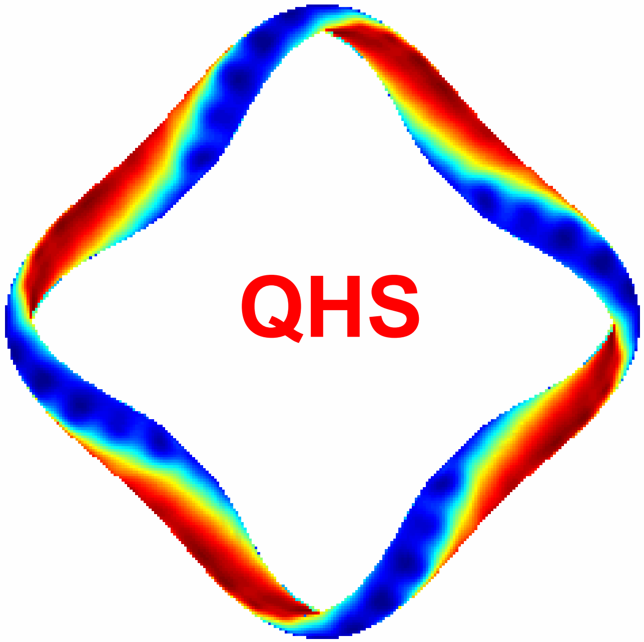
HSX was designed to test possible benefits of quasisymmetry

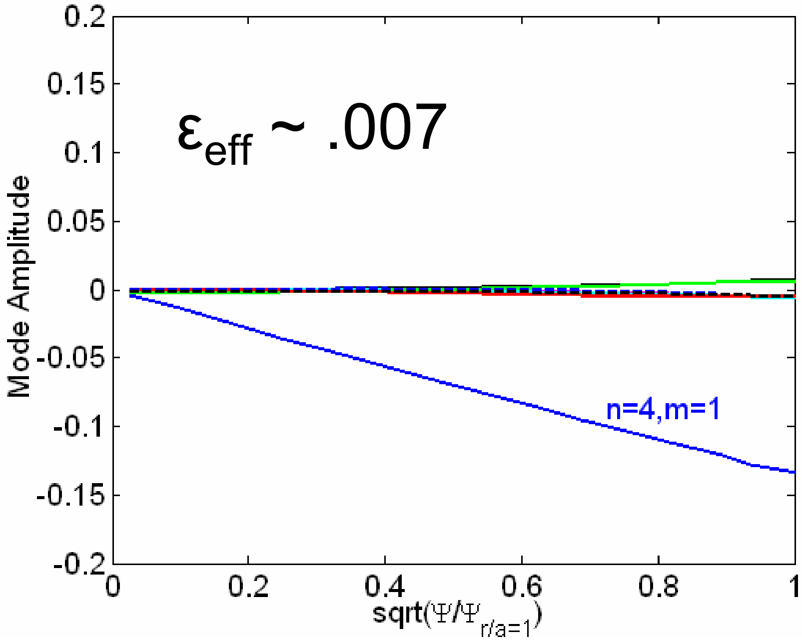


Major Radius	1.2 m
Minor Radius	0.12 m
Number of Field Periods	4
Coils per Field Period	12
Rotational Transform	1.05 $\rightarrow$1.12
Magnetic Field	0.5 T
ECH Power (2^{nd} Harmonic)	50 kW 28 GHz

Present emphasis is to drive electrons into low collisionality regime with Electron Cyclotron Heating

HSX is a Quasihelically Symmetric Stellarator





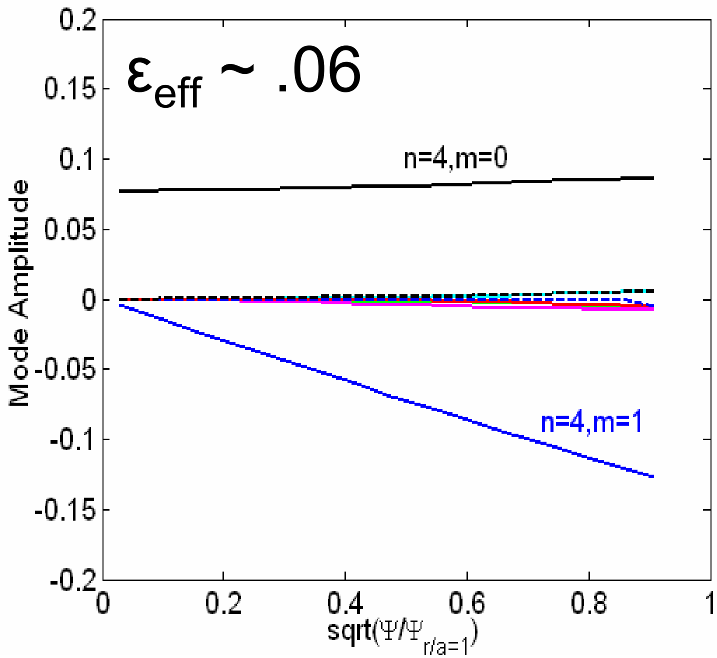
$$B = B_0\left[1 + \varepsilon_h \cos\left(N - m\iota\right)\phi\right]$$

Effective transform = $N - m\iota$ = 4 – 1 ~ 3

HSX has a helical axis of symmetry in |B|

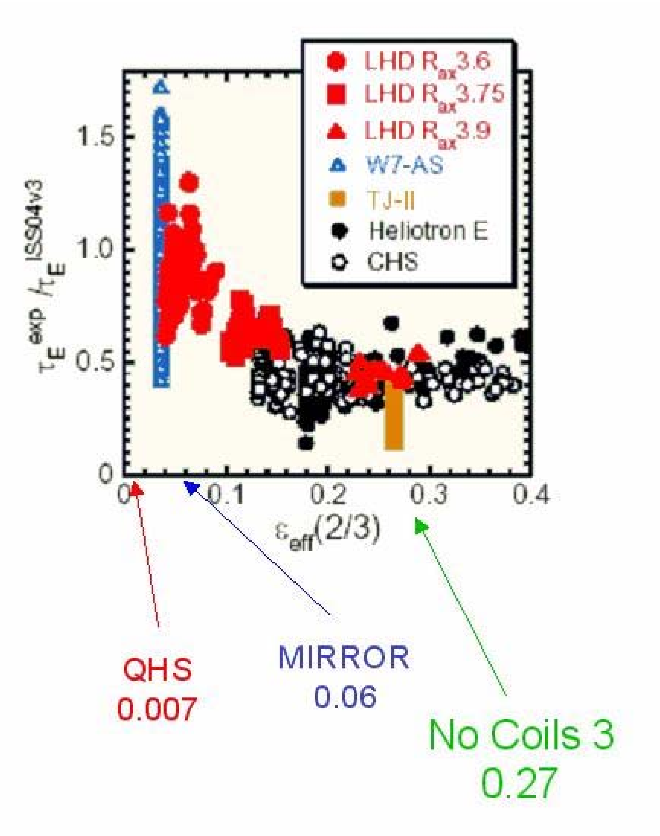
⇒ Very low level of neoclassical transport

Symmetry Can Be Broken With Auxiliary Coils



- Effective ripple increased nearly factor of 10 with n = 4, m = 0 mirror mode.
- Effect is to increase neoclassical transport and parallel viscous damping closer to conventional stellarator.

Stellarator Confinement Improves With Decreasing Effective Ripple



- Neoclassical transport reduced with lower ripple.
- But LHD results shows enhancement of confinement at low ripple even at high collisionality.
- Is this real? Lower flow damping, zonal flow formation, trapped particle instabilities, heating efficiency, direct orbit losses? Or artifact of multiple machines?
- HSX has the lowest ε_{eff} of any existing stellarator. Desirable to scan ripple within same experiment.

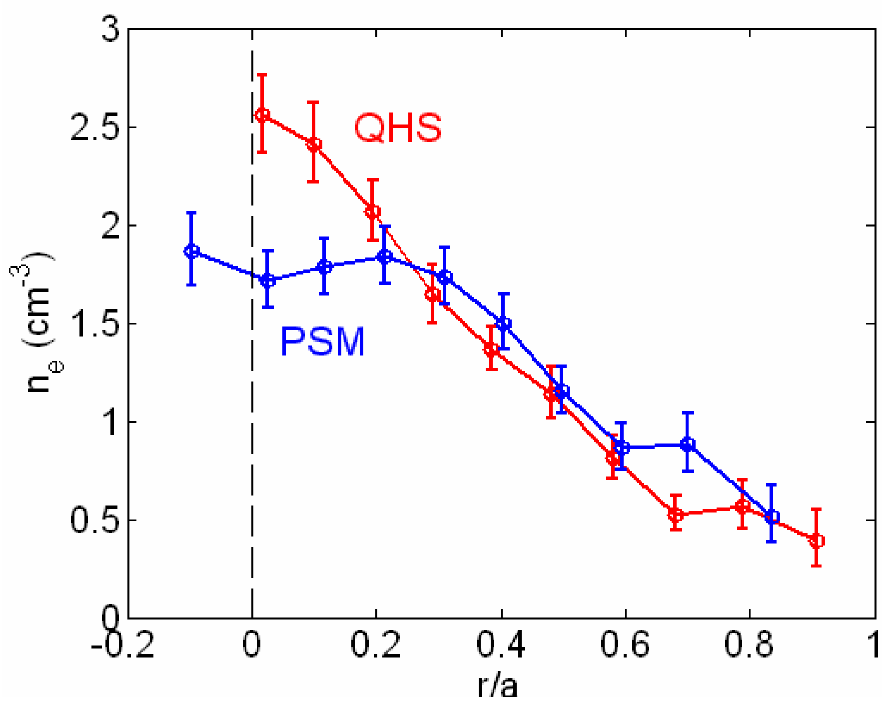
How can theory and modeling explain reduction of anomalous transport with lower ripple?

Reduced Particle Transport Leads to Peaked Density Profiles in QHS

$$\Gamma = -n\left\{ D_{11}\left(\frac{n'}{n} - \frac{qE_r}{T}\right) + D_{12}\frac{T'}{T} \right\}$$

D_{12} is smaller due to quasi-symmetry

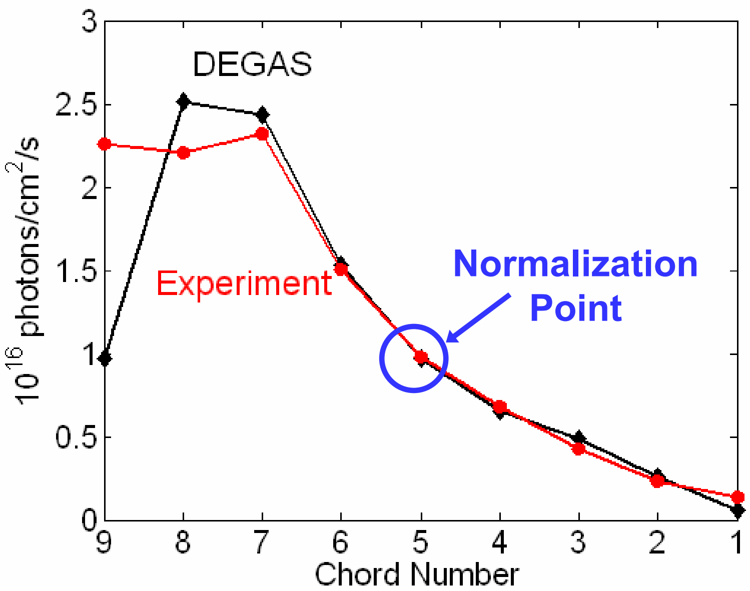
Peaked density profiles in QHS

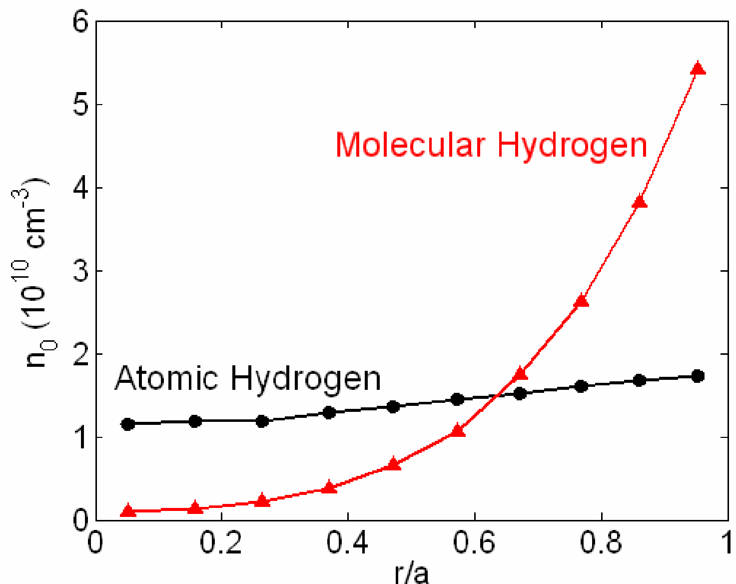


- All conventional stellarators show hollow or flat density profiles with central ECH heating
- Thermodiffusion: Particle flux due to temperature gradient
- Quasisymmetry reduces thermodiffusive term

3D DEGAS Modeling Coupled to H_α Measurements Gives Radial Particle Flux

- With single point normalization, numerically integrated DEGAS H_α emission matches experimental profile
- Atomic hydrogen profile is flat (λ_H~1m)
  Molecular hydrogen profile decays towards core (λ_{H2}~3 cm)
- H_α measurements + modeling yields the particle source rate density ⇒ total radial particle flux
- Collaboration with ORNL to develop 3-D model with DEGAS





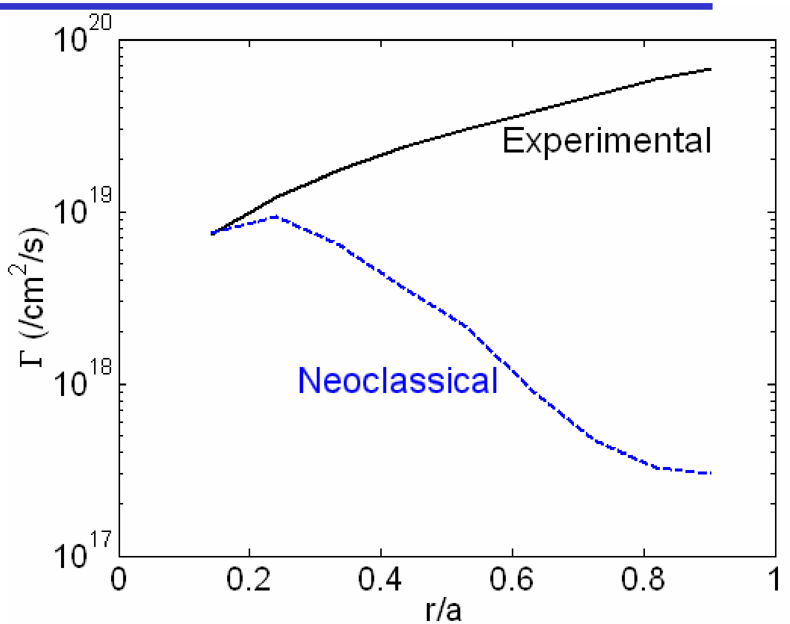
Neoclassical Thermodiffusion Accounts for Hollow Density Profile in Mirror Configuration

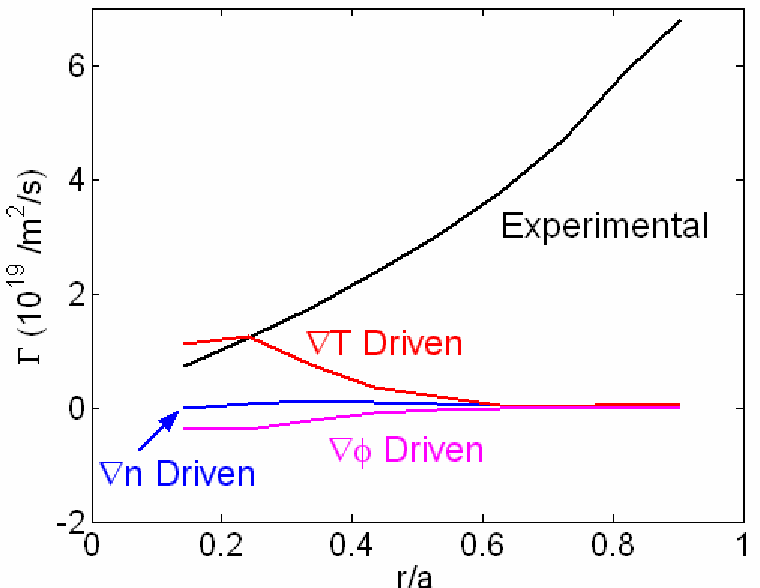
- Figure shows experimental particle flux from H_α + DEGAS, neoclassical prediction

- In region of hollow density profile, neoclassical and experimental fluxes comparable

- The ∇T driven neoclassical flux is dominant

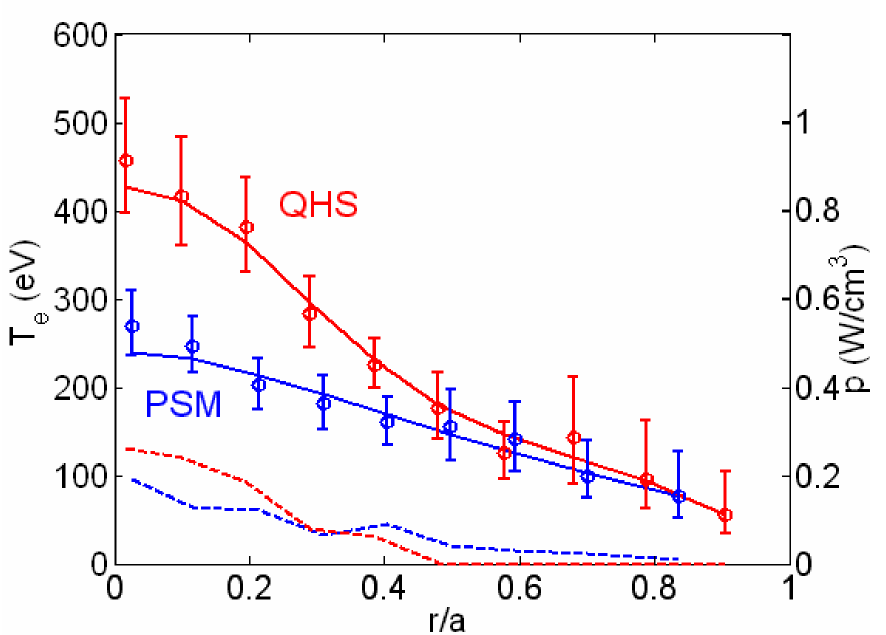
$$\Gamma = -n\left\{D_{11}\left(\frac{n'}{n} - \frac{qE_r}{T}\right) + D_{12}\frac{T'}{T}\right\}$$



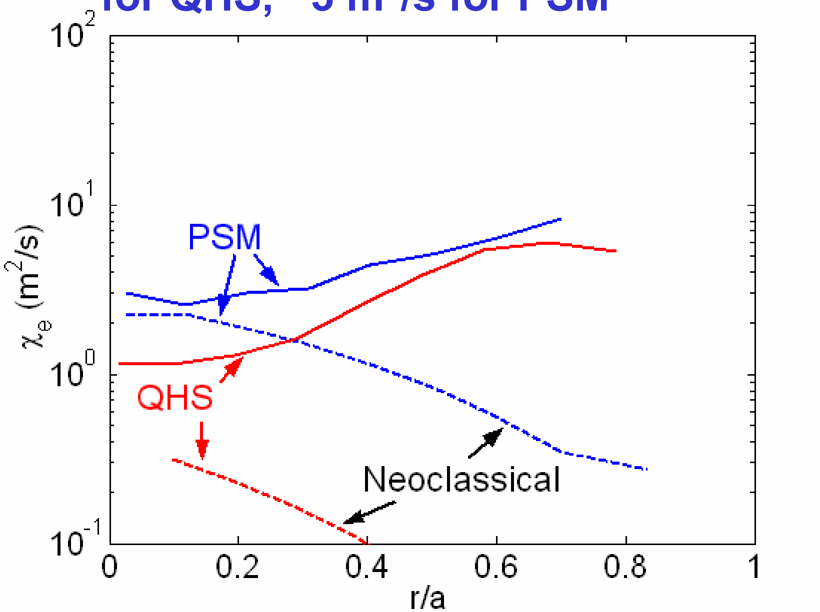


Central Electron Temperature Increases by 200 eV with Quasisymmetry

Higher T_e in QHS with same absorbed power



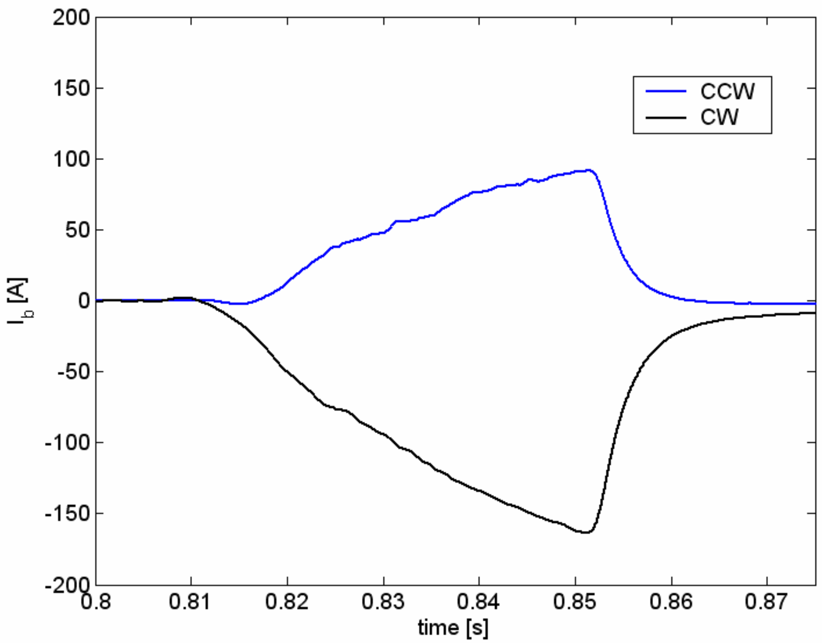
Thermal diffusivity at r/a=.3 ~1m^2/s for QHS, ~3 m^2/s for PSM



- Neoclassical χ_e including ambipolar electric field.
- QHS exhibits anomalous transport levels.
- Neoclassical above anomalous in core of phase-shifted mirror discharges. Similar χ_e in outer half of the plasma for both configurations.

QHS has longer confinement time: $\tau_E^{QHS} \sim 1.5$ ms, $\tau_E^{PSM} \sim 0.9$ ms

First Data Indicating Bootstrap Current Unwinds Transform in HSX



- Reversal of magnetic field shows reversal of plasma current → ECH driven currents probably small.
- Stored energy from diamagnetic loop and Thomson is stationary within 3-5 ms.
- Current continues to rise over 30 ms length of discharge.

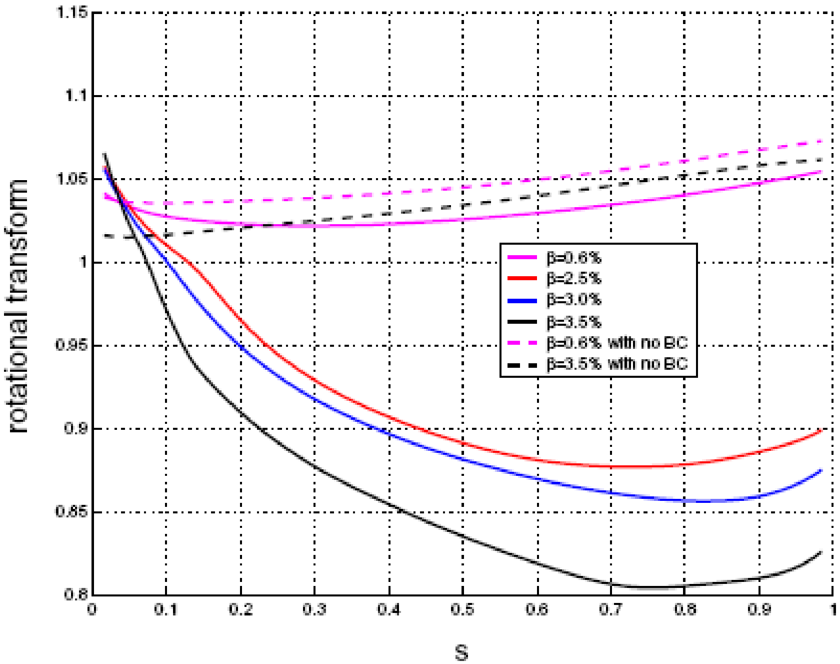
- Direction of current is to *unwind* the rotational transform.
- Current direction depends on magnetic spectrum: n=4, m=1 HSX in opposite direction compared to n=0, m=1 tokamak.

$$\Delta_0 = 1.46\sqrt{b_{mn}}\,\frac{M}{\iota M - N}$$

$$J_b = -\Delta_0 \frac{g}{B_0}[1.67(T_e + T_i)\frac{dn}{d\psi} + 0.47n\frac{dT_e}{d\psi} - .29n\frac{dT_i}{d\psi}]$$

(Boozer, 1990)

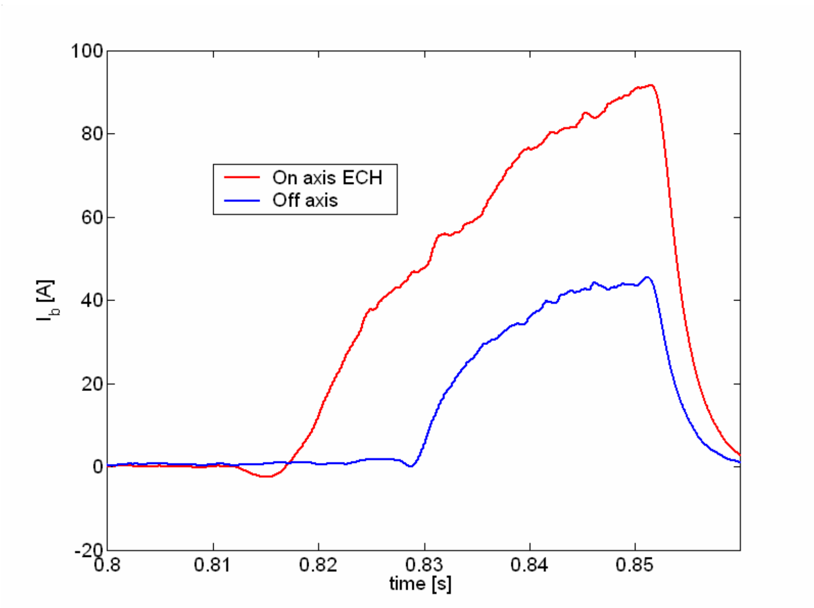
Quasihelical Equilibrium with Self-Consistent Bootstrap Current Needs to Be Re-examined

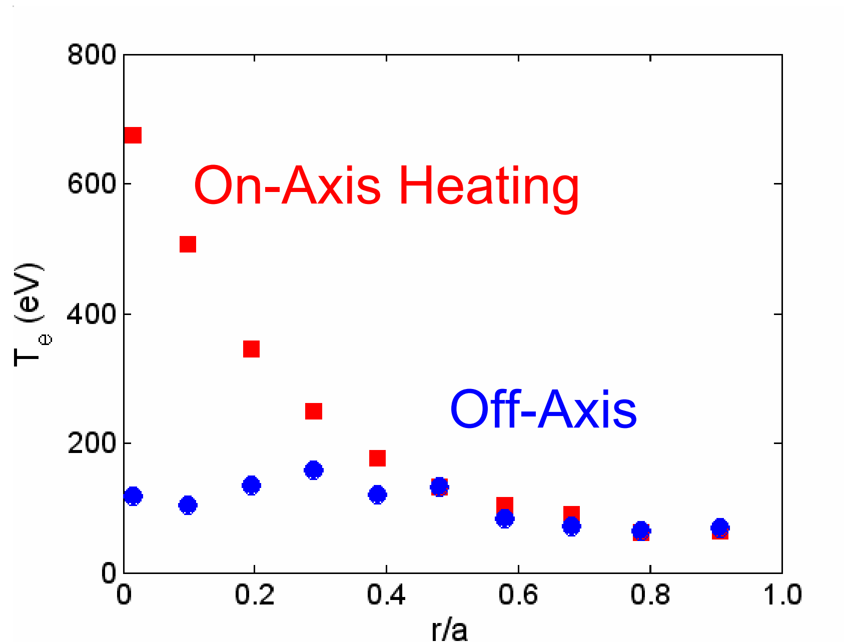


- Margalet and Cooper scaled HSX to reactor size; VMEC equilibria computed until BC converges FS&T **46** 44 (2004)
- BC calculated with modified Shaing form (Johnson PoP 1999) in low collisionality regime, no E_r.
- Transform decreases with increasing β through iota = 1 rational surface

- Results did not converge for β > 3.5%, even though spectrum was unchanged
- No convergence for ideal helically symmetric configuration either!
- These results need to be re-examined; good opportunity for collaboration!

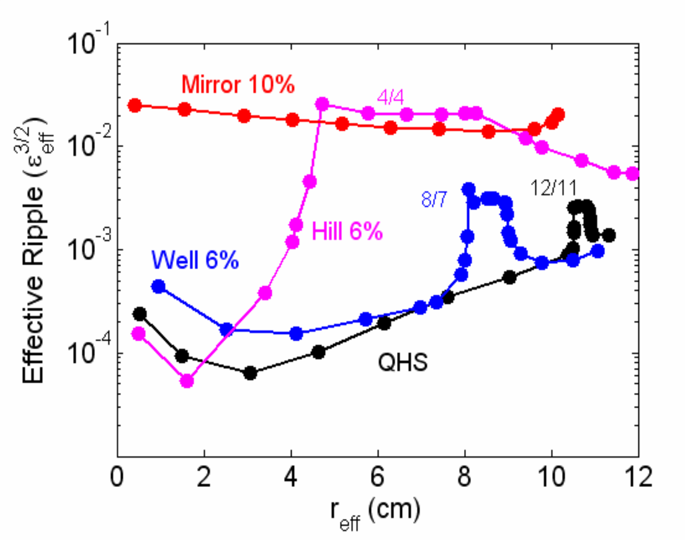
Longer Time-Scale for Bootstrap Current Evolution with On-Axis Heating

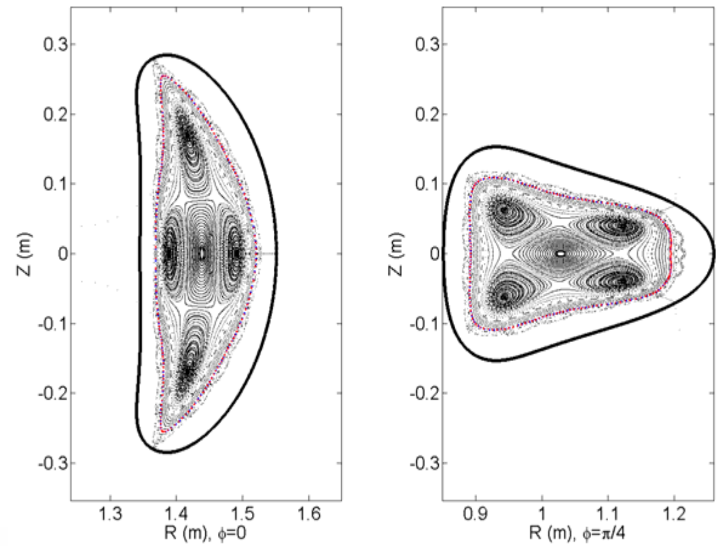


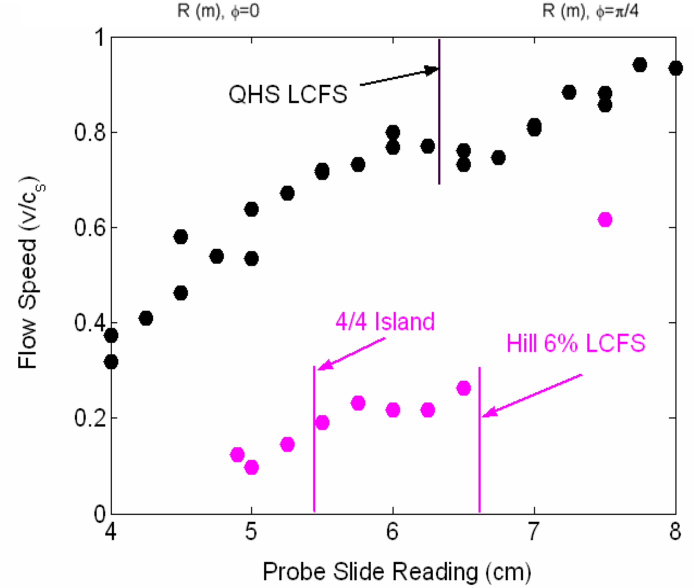


- Bootstrap current still evolving for on-axis ECH.
- With off-axis heating, Te is lower, shorter time to reach steady-state.

How Do Islands Affect Flows and Currents?





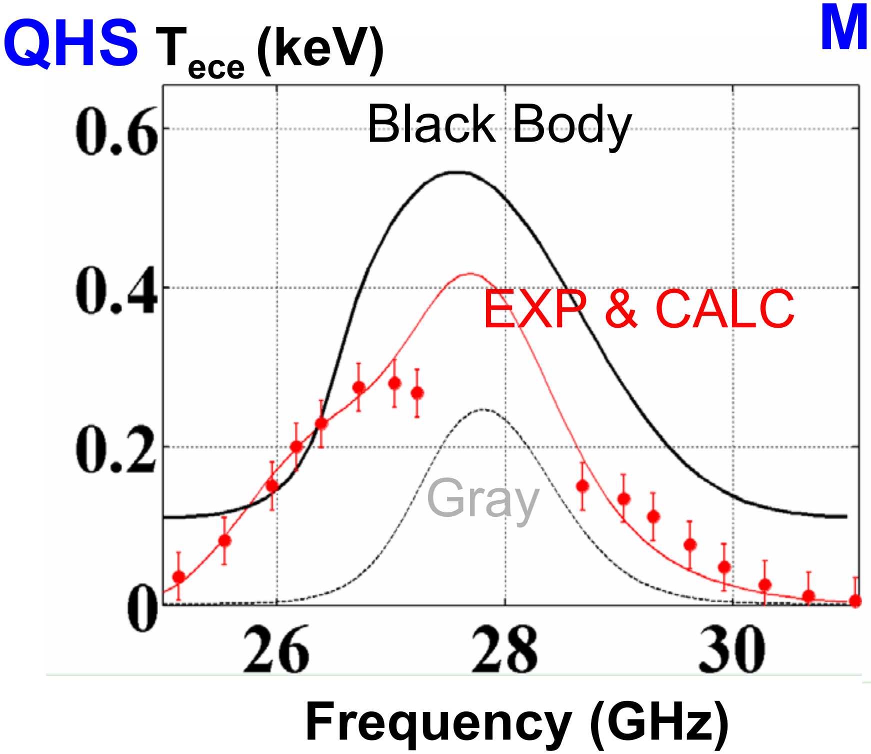


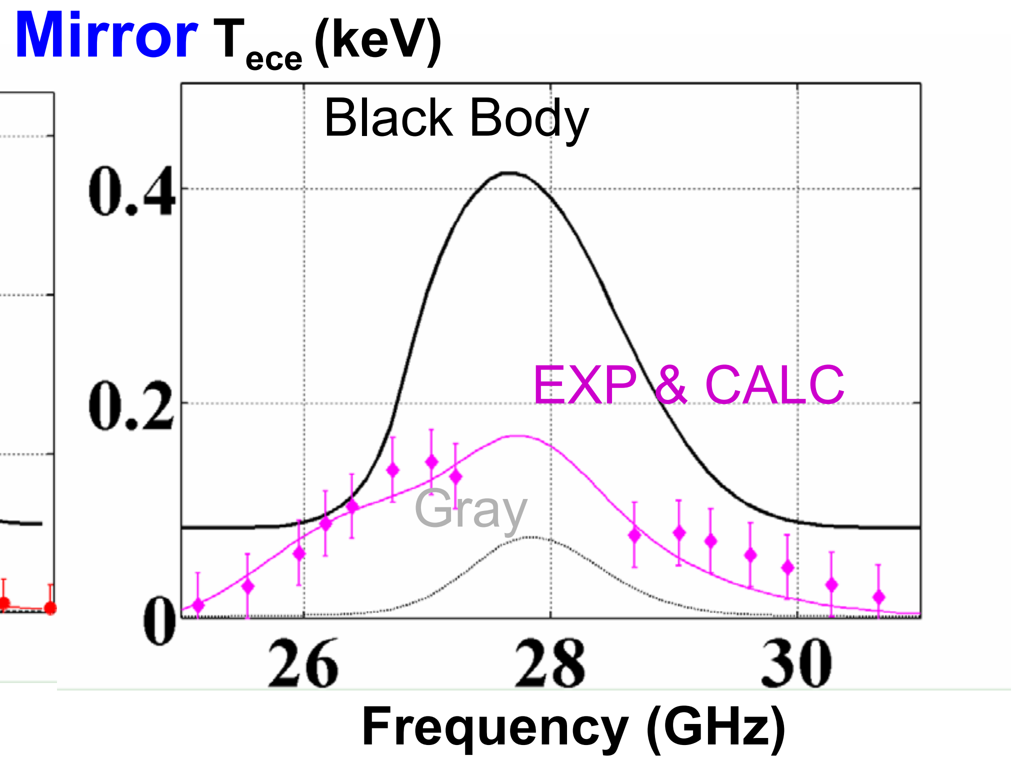
- Effective ripple can be raised throughout plasma or locally with magnetic islands
- An island with [4,4] symmetry interacts with [4,1] mode to give [8,5] and [0,3] spectral terms
- Evidence of decreased flow with high effective ripple

Couple NCLASS Stellarator Code to Bootstrap Current Evolution

- Spong has made excellent progress on developing moments method/DKES code to calculate flows, particle and heat fluxes, electric fields and currents in stellarators.
- We will be making comparisons of flows, electric field and bootstrap currents to these code results → It would be good to include islands in the model.
- Long time-scale of bootstrap current evolution in HSX demonstrates need to couple magnetic flux evolution to bootstrap current calculation (NCLASS stellarator code) and plasma equilibrium (VMEC, PIES)
    - Similar to Strang and Houlberg THRIFT code (three dimensional inductive flux evolution in toroids) PoP 8, 2782 (2001)

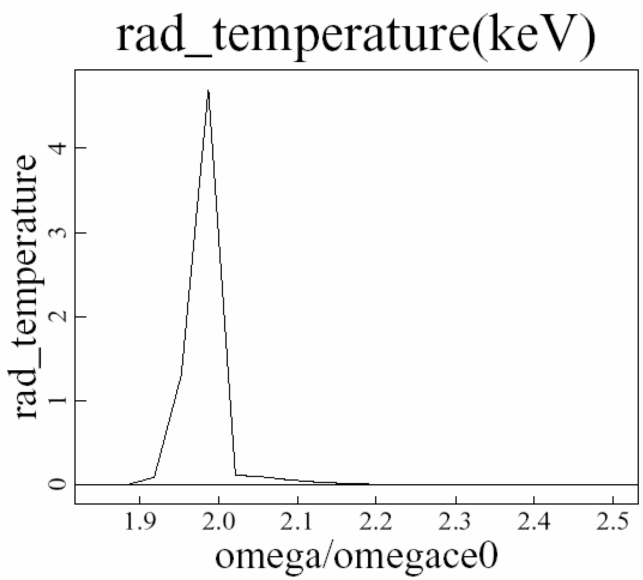
Evidence of Differences in Distribution Function for Symmetric vs Nonsymmetric Plasmas





- Blackbody and resulting gray spectrum based on Thomson T_e and n_e data.
- BiMaxwellian modeling yields best fit of ECE data: 4.8 keV tail population in QHS and 3.5 keV in Mirror.

Calculated Radiation Temperature with CQL3D Comparable to ECE Measurements



- Tokamak model field, circular cross-section
- The plasma parameters are as follows: central T_e = 0.4 keV, central $N_e = 1 \cdot 10^{12}$ cm^{-3} and input power is 100 kW
- ECE temperature for the non-Maxwellian electron distribution function is above 4 keV
- Further work needed to understand why CQL3D predicts low ECH absorption in HSX plasmas

Need for Improvements in ECH Modeling

• Collaboration with R. Harvey on CQL3D, which solves bounce-averaged Fokker-Planck in 2 velocity dimensions and one spatial.

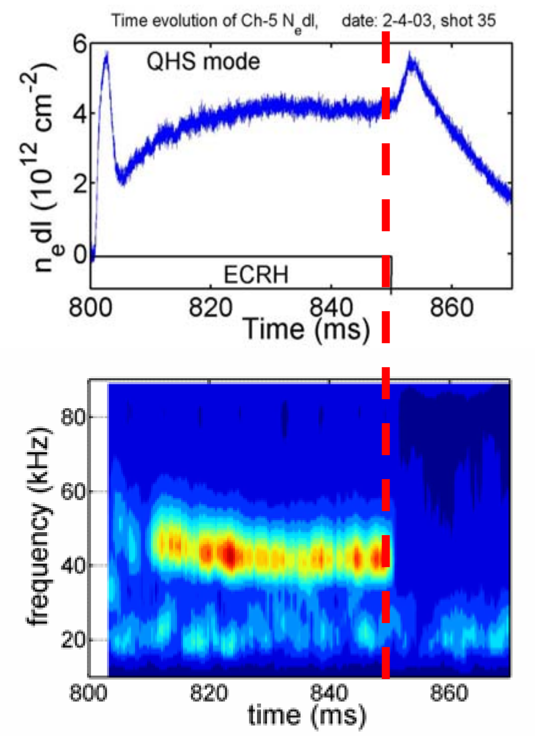
• Assumption that distortion from Maxwellian distribution is small may be incorrect. Nonlinear rf interaction may be important to describe superthermal trapped electrons during 2^{nd} harmonic X-mode in stellarators (Kamendje PoP 2003).

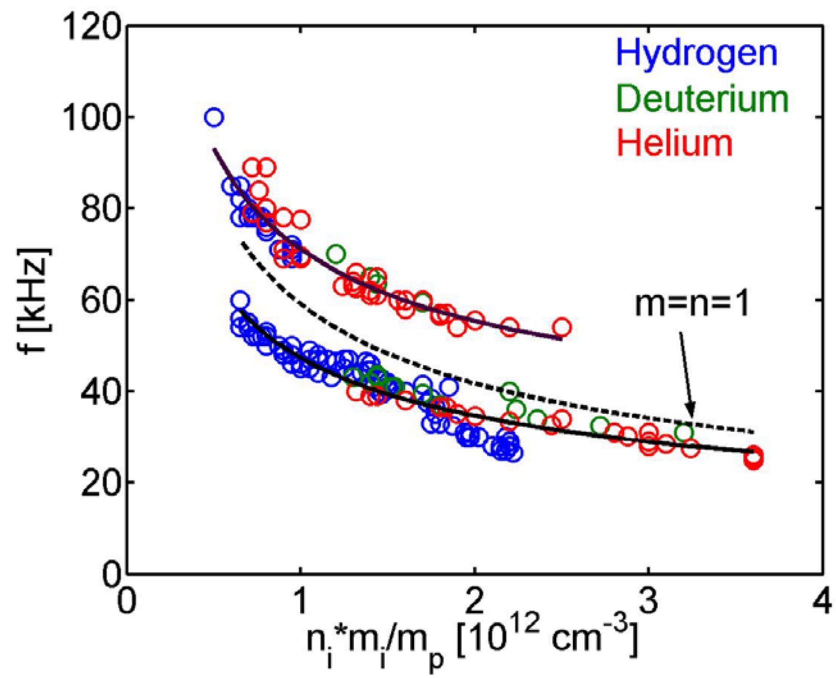
• 5-D Fokker-Planck modeling to account for differences in magnetic geometry.

• Self-consistent modeling of superthermal electron flux on calculation of ambipolar electric field.

MHD Mode Observed Only in QHS Plasmas

$$\omega_{GAE} \le k_{//} v_A = \frac{(m\iota - n)}{R} \frac{B}{\sqrt{4\pi n_i m_i}}$$





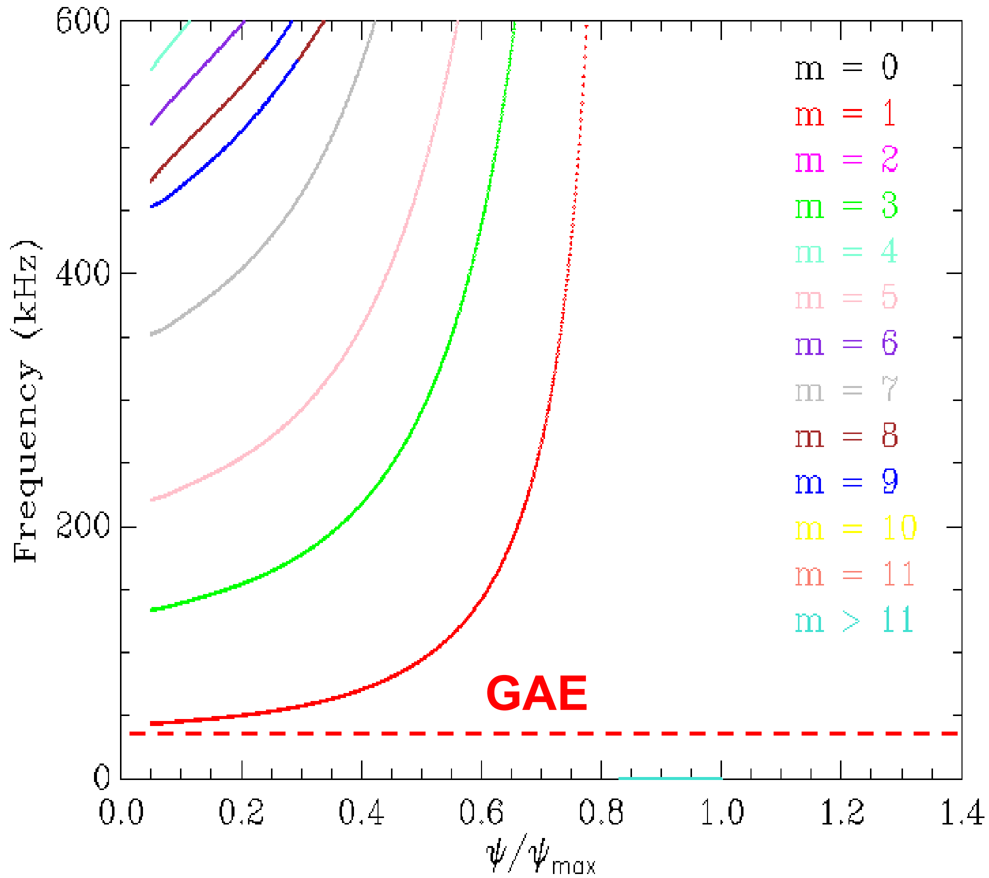
Frequency and Mass Scaling consistent with Alfvenic mode

GAE Gap Exists Where Fluctuation Resides

- GAE Gap: B=0.5 T
  0 - 50 kHz for m=1,n=1
  $n_e(0)=1.8\times10^{12}\ cm^{-3}$

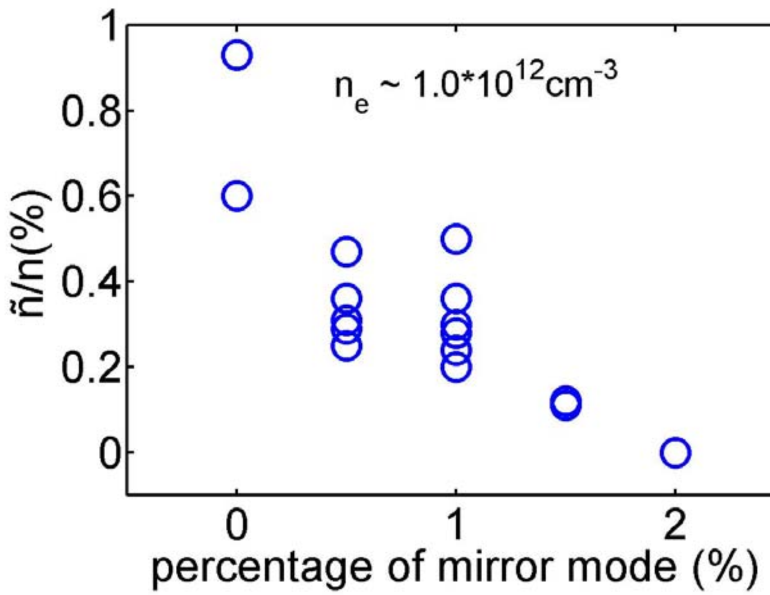
- Mirror configuration is similar

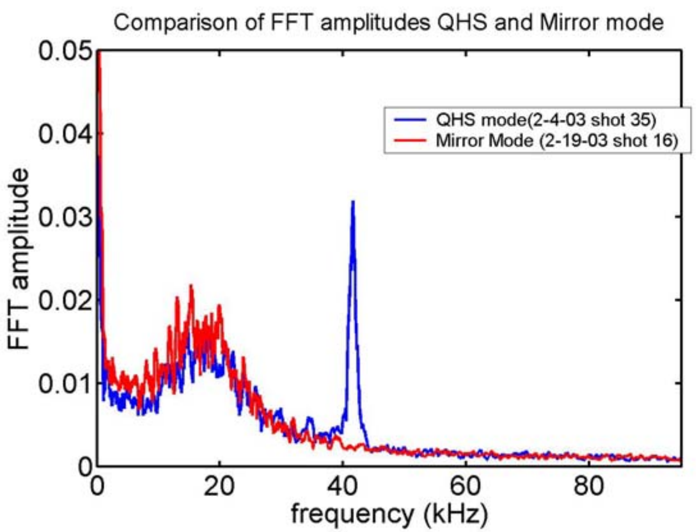
N = 1 mode family



STELLGAP code (D. Spong)

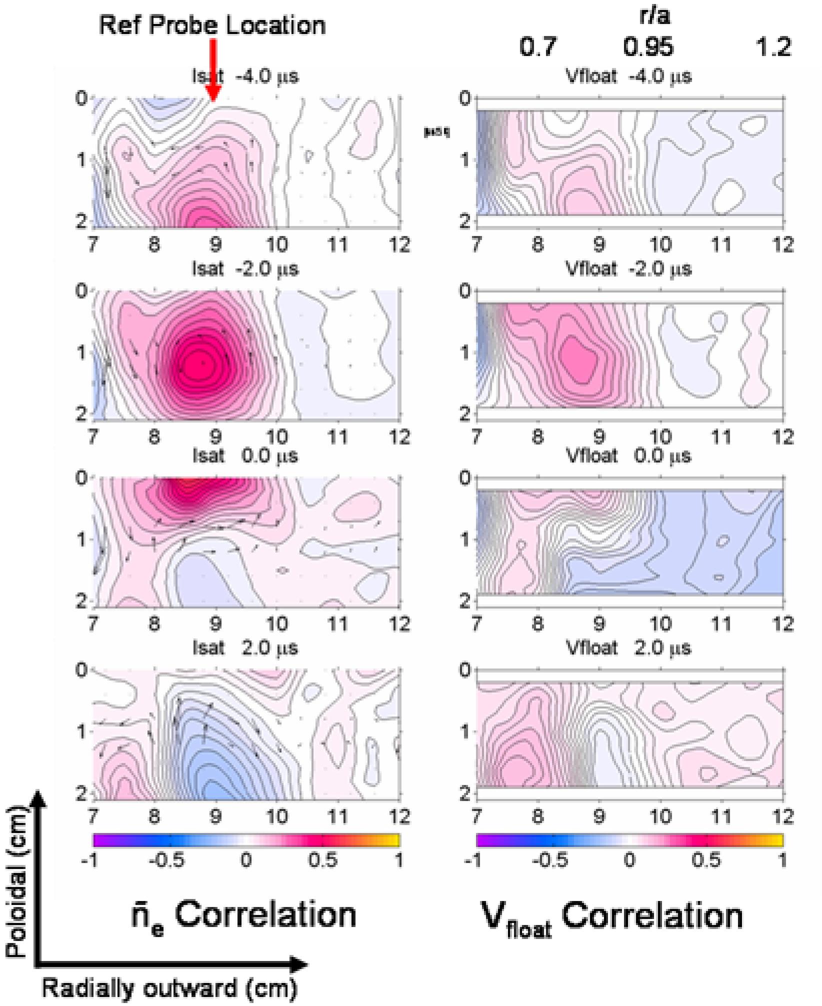
Need for a Stability Calculation to Understand How Nonthermal Electrons Drive the Mode





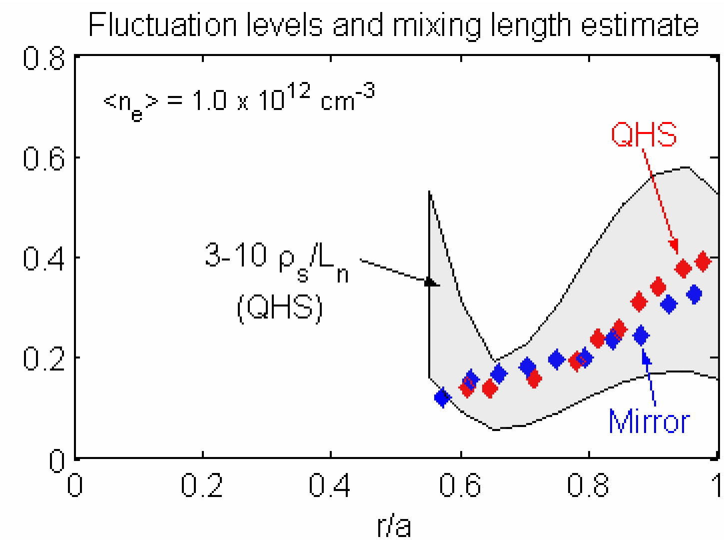
- Mode vanishes with small toroidal mirror term. Why?
- Mode initially absent when iota ~ 1, but suddenly reappears with jump in stored energy
- Don't observe frequency scaling with transform
- How does nonthermal electron population destabilize the mode?

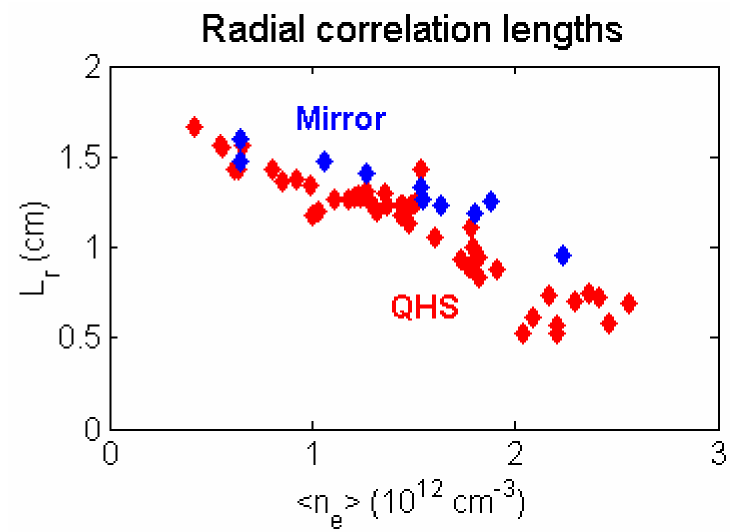
Does Anomalous Transport Differ Between Symmetric and Non-Symmetric Plasmas?

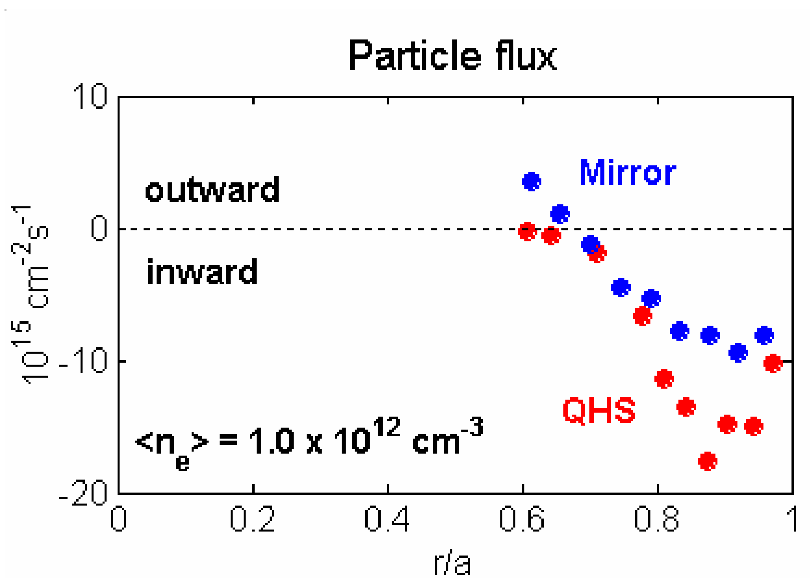


- Movable 16 pin probe and single fixed probe yields 2-dimensional correlation function.
- Evidence of turbulent structures moving poloidally at E x B velocity.
- Phase between density and potential is small, typical of drift wave dynamics.
- Mirror configuration shows similar structures.

Turbulence in QHS vs Mirror at Edge Is Similar

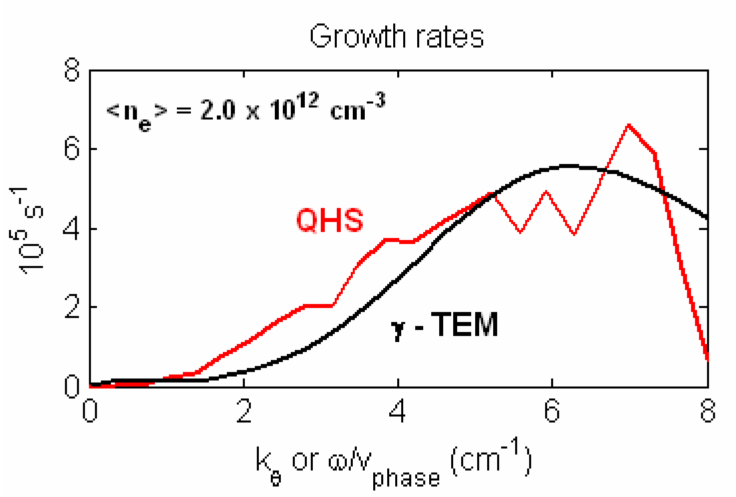


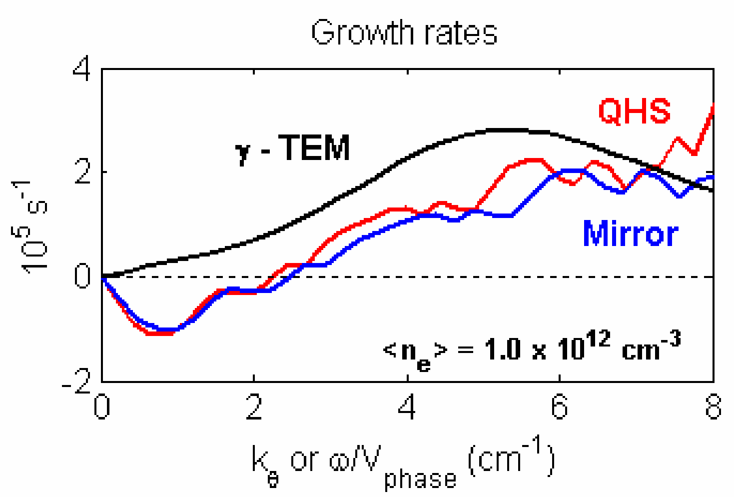




- Fluctuation Levels 20-40% at edge, consistent with mixing length estimates
- Correlation lengths in QHS and Mirror similar over range of densities

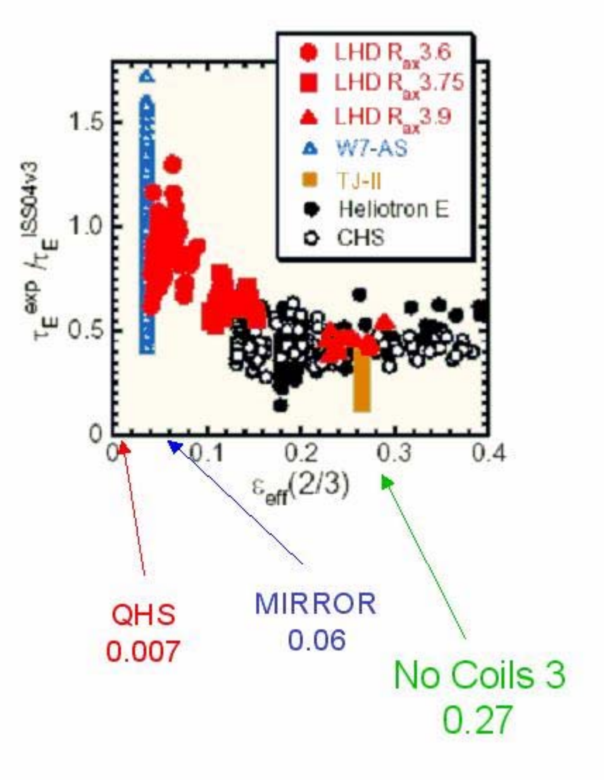
Growth Rates in QHS vs Mirror Are Similar





- Experimental growth rates determined from bispectral analysis
- At high density, QHS growth rates are very similar to linear TEM prediction (Horton, 1976)
- At low density, QHS & Mirror inferred growth rates are similar

Can Theory Help HSX Explain Why Lower Effective Ripple Decreases Anomalous Transport?



- Are there configurations in HSX which have different linear growth rates than QHS? (FULL code showed high growth rate due to bad curvature (Rewoldt 2005)) Can we observe the difference?

- Fraction of trapped particles very small towards center of QHS compared to Mirror case which has finite ripple. How does this effect TEM at core for our collisionalities?

- Include proper flow damping for quasisymmetric stellarators in nonlinear simulations of turbulence to determine zonal flow damping

Can one use multi-mode Baldur-like model (Bateman PoP 1998) to predict not just global confinement times, but density and temperature profiles in stellarators?

Near Term Plans

- **Increase heating power to 200 kW with new quasioptical transmission line (mid-April)**

- **Install strain gages and finish comparison to ANSYS calculations. Increase the field to B=1.0T (summer 2006).**
  - **Fundamental ECH at densities up to 1 x 10^{13} cm^{-3}.**
  - **Reduction of energetic tail population.**

- **Measurement of E_r with Diagnostic Neutral Beam on loan from MST (summer 2006).**
  - **Comparison with neoclassical theory**

- **Core fluctuation density fluctuations with reflectometer (soon)**
  - **Evidence of increase in TEM activity for Mirror?**

- **Continue installation of 2^{nd} 200 kW 28 GHz ECH system (2007)**
  - **Power modulation, EBW experiments**