

Reduction of Neoclassical Transport and Observation of a Fast Electron Driven Instability with Quasisymmetry in HSX

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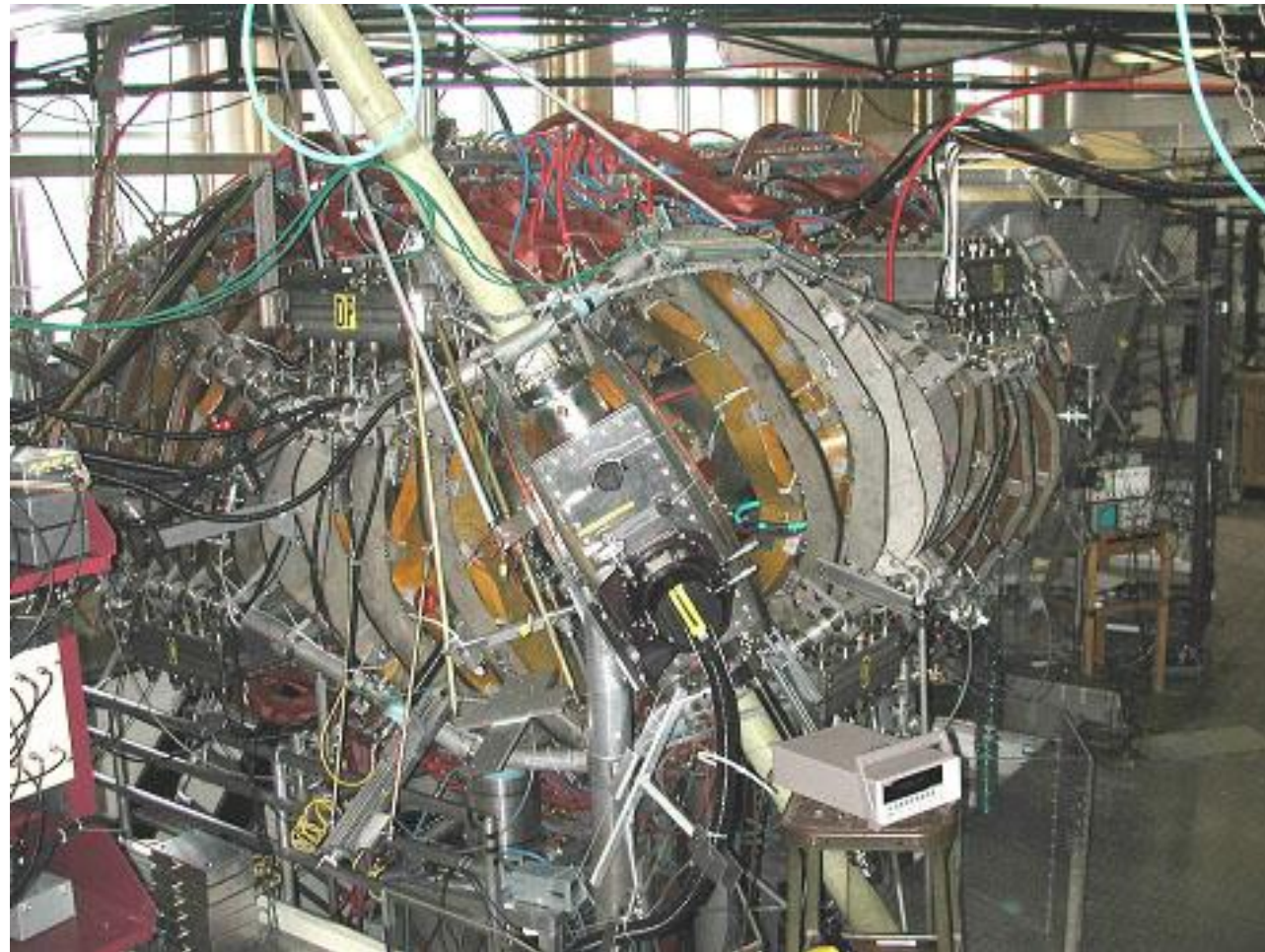
Outline

- HSX operational configurations for studying transport with and without quasisymmetry
- Particle Transport
 - Without quasisymmetry, density profile is hollow due to thermodiffusion
 - With quasisymmetry, density profiles are peaked
- Electron Thermal Transport
 - With quasisymmetry, electron temperature is higher for fixed power
 - Reduction in core electron thermal diffusivity is comparable to neoclassical prediction
- Alfvénic Mode Activity
 - Coherent mode is driven by fast electrons
 - Mode is observed only with quasisymmetry

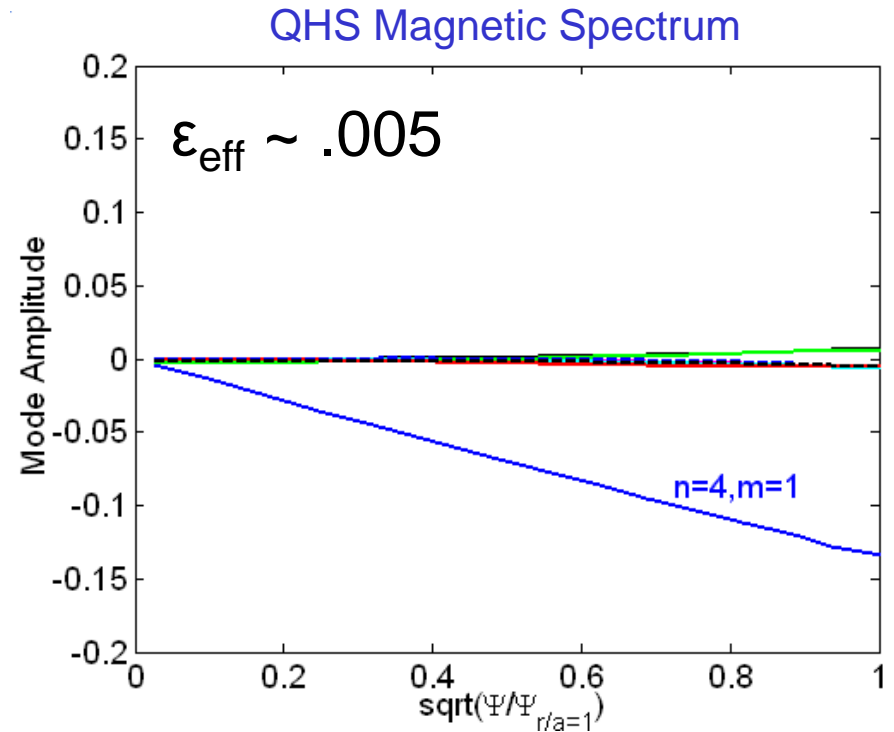
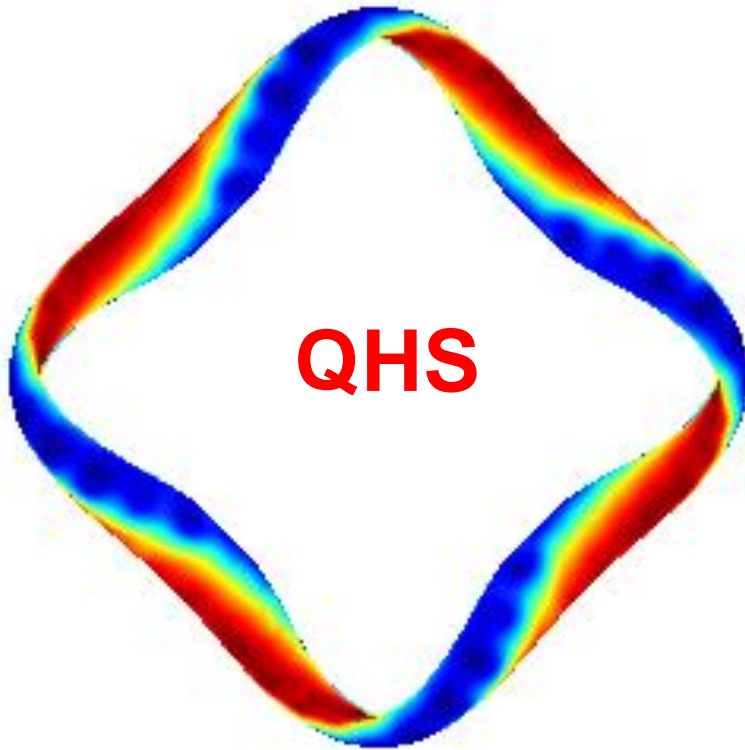


HSX: The Helicallly Symmetric Experiment

Major Radius	1.2 m
Minor Radius	0.12 m
Number of Field Periods	4
Coils per Field Period	12
Rotational Transform	1.05 →1.12
Magnetic Field	0.5 T
ECH Power (2 nd Harmonic)	<100 kW 28 GHz



HSX is a Quasihelically Symmetric Stellarator



HSX has a helical axis of symmetry in $|\mathbf{B}|$

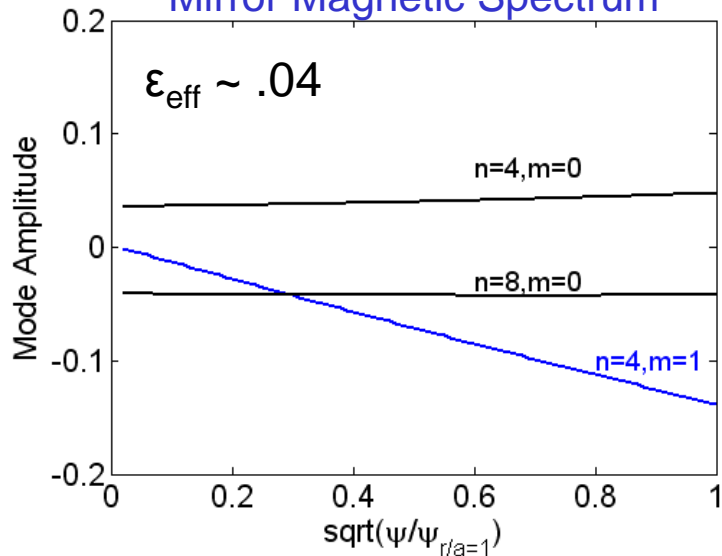
\Rightarrow Very low level of neoclassical transport



Symmetry can be Broken with Auxiliary Coils

- Aux coils add $n=4$ and 8 , $m=0$ terms to the magnetic spectrum
 - Called the Mirror configuration
 - Raises neoclassical transport towards that of a conventional stellarator
- Other magnetic properties change very little compared to QHS
 - Axis does not move at ECRH/Thomson scattering location
 - Favorable for heating and diagnostics

Mirror Magnetic Spectrum



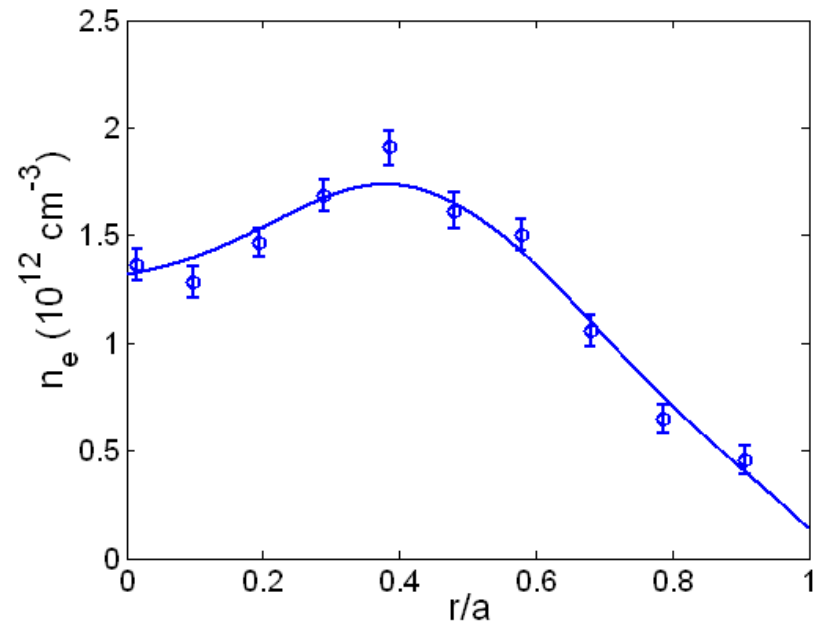
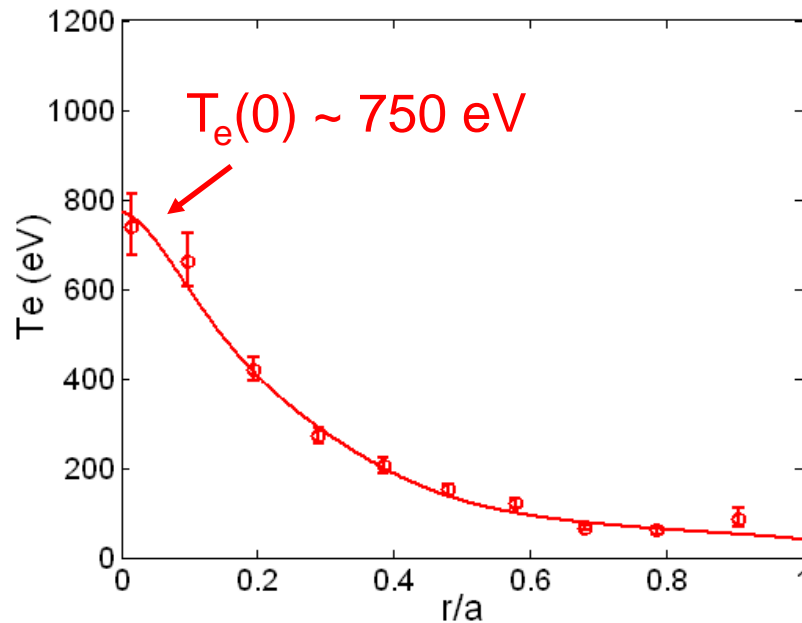
	QHS	Mirror
Transform ($r/a = 2/3$)	1.062	1.071
Volume (m^3)	0.384	0.355
Axis location (m)	1.4454	1.4447
Effective Ripple	0.005	0.040

Change:
 < 1%
 < 10%
 < 1 mm shift
 factor of 8



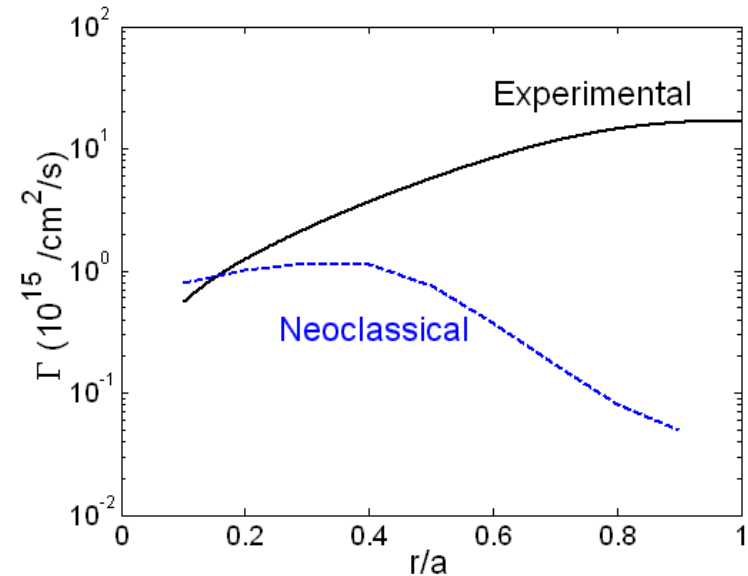
Mirror Plasmas Show Hollow Density Profiles

- Thomson scattering profiles shown for Mirror plasma
 - 80 kW of ECRH, central heating
- Density profile in Mirror is similar to those in other stellarators with ECRH: flat or hollow in the core
 - Hollow profile also observed using 9-chord interferometer
 - Evidence of outward convective flux



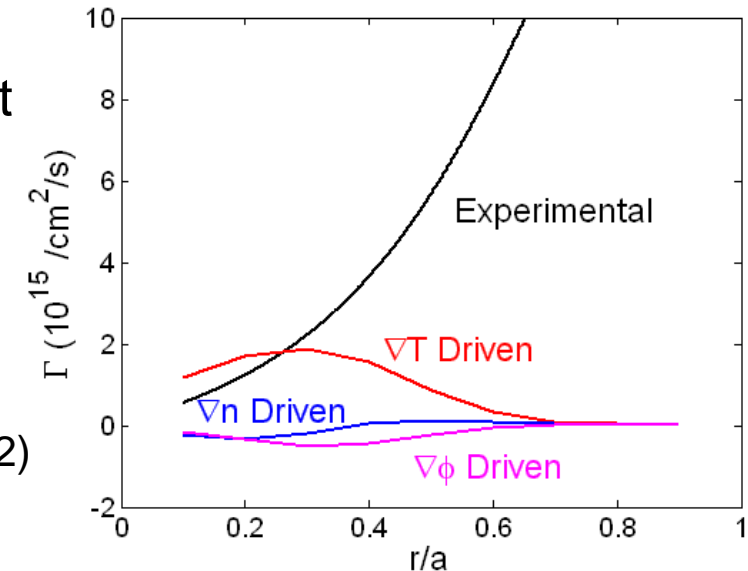
Neoclassical Thermodiffusion Accounts for Hollow Density Profile in Mirror Configuration

- Figure shows experimental and neoclassical particle fluxes
 - Experimental is from absolutely calibrated H_α measurements coupled to 3D neutral gas modeling using DEGAS code [1]
- In region of hollow density profile, neoclassical and experimental fluxes comparable



- The ∇T driven neoclassical flux is dominant

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



[1] D. Heifetz et al., J. Comp. Phys. **46**, 309 (1982)

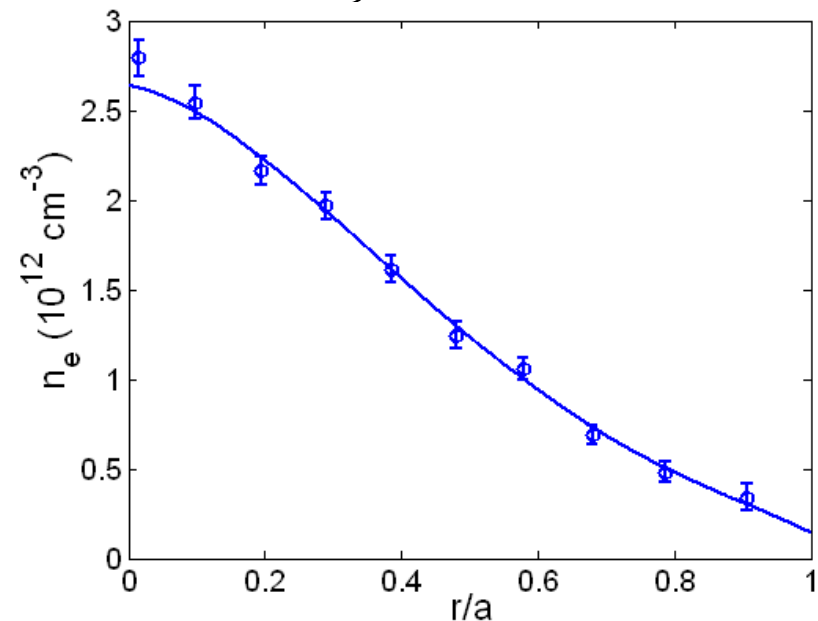
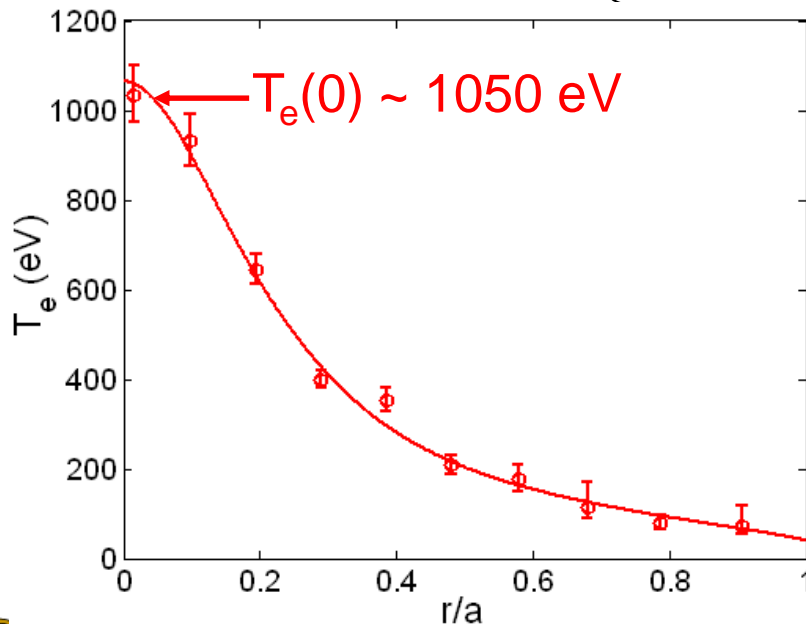


Quasisymmetric Configuration has Peaked Density Profiles with Central Heating

- Both the temperature and density profiles are centrally peaked in QHS
 - Injected power is 80 kW; same as Mirror case
 - Thermodiffusive flux not large enough to cause hollow profile
 - Total neoclassical flux is much less than anomalous

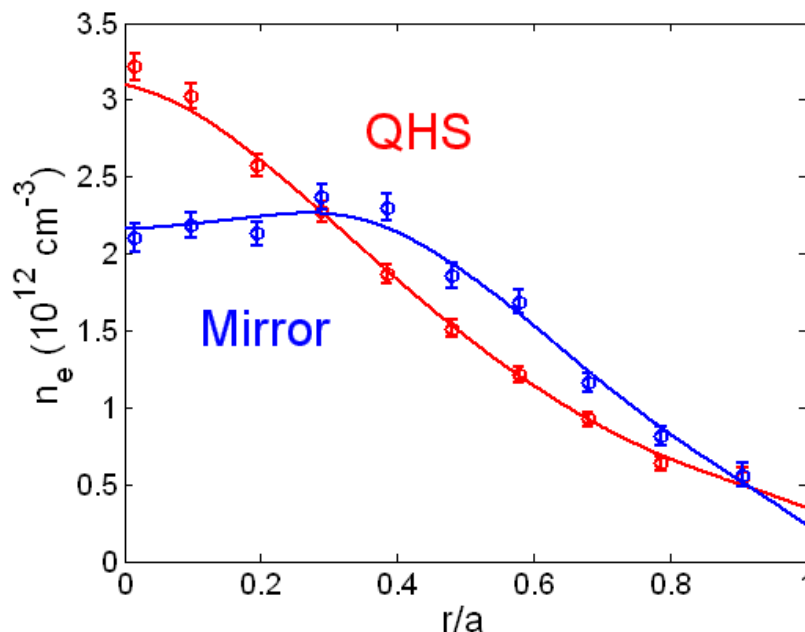
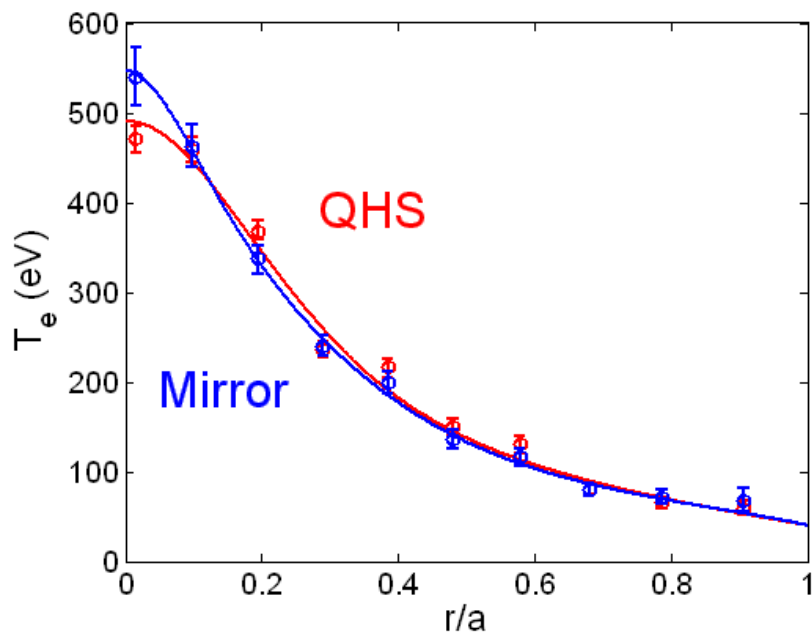
$$\Gamma = -n \left\{ D_{11} \left(\frac{n'}{n} - \frac{qE_r}{T} \right) + D_{12} \frac{T'}{T} \right\}$$

D_{12} is smaller due to quasi-symmetry



Electron Temperature Profiles can be Well Matched between QHS and Mirror

- To get the same electron temperature in Mirror as QHS requires 2.5 times the injected power
 - 26 kW in QHS, 67 kW in Mirror
 - Density profiles don't match because of thermodiffusion in Mirror



The Bulk Absorbed Power is Measured

- The power absorbed by the bulk is measured with the Thomson scattering system
 - Time at which laser is fired is varied over many similar discharges
 - Decay of kinetic stored energy after turn-off gives total power absorbed by the bulk, rather than by the tail electrons
 - At high power, HSX plasmas have large suprathermal electron population (ECE, HXR)

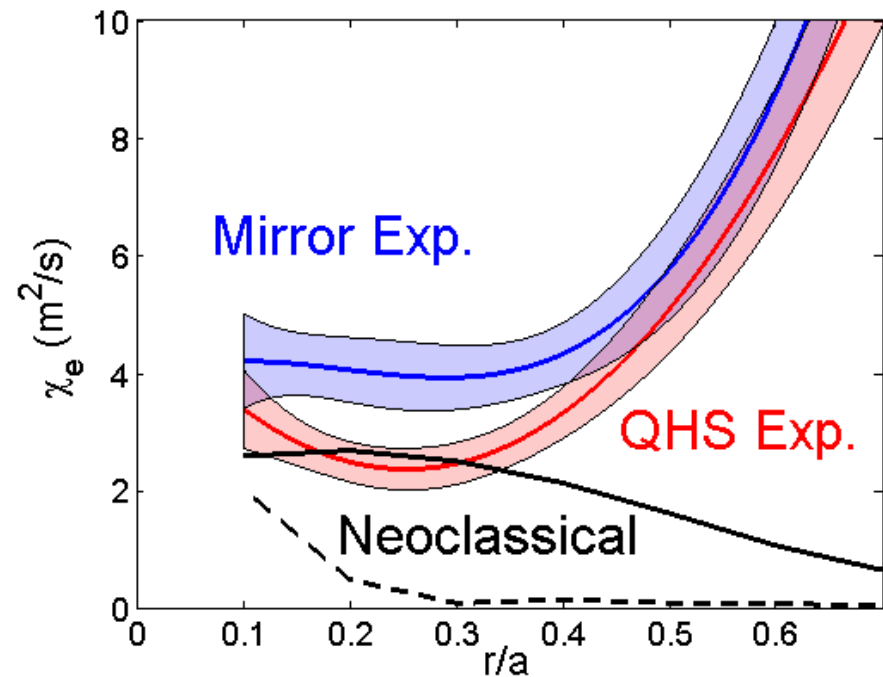
	QHS	Mirror
P_{abs}	10 kW	15 kW
τ_E	1.7 ms	1.1 ms

QHS has 50% improvement in confinement time



Transport Analysis Shows Reduced Thermal Conductivity in QHS

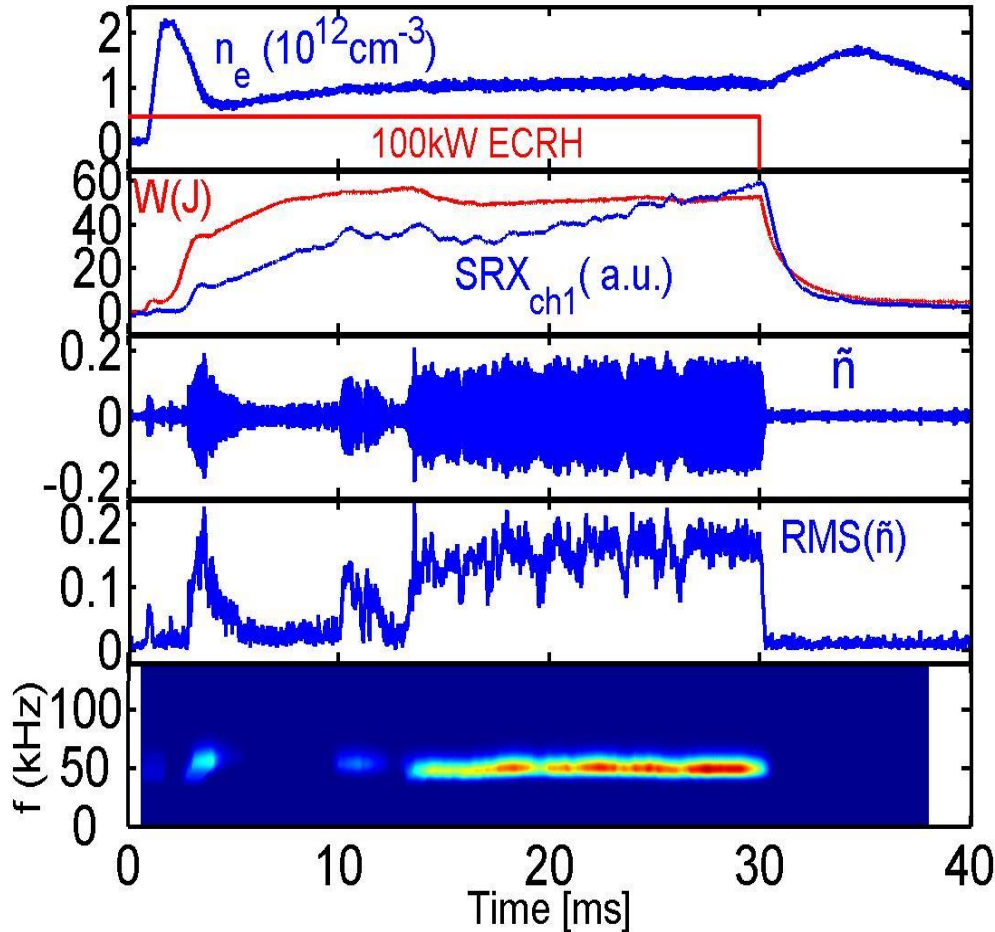
- Absorbed power profile is based on ray-tracing
 - Absorption localized within $r/a \sim 0.2$
 - Very similar profiles in the two configurations
- Convection, radiation, electron-ion transfer $\sim 10\%$ of total loss inside $r/a \sim 0.6$
- **QHS has lower core χ_e**
 - Difference is comparable to neoclassical reduction



$$q_e = -n\chi_e \nabla T_e$$



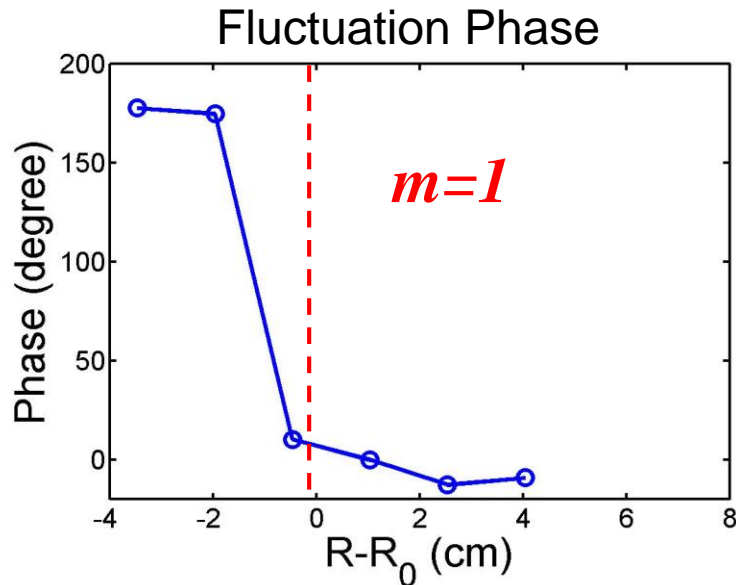
Coherent Density Fluctuations are Observed on the Interferometer



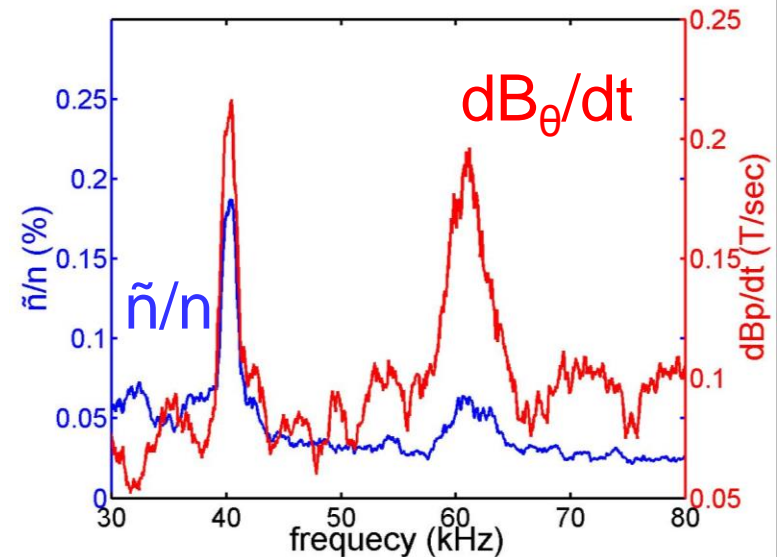
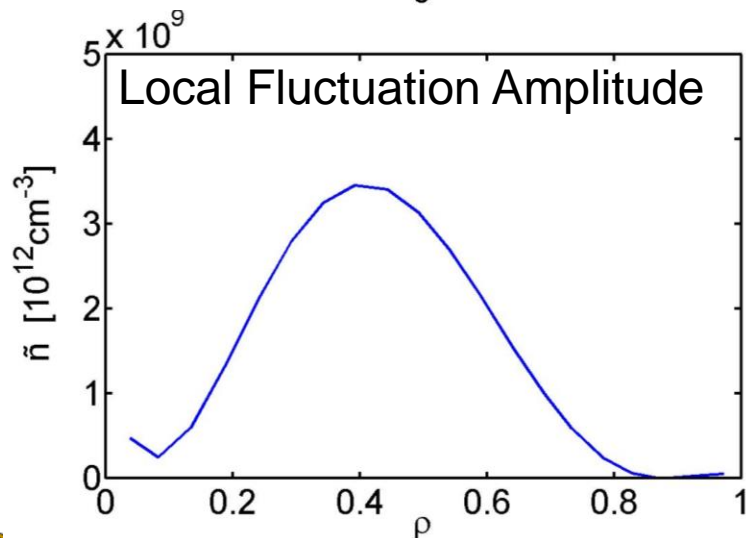
- Mode is observed in frequency range of 20-120 kHz
- Appearance of mode at $t = 14$ msec, coincides with 15% drop in stored energy
- 2nd Harmonic X-mode heating generates superthermal electrons
 - No source for fast ions ($T_i \sim 20$ eV)
 - Energetic electrons are available to drive mode



Fluctuation Shows Global Features

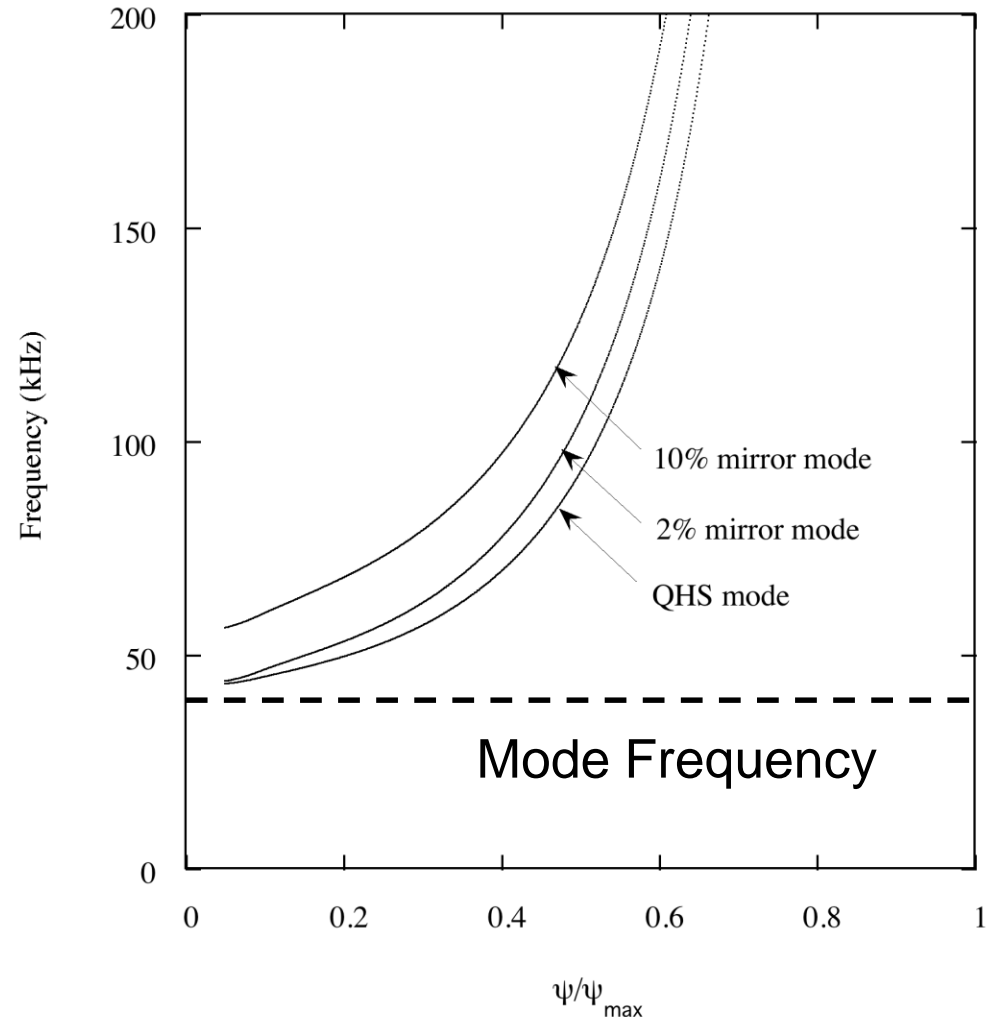


- $m=1$ (180° phase shift across axis)
- Fluctuation magnitude peaks in steep gradient region
- **Electromagnetic component**
- Satellite mode appears at low densities, $\Delta f \sim 20$ kHz
- Only observed in QHS plasmas



Calculations show a GAE Gap in the Spectral Region of Observed Mode

- STELLGAP code used with HSX equilibria
- GAE Gap: 0 - 50 kHz for $B=0.5$ T
 $m=1, n=1$ $n_e(0)=1.8 \times 10^{12}$ cm^{-3}
- Gap for Mirror mode is similar
 - Lack of drive responsible for disappearance of mode in Mirror
- Resonance condition for Alfvénic modes depends on particle energy, not mass
 - Energetic electrons can drive modes, as well as ions



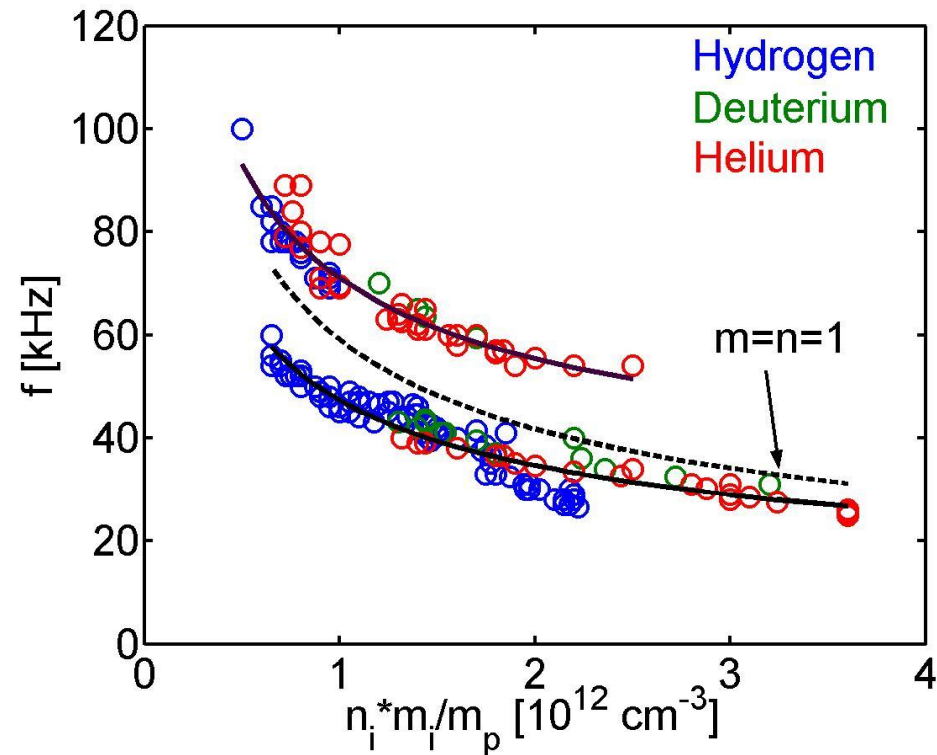
(D.A. Spong)



Mode Frequency Scaling with Mass Density is Consistent with Alfvénic Mode

- Mode frequency decreases with ion mass
- Dashed line is predicted frequency for $m=1, n=1$; GAE gap is below this frequency

$$\omega_{GAE} \leq k_{\parallel} v_A = \frac{(m\ell - n)}{R} \frac{B}{\sqrt{4\pi n_i m_i}}$$



Conclusions

- Quasisymmetry leads to reduced neoclassical transport
 - Lower thermodiffusion results in peaked density profiles
 - Lower thermal conductivity gives higher electron temperatures
- Well confined fast electrons drive an Alfvénic instability
 - Only observed in the quasihelically symmetric configuration; disappears with addition of small symmetry breaking terms

