Effects of Quasisymmetry on Particle and Thermal Transport in HSX

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Outline

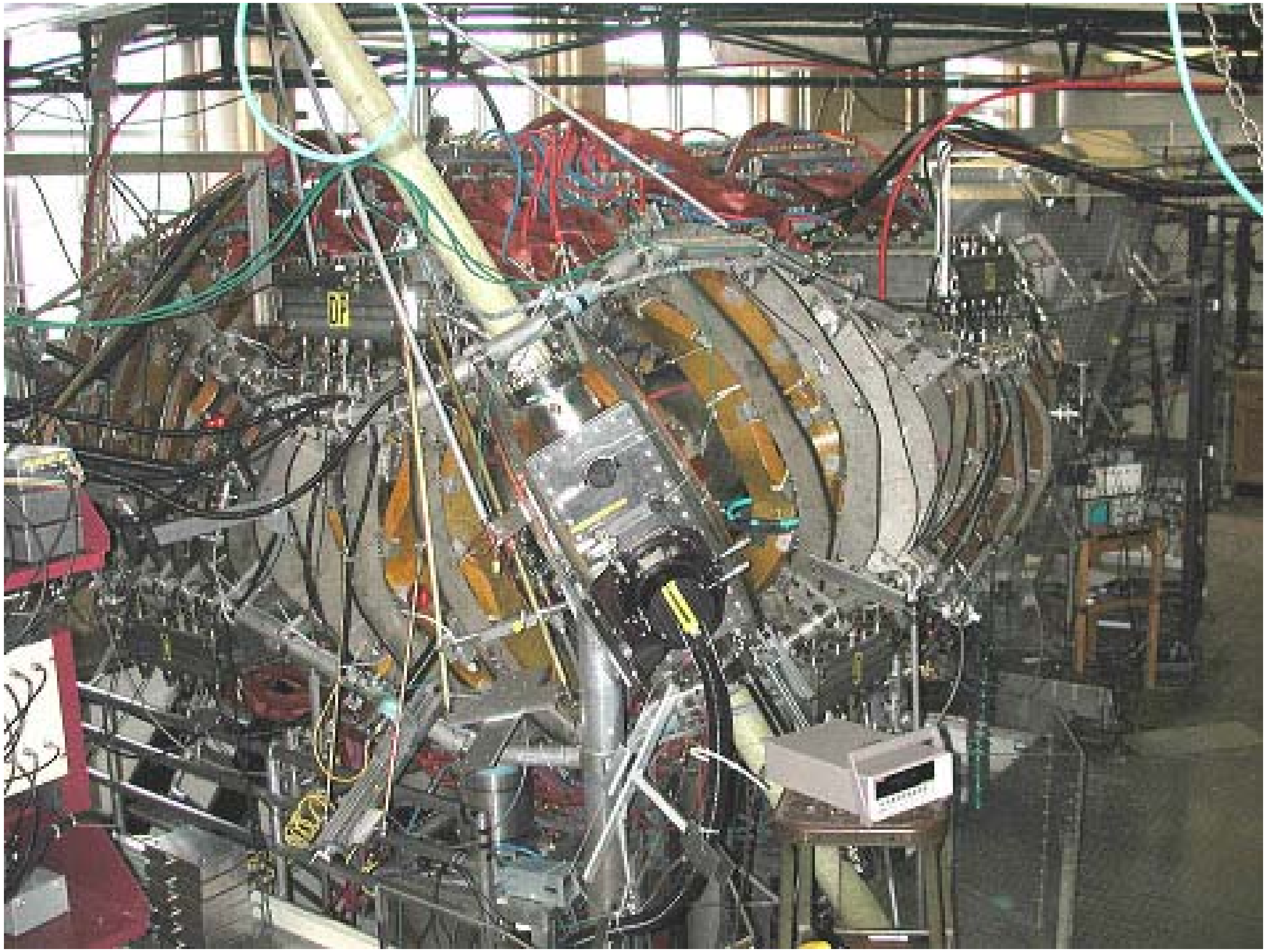
- HSX operational configurations for studying transport with and without quasisymmetry

- Particle Transport
  - H_α measurements and neutral gas modeling give plasma source rate
  - Without quasisymmetry, density profile is flat/hollow due to thermodiffusion
  - With quasisymmetry, density profiles are peaked

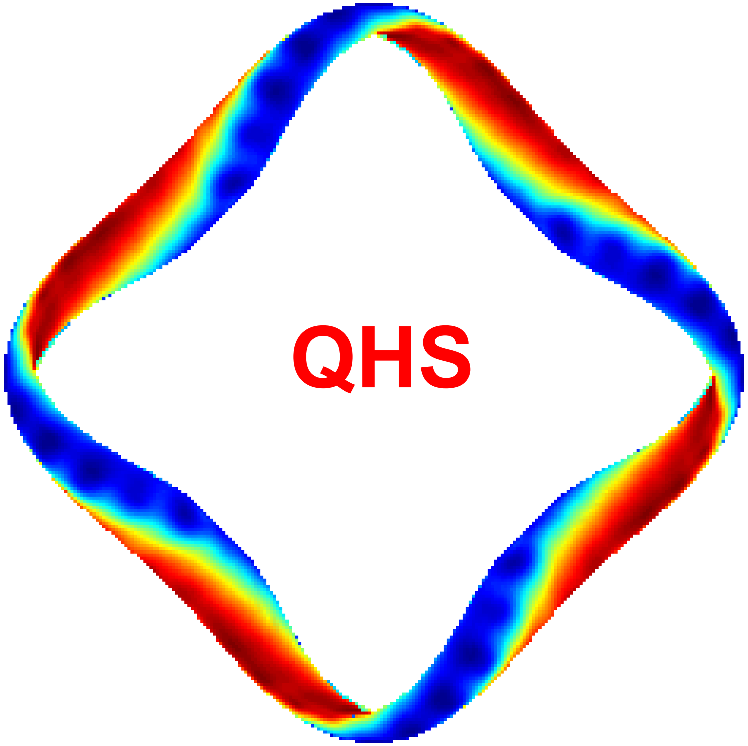
- Electron Thermal Transport
  - Absorbed power profile is measured at ECRH turn-off
  - With quasisymmetry
    - Central electron temperature is higher
    - Core electron thermal diffusivity is lower

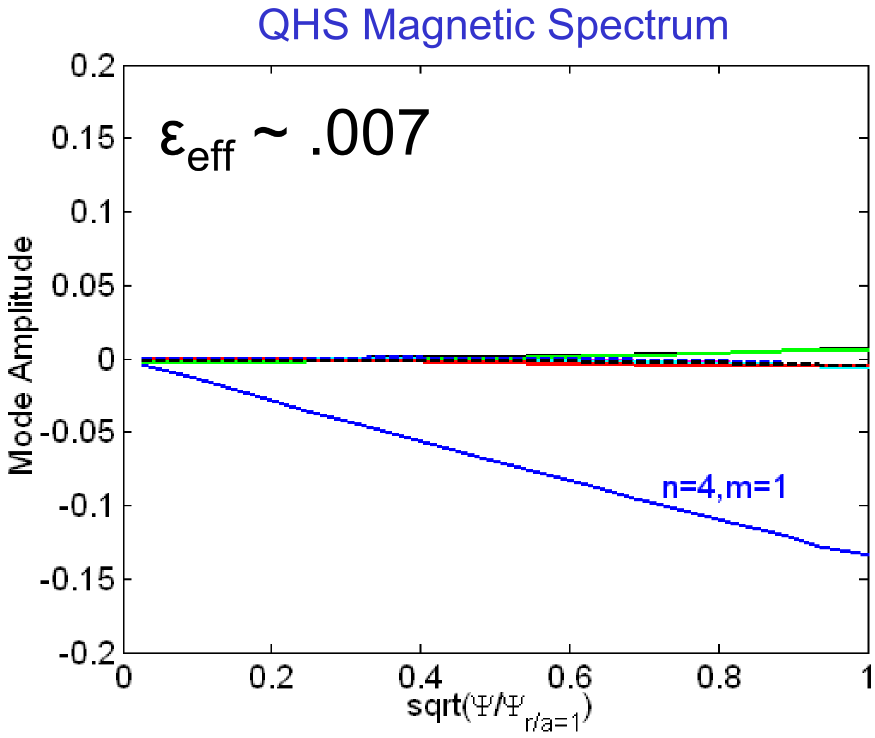
HSX Machine Parameters

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 (2nd Harmonic)	50 kW 28 GHz



HSX is a Quasihelically Symmetric Stellarator

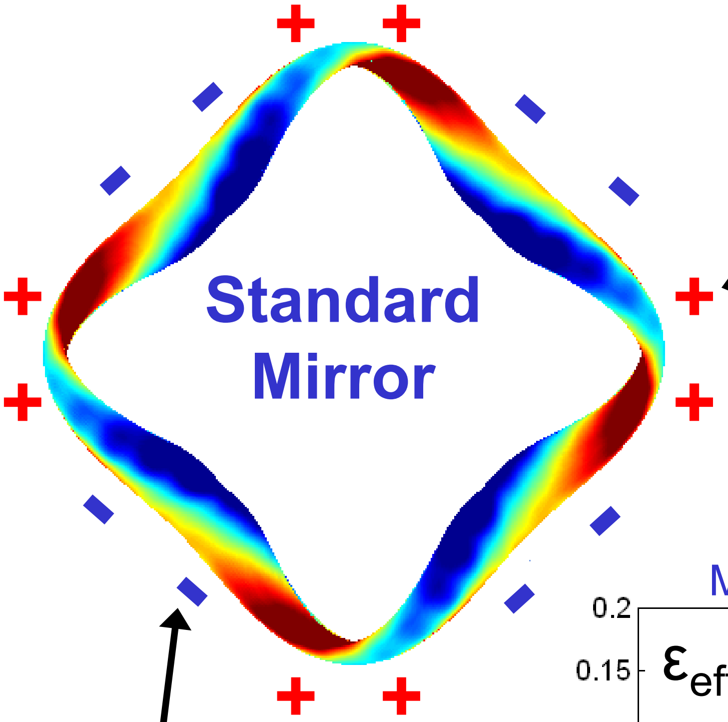




HSX has a helical axis of symmetry in |B|

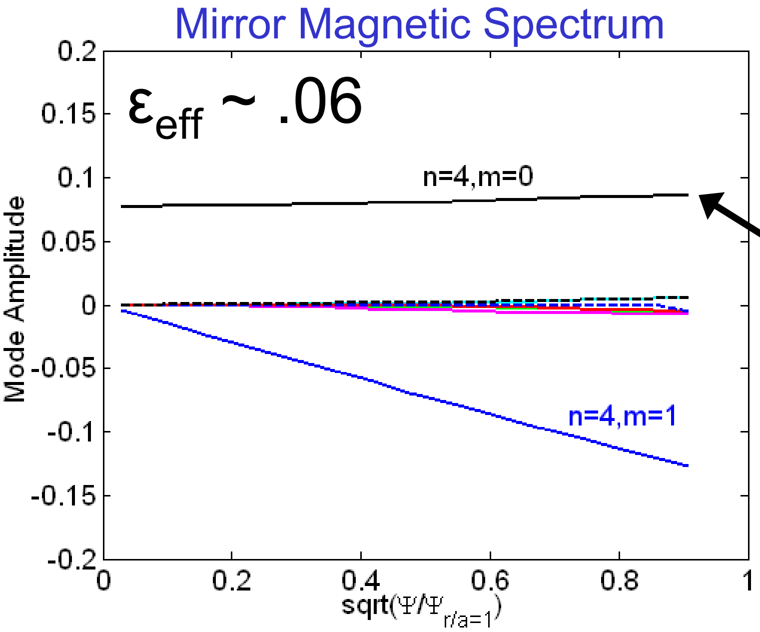
⇒ Very low level of neoclassical transport

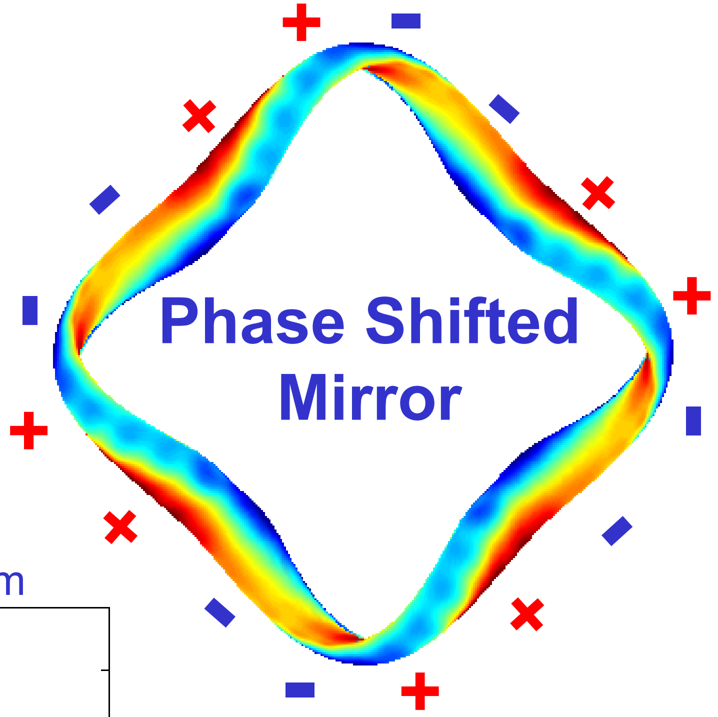
Symmetry can be Broken with Auxiliary Coils



Auxiliary coils add |B|

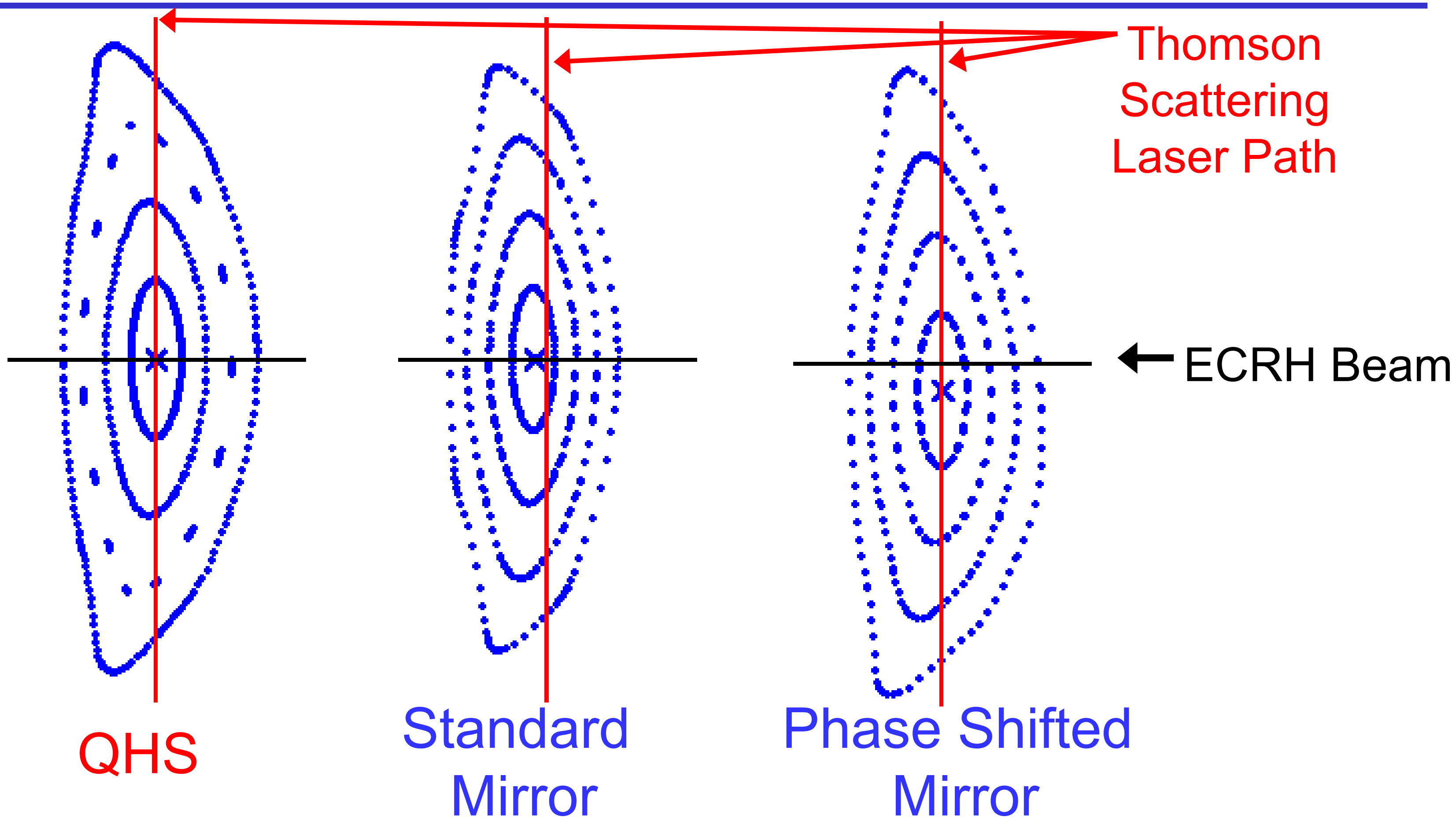
Auxiliary coils subtract |B|





Mirror term has different toroidal phase in two configurations

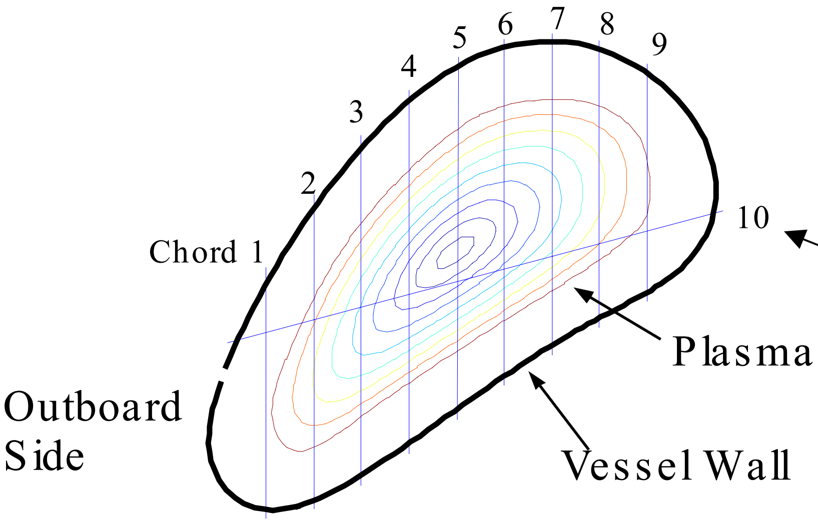
The Two Mirror Configurations have Different Axis Shifts

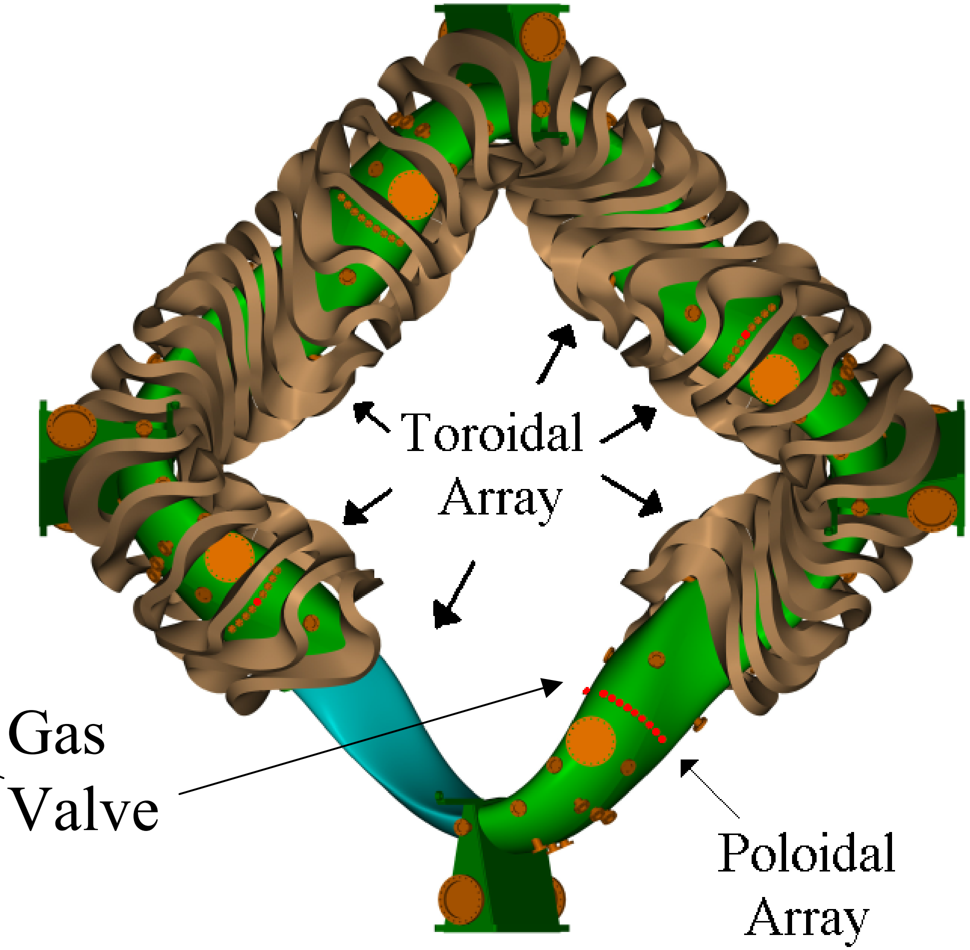


	On-axis TS	On-axis Heating
QHS	Yes	Yes
Standard Mirror	No	Yes
Phase Shifted Mirror	Yes	No

Particle Source is Measured with H_α Array

- HSX has 15 absolutely calibrated H_α detectors forming two arrays
  - Toroidal array: 7 detectors on magnetically equivalent ports
  - Poloidal array: 9 detectors viewing cross section of plasma



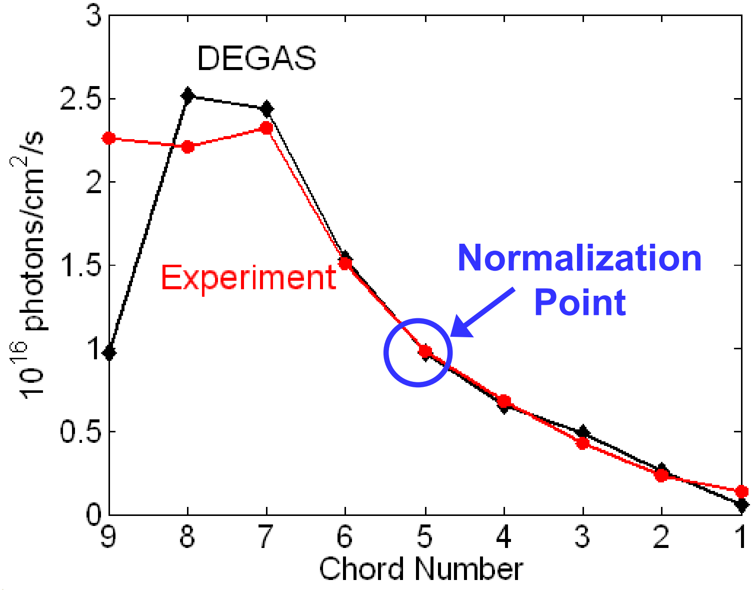


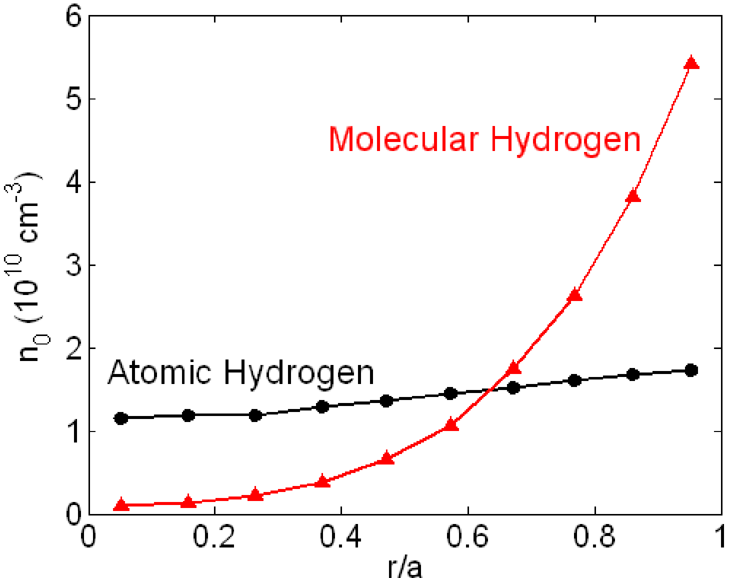
3D DEGAS Modeling Coupled to H_α Measurements Gives Radial Particle Flux

- 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}~3cm)

- H_α measurements + modeling yields the particle source rate density ⇒ total radial particle flux

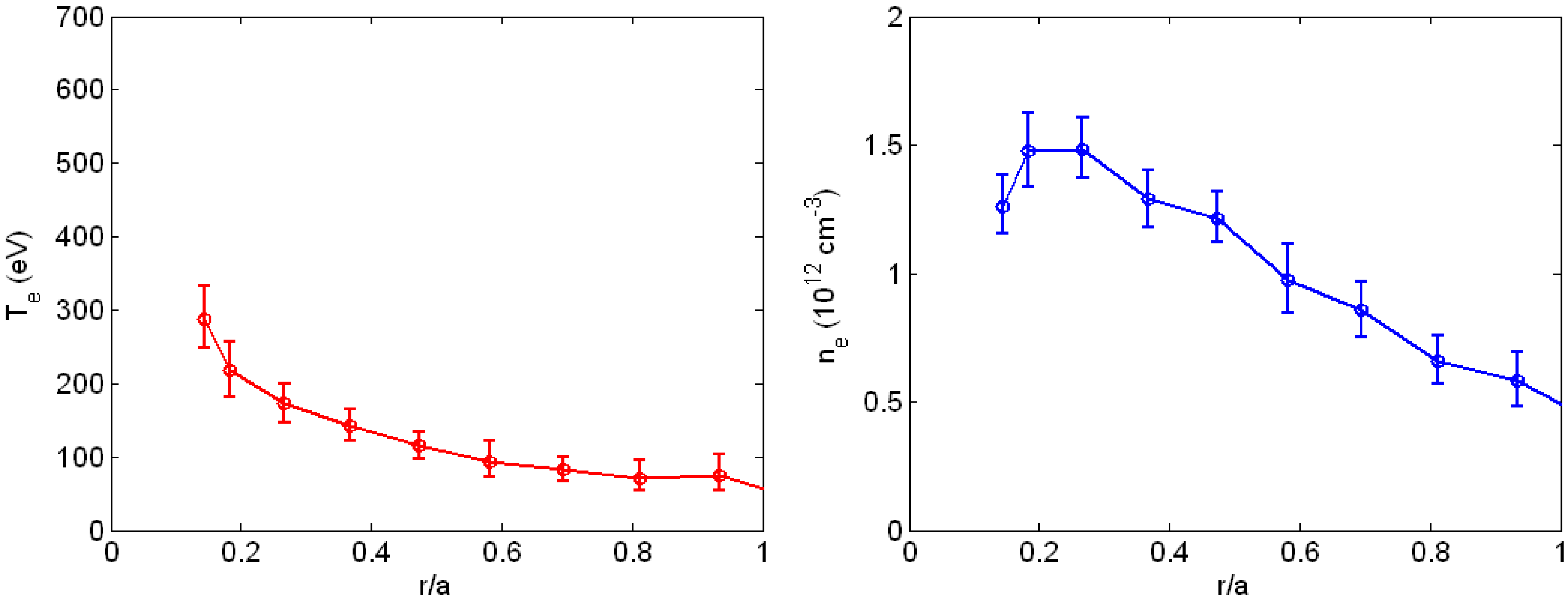




Mirror Plasmas Show Hollow Density Profiles

- Thomson scattering profiles shown for plasma with central heating in Standard Mirror
  - On-axis heating, no on-axis Thomson scattering

- Density profile in Mirror is similar to those in other stellarators with ECRH: flat or hollow in the core
  - Evidence of outward convective flux -> Thermodiffusion?

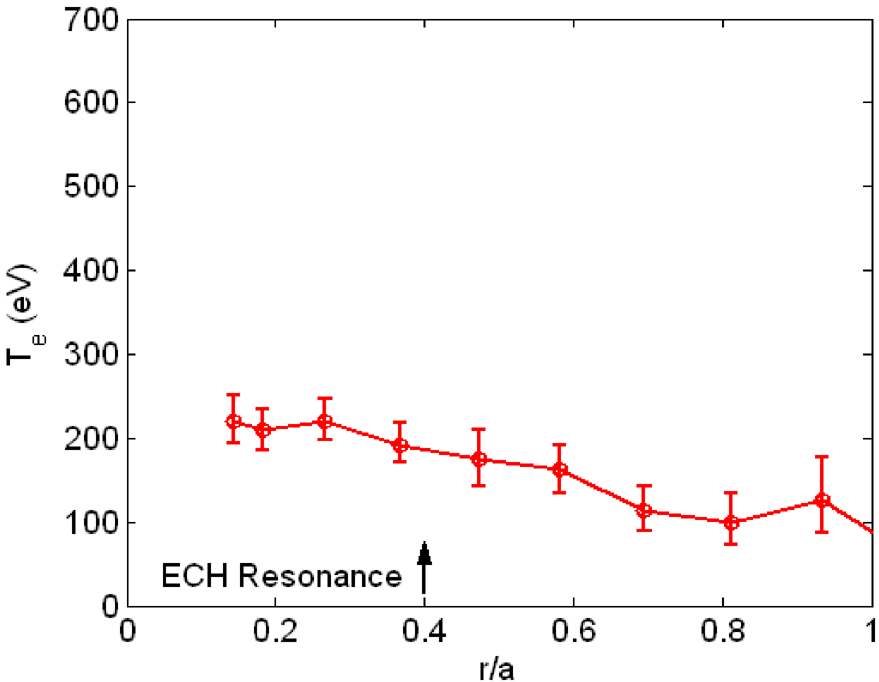


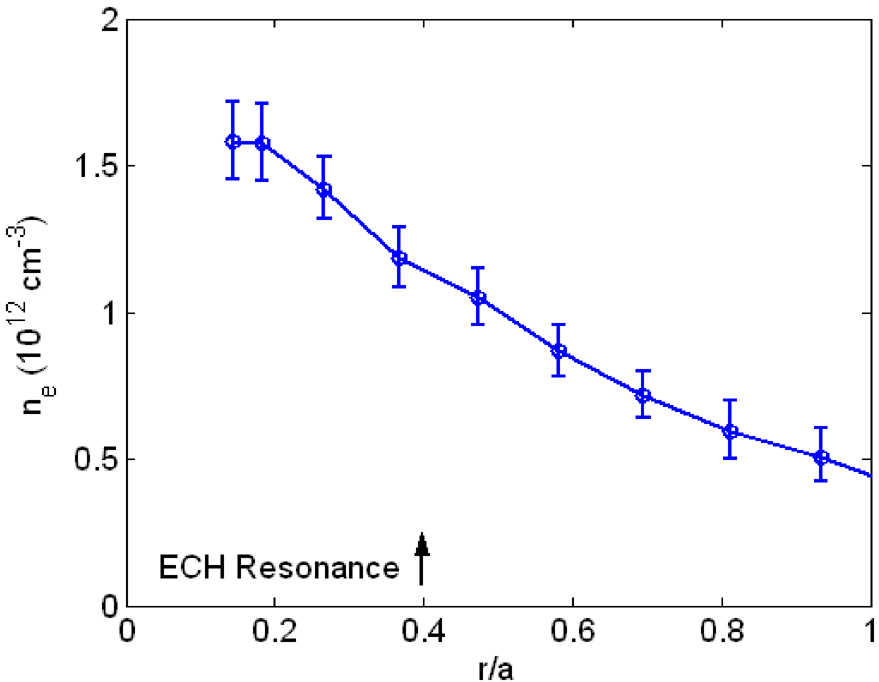
Mirror Density Profile Peaks with Off-axis Heating

- Profiles shown for a plasma with heating at r/a ~ 0.4

- Core temperature flattened, density profile peaked
  - Anticorrelation between temperature and density gradients

- Support for large thermodiffusive flux with on-axis heating





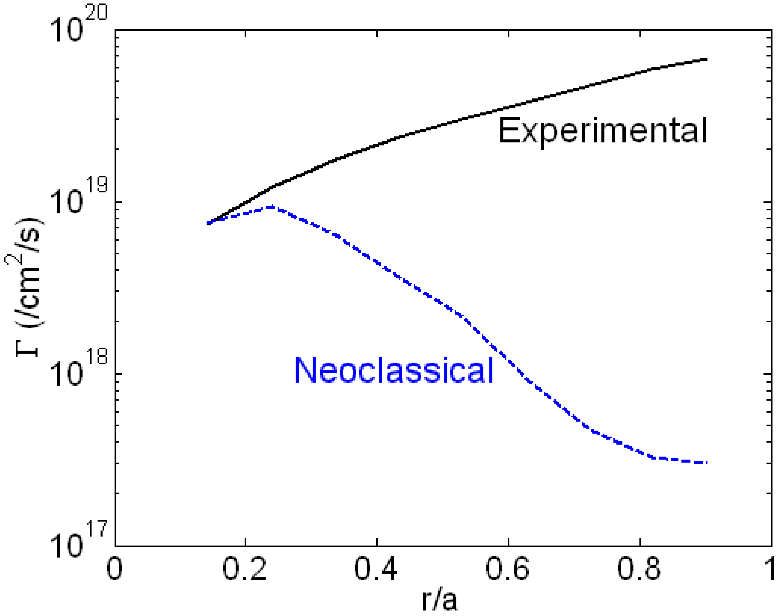
Neoclassical Thermodiffusion Accounts for Hollow Density Profile in Mirror Configuration

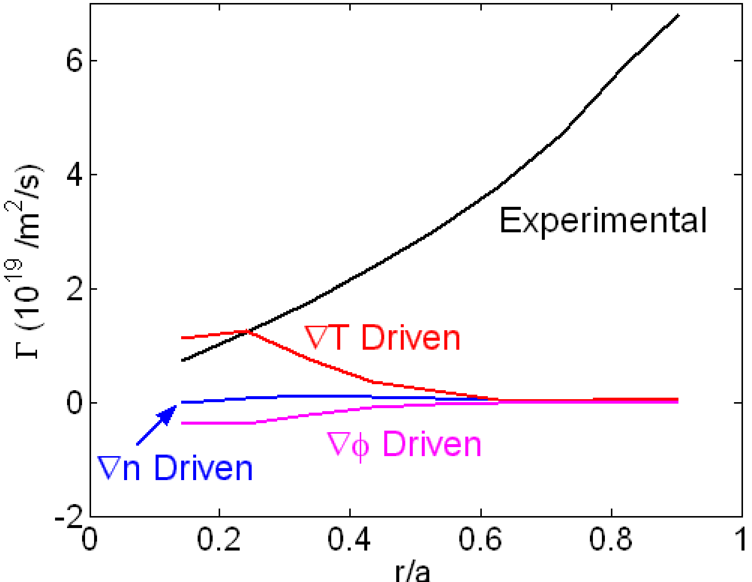
- Figure shows experimental particle flux from H_α + DEGAS, neoclassical prediction

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

- The ∇T driven neoclassical flux is dominant

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



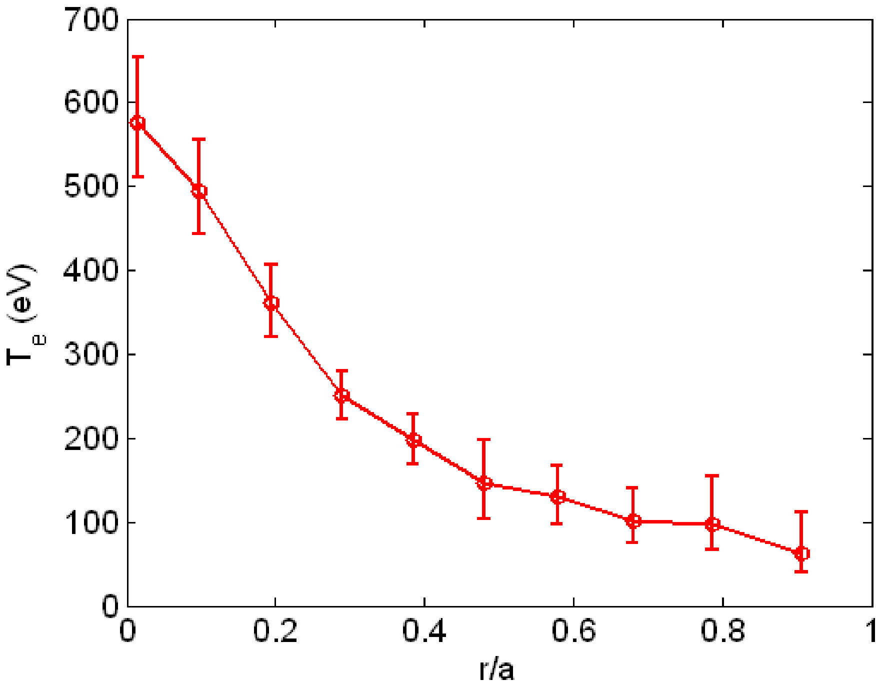


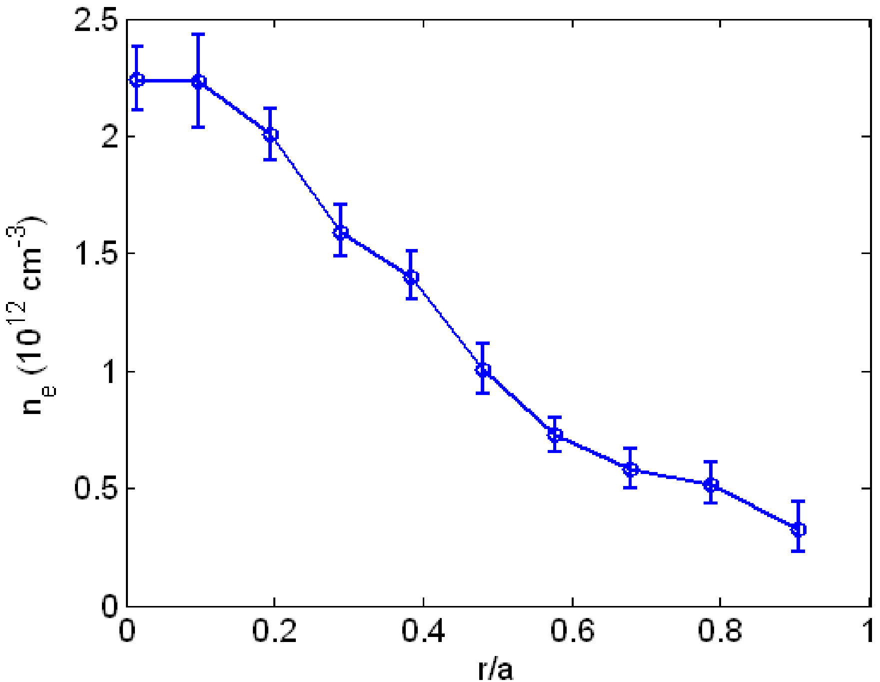
Quasisymmetric Configuration has Peaked Density Profiles with Central Heating

- Both the temperature and density profiles are centrally peaked in QHS
  - Thermodiffusive flux not large enough to cause hollow profile

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

D_{12} is smaller due to quasi-symmetry





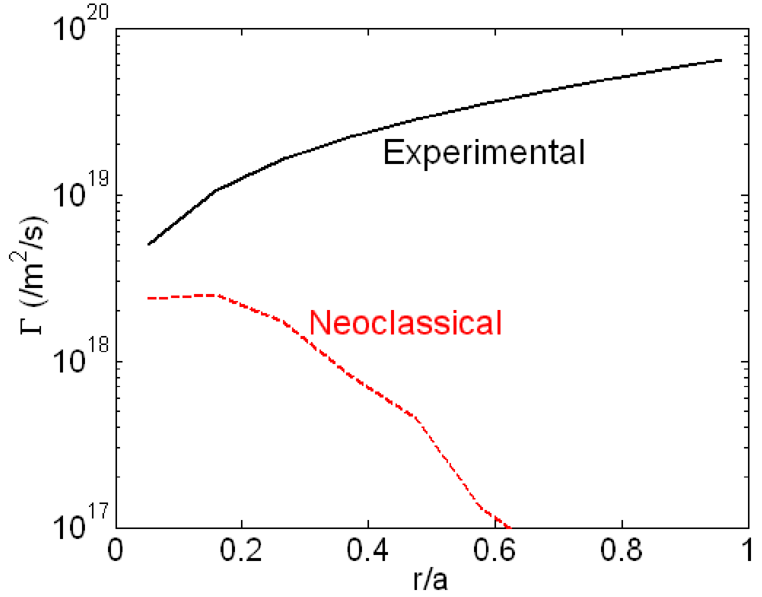
Neoclassical Particle Transport is Dominated by Anomalous in QHS

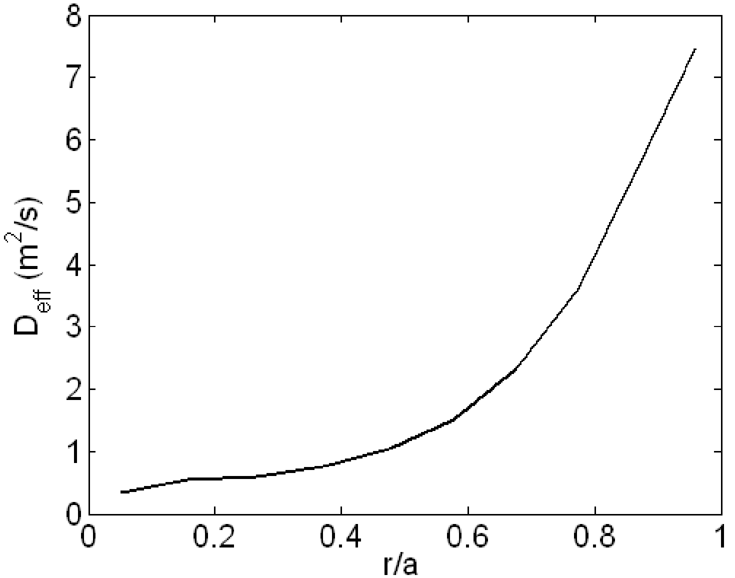
- Neoclassical particle flux now much less than experiment

- Assuming diffusive anomalous transport, effective diffusion coefficient can be estimated:

  $D_{eff} = -\Gamma/\nabla n$

- $D_{eff} \sim 0.5\ m^2/s$ in core, increases towards edge





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Thermal Transport Measurements

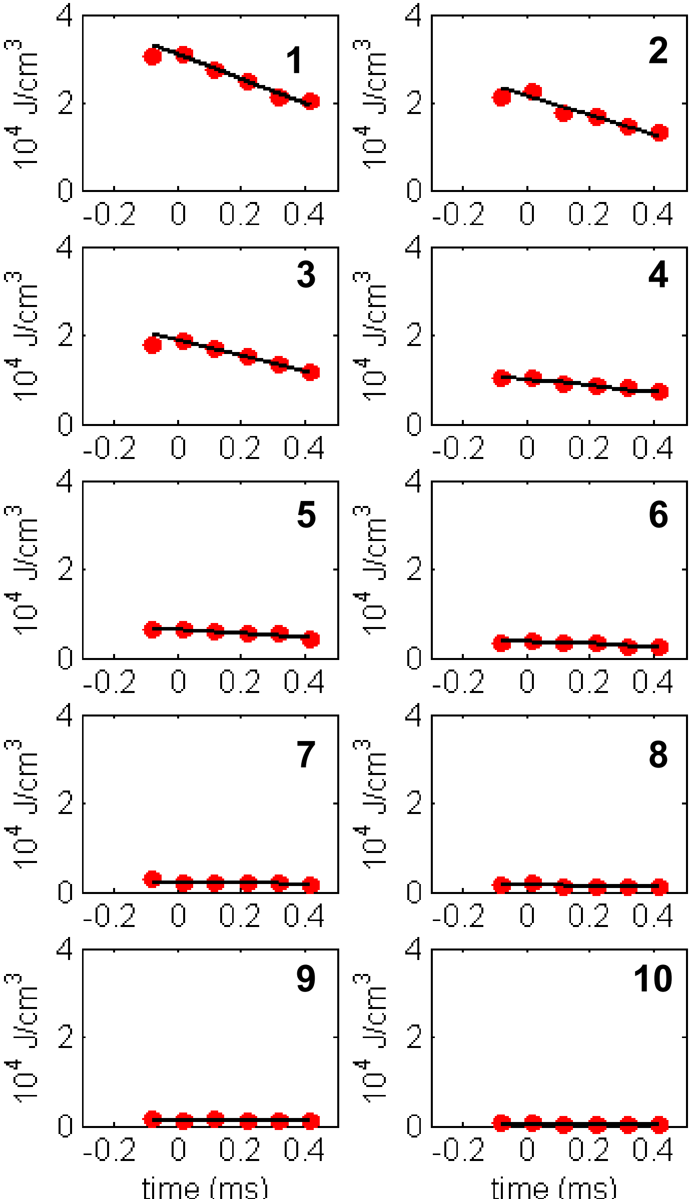
- Absorbed power profile can be obtained from time evolution of plasma profiles after the ECRH turn-off:

$$p_{ECRH} = \frac{\partial}{\partial t}\left[\frac{3}{2} n_e T_e\right]\left(t = t_0^-\right) - \frac{\partial}{\partial t}\left[\frac{3}{2} n_e T_e\right]\left(t = t_0^+\right)$$

t_0 is the ECH turn-off time

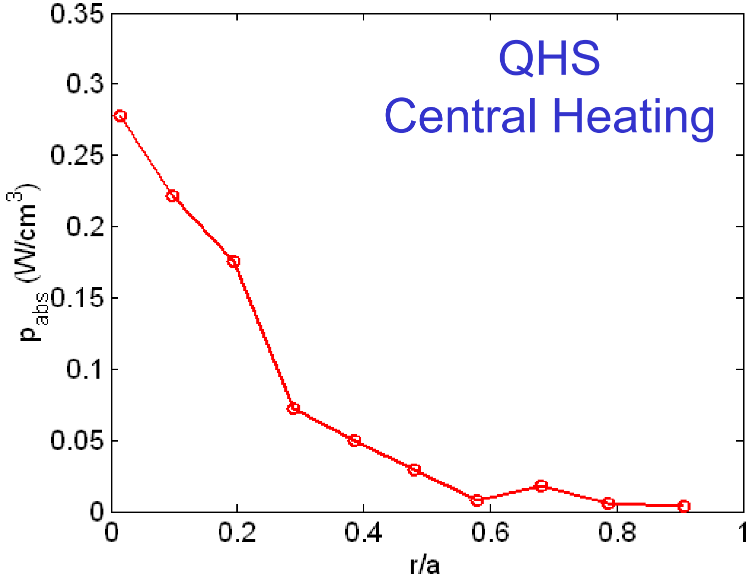
- Time-dependent plasma profiles are measured with the Thomson scattering system
  - ~100 similar plasma discharges, 6 time points
  - Thomson timing changed in increments of 100 μs (τ_E ~ 1.5 ms)
  - Profiles are measured through ECRH turn-off

The Absorbed Power Profile has been Measured



- Figure shows 3/2 nT for each Thomson scattering spatial location vs. time (t=0 is ECH turn-off)

- Total absorbed power is 10 kW (40 kW injected)
  - 25% absorption consistent with ray-tracing



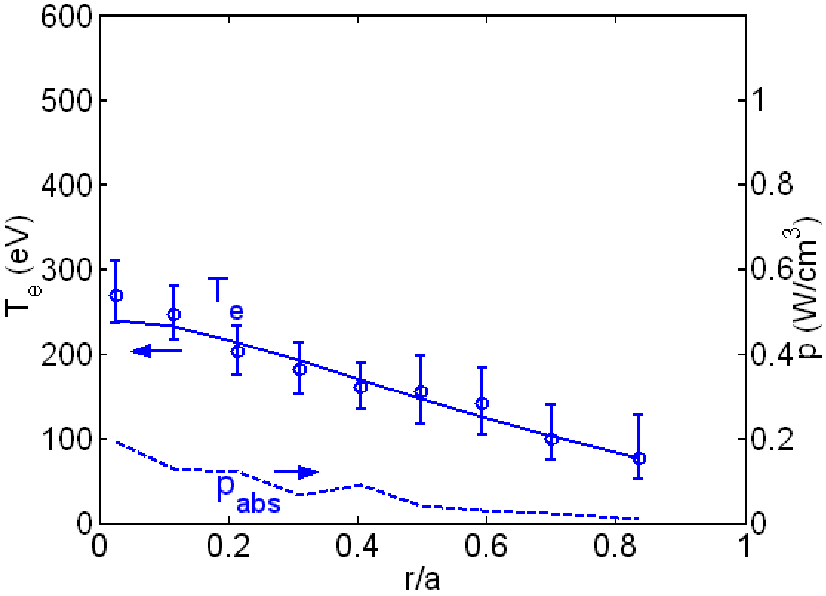
Phase Shifted Mirror has Core Thermal Transport Close to Neoclassical

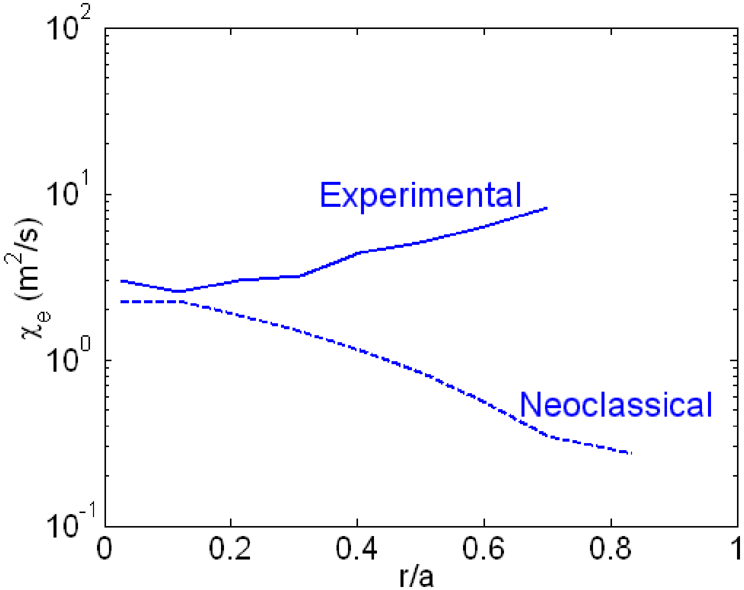
- In Phase Shifted Mirror (PSM), heating is slightly off axis (r/a ~ 0.1), Thomson scattering can make on-axis measurements

- Density, temperature and absorbed power profiles yield electron thermal diffusivity:

$$q_e = \frac{1}{r}\int_0^r r' p_{abs}\left(r'\right)dr' = -n\chi_e \nabla T_e$$

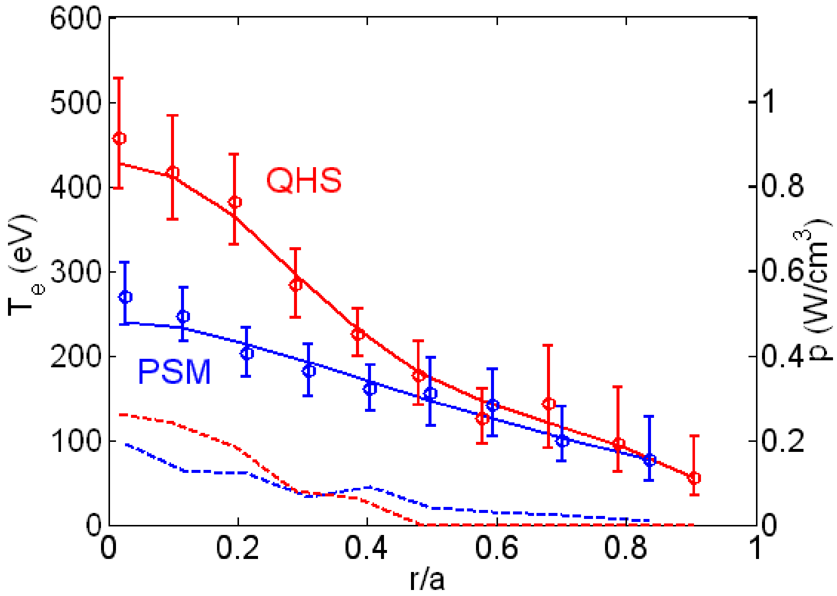
- Core diffusivity is close to the neoclassical value (~ 3 m^2/s)

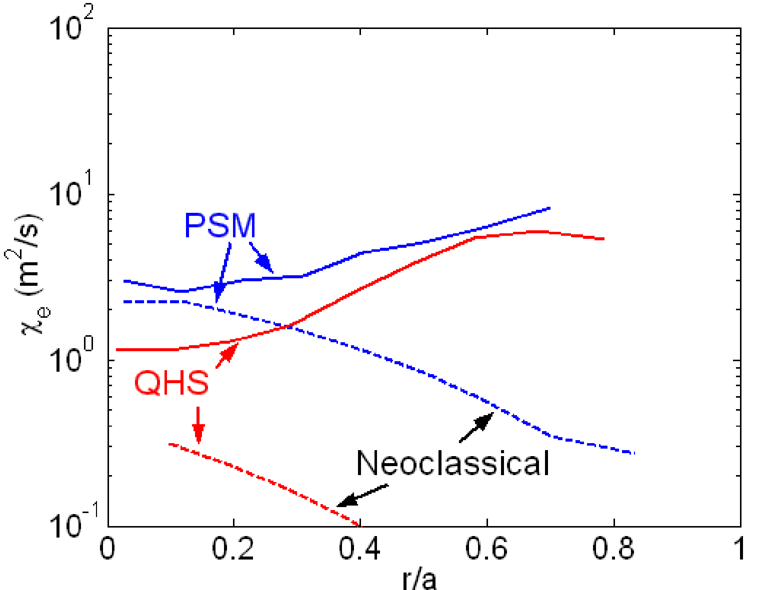




Quasisymmetric Configuration has Higher Electron Temperature

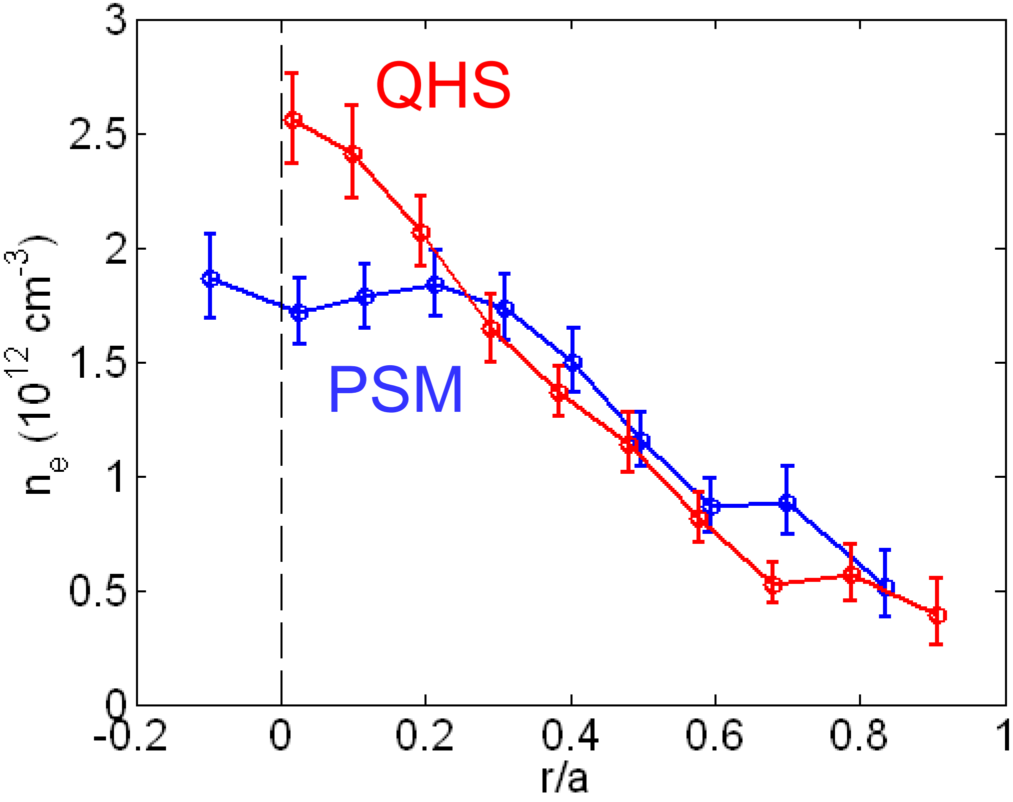
- Heating in QHS at r/a ~ 0.1 to mimic PSM p_{abs} profile
  - Total absorbed power in both configurations is ~ 10 kW
- Central temperature in symmetric configuration ~ 200 eV higher
- Thermal diffusivity at r/a~0.3 is reduced in QHS compared to Mirror (~1 vs. ~3 m^2/s)
- QHS has longer confinement time: $\tau_E^{QHS} \sim 1.5$ ms, $\tau_E^{PSM} \sim 0.9$ ms





Phase Shifted Mirror Plasmas also have Hollow Density Profile

- Similar to Standard Mirror, but with measurements on-axis



Quasisymmetry has a Large Impact on Plasma Profiles

1. Density
   - Thermodiffusion causes hollow profiles when symmetry is broken
   - In QHS, reduced thermodiffusion leads to peaked profiles

2. Temperature
   - The core electron thermal diffusivity is reduced in QHS
   - With the same absorbed power, central temperature is almost 200 eV higher than in Mirror configuration