

Reduction of Particle and Heat Transport in HSX with Quasisymmetry

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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 hollow due to thermodiffusion
 - With quasisymmetry, density profiles are peaked
- Electron Thermal Transport
 - Power absorption is measured at ECRH turn-off using Thomson scattering
 - With quasisymmetry, electron temperature is higher for fixed power
 - Reduction in core electron thermal diffusivity is comparable to neoclassical prediction

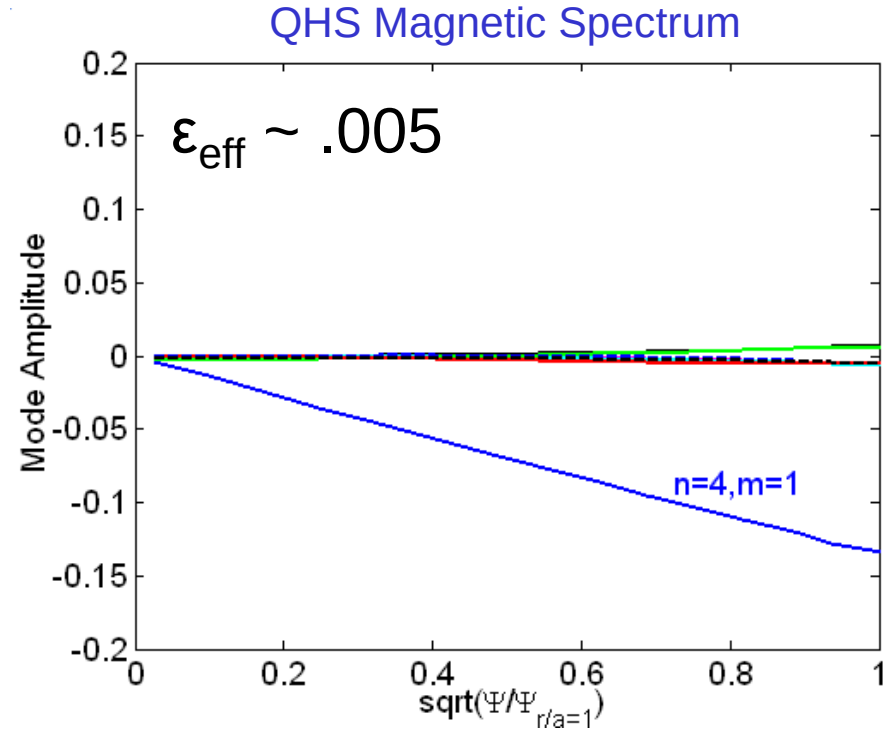
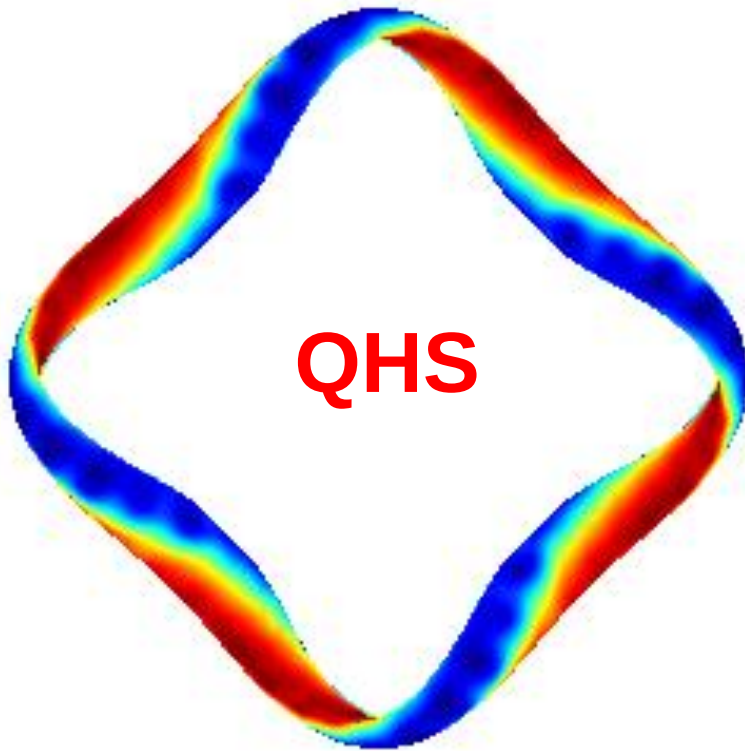


HSX: The Helically Symmetric Experiment

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 Quasi-helically Symmetric Stellarator



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

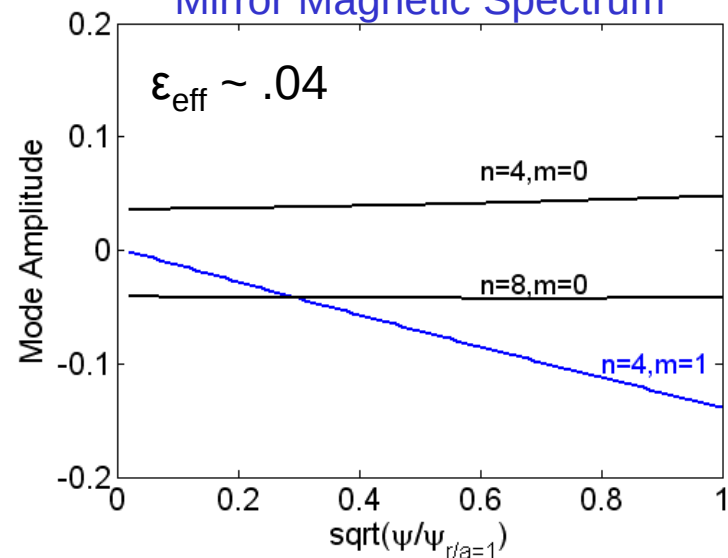
$\Rightarrow$ Very low level of neoclassical transport



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

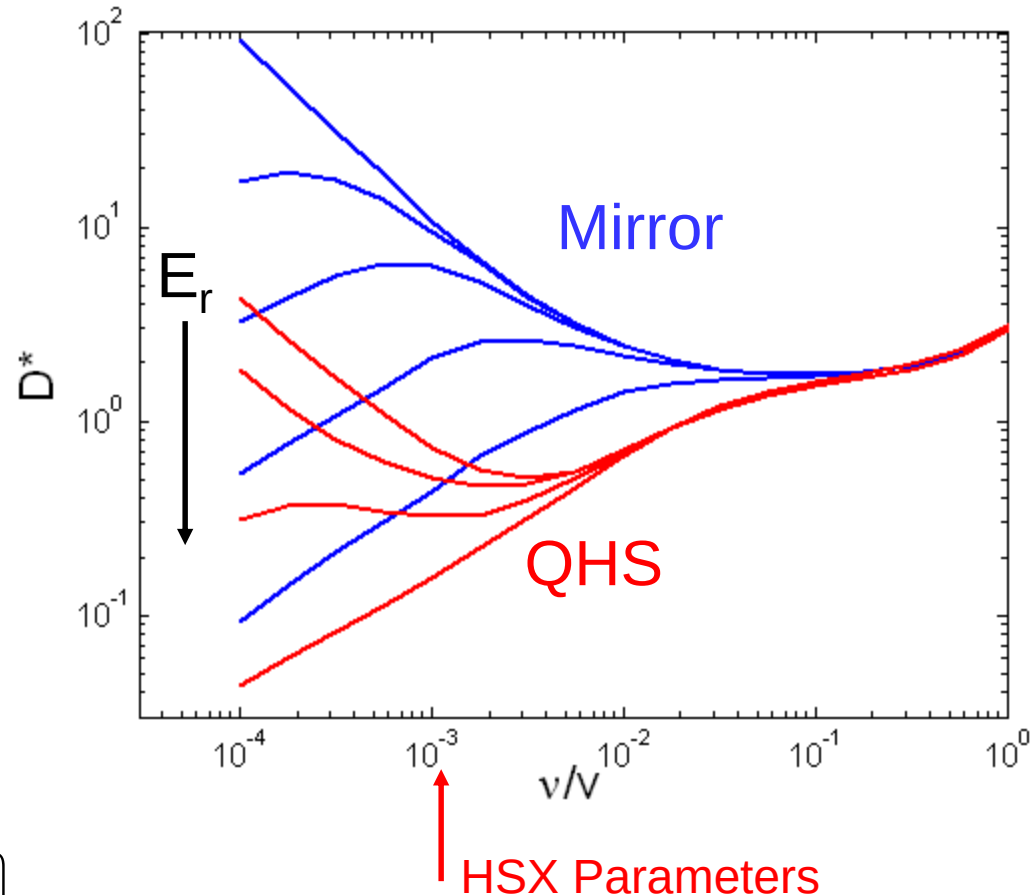


Neoclassical Transport is Reduced in the Quasisymmetric Configuration

- Monoenergetic diffusion coefficients calculated with Drift Kinetic Equation Solver (DKES*)
- Data is fit to an analytic form, including $1/\nu$, $\nu^{1/2}$, and ν regimes of low-collisionality transport
- Integration over Maxwellian forms thermal transport matrix

$$\Gamma_k = -n \left\{ D_{11}^k \left(\frac{n'}{n} - \frac{q_k E_r}{T_k} \right) + D_{12}^k \frac{T_k'}{T_k} \right\}$$

$$Q_k = -n T_k \left\{ D_{21}^k \left(\frac{n'}{n} - \frac{q_k E_r}{T_k} \right) + D_{22}^k \frac{T_k'}{T_k} \right\}$$



*W.I. van Rij and S.P. Hirshman, Phys. Fluids B **1**, 563 (1989).

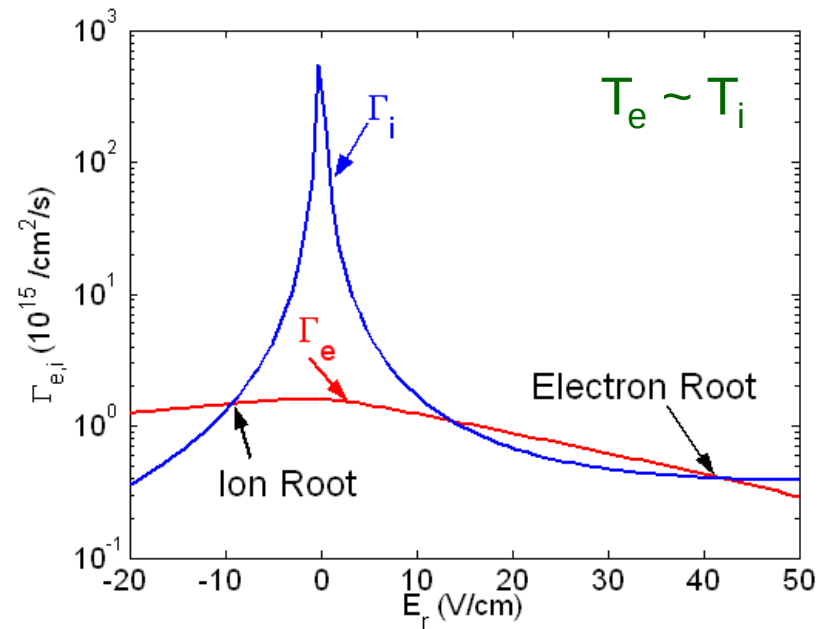


The Ambipolar Electric Field has a Large Effect on Neoclassical Transport

- Electric field is determined by ambipolarity constraint on neoclassical fluxes

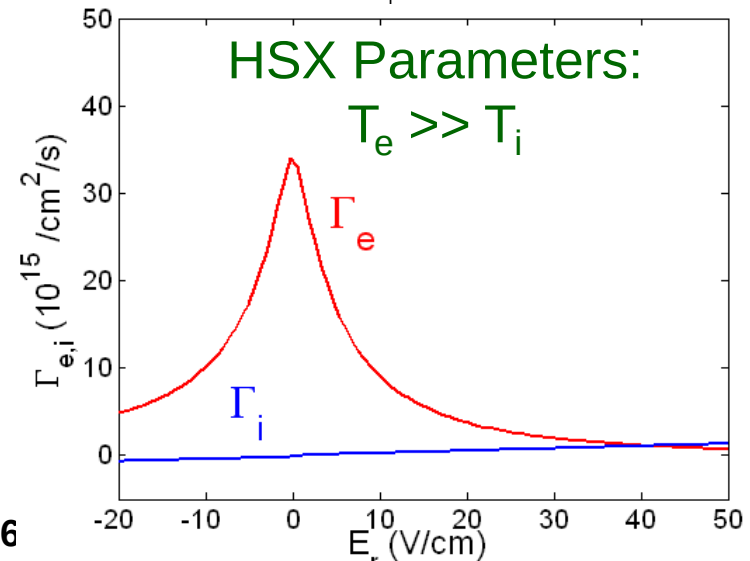
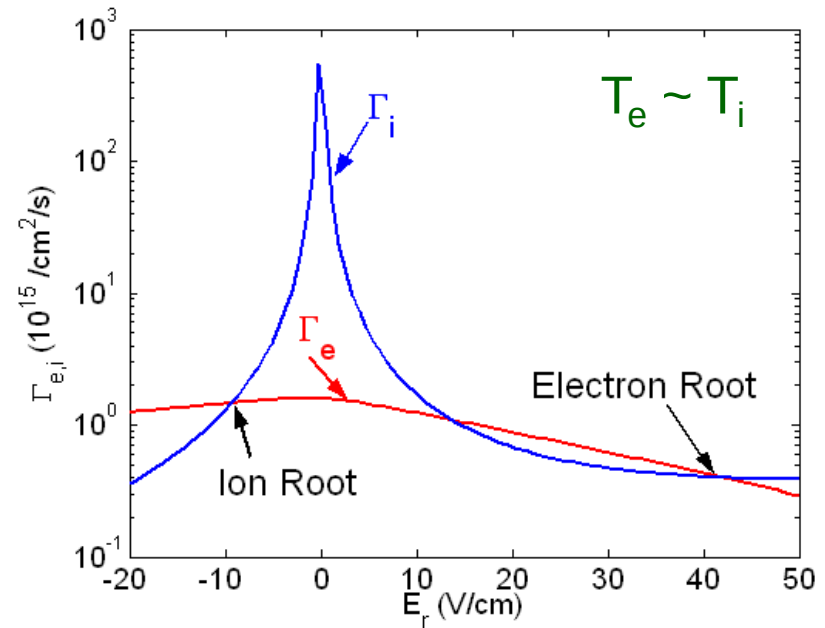
$$\Gamma_e = Z_i \Gamma_i$$

- This has up to three solutions: the ion and electron roots, and an unstable intermediate root



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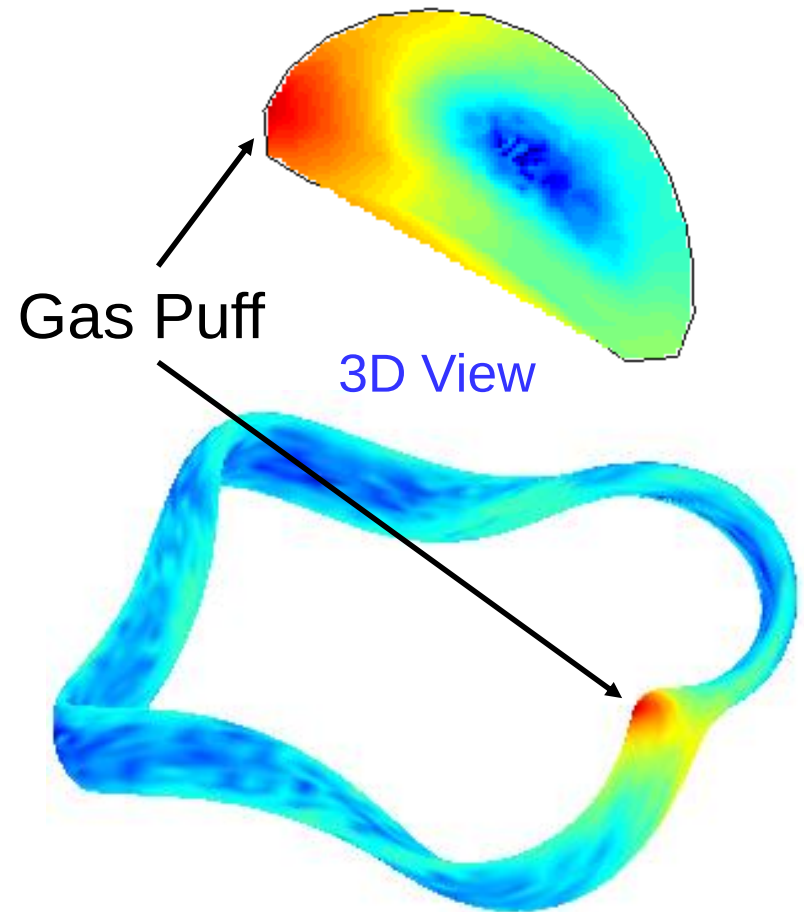
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$$\Gamma_e = Z_i \Gamma_i$$
- This has up to three solutions: the ion and electron roots, and an unstable intermediate root
- In HSX plasmas $T_e \gg T_i$
 - In Mirror, only electron root exists
 - Large electric field reduces Mirror transport, masks neoclassical difference with quasisymmetric field



Particle Source is Calculated with DEGAS

- DEGAS* uses Monte Carlo method to calculate neutral distribution
 - Gives neutral density, particle source rate, H_α emission, etc.
- 3D HSX geometry is used in calculations, along with measured n and T profiles
- Two gas sources are included
 - Gas valve as installed on HSX
 - Recycling at locations where field lines strike wall
 - Magnitude of gas source rate must be specified

Molecular Hydrogen Density:
Plasma Cross Section

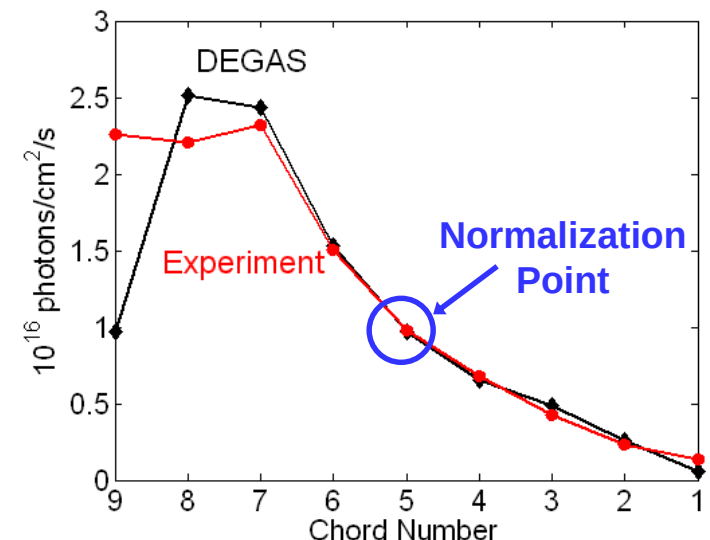
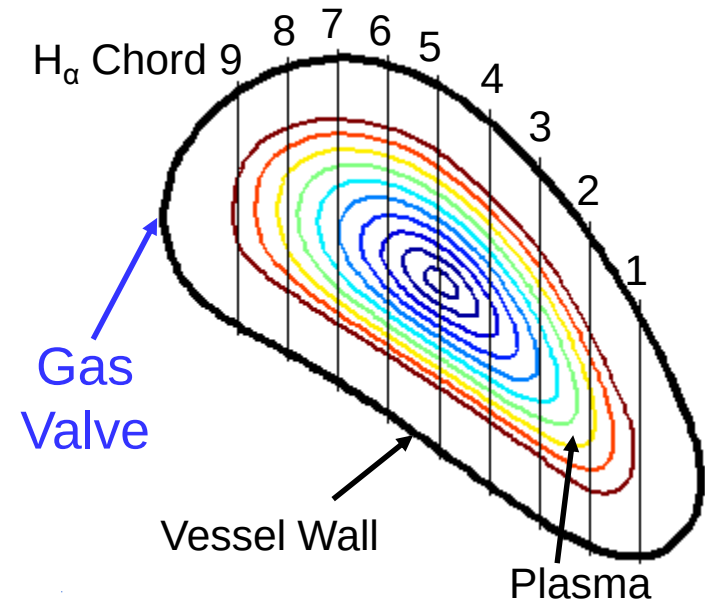


*D. Heifetz et al., J. Comp. Phys. **46**, 309 (1982)



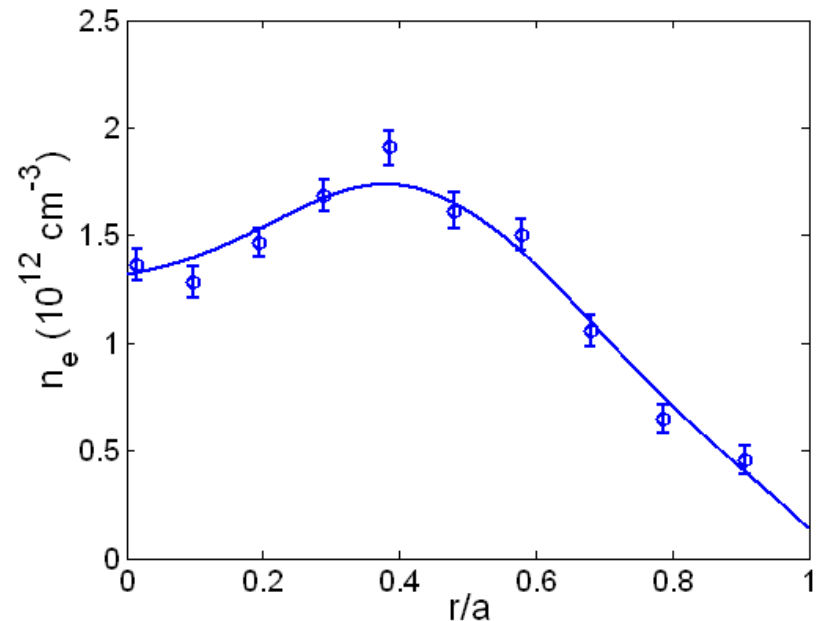
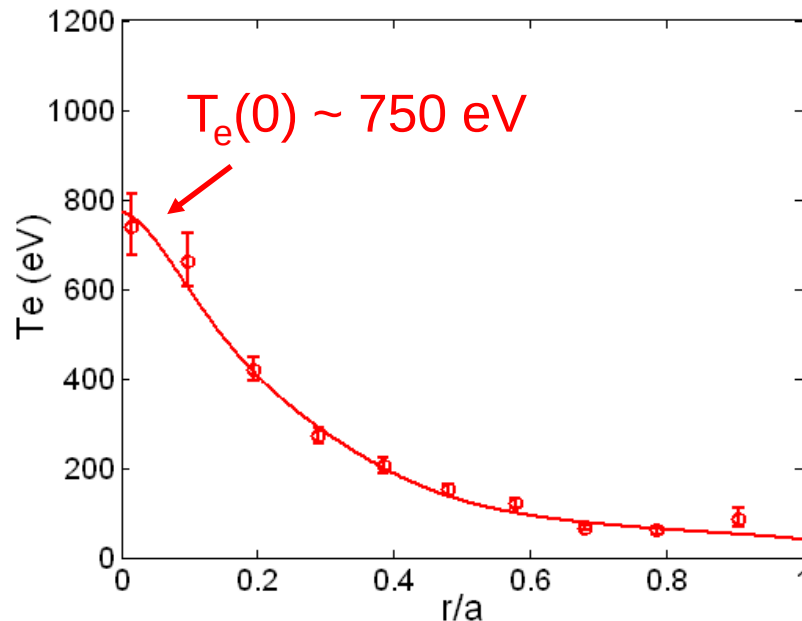
DEGAS Calculations are Calibrated to H_α Measurements

- HSX has a suite of absolutely calibrated H_α detectors
 - Toroidal array: 7 detectors distributed around the machine
 - Radial array: 9 detectors viewing cross section of plasma
- Gas puff rate input to DEGAS is scaled so that DEGAS H_α emission matches experiment at one detector
 - Results in good agreement in profiles of H_α brightness
 - Toroidal array used for recycling contribution
- H_α measurements + modeling yields the particle source rate density $\Rightarrow$ **total radial particle flux**



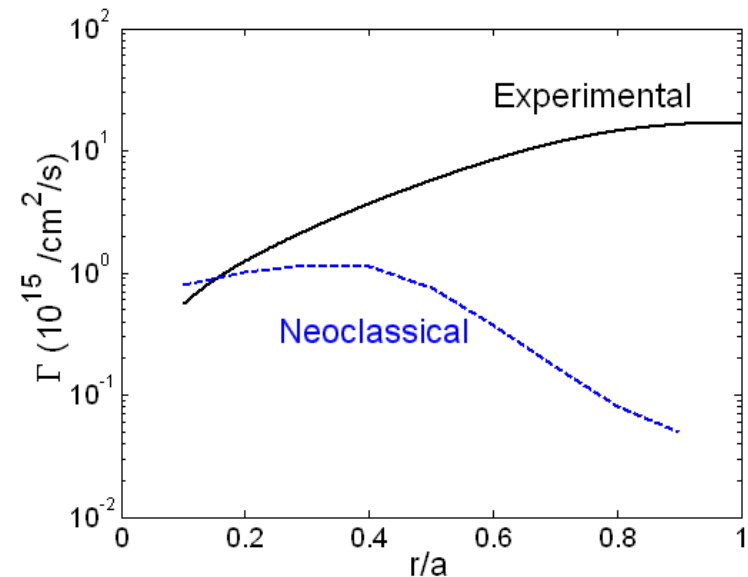
Mirror Plasmas Show Hollow Density Profiles

- 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



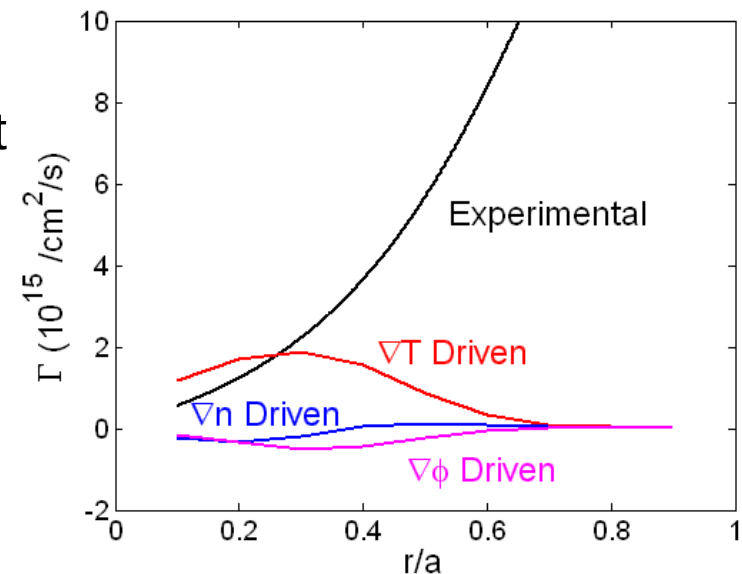
Neoclassical Thermodiffusion Accounts for Hollow Density Profile in Mirror Configuration

- Figure shows experimental and neoclassical particle fluxes
 - Experimental from H_α /DEGAS
 - Neoclassical from DKES calculations
- In region of hollow density profile, neoclassical and experimental fluxes comparable



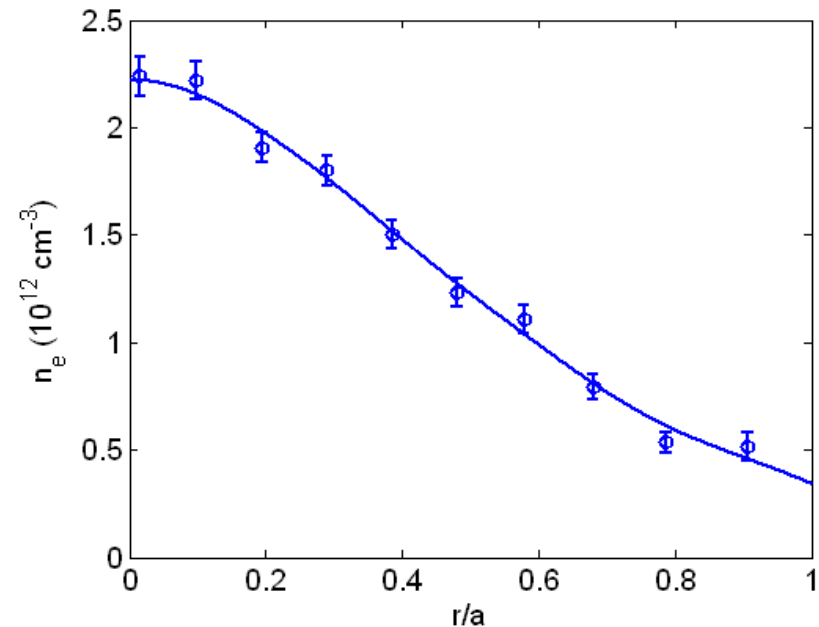
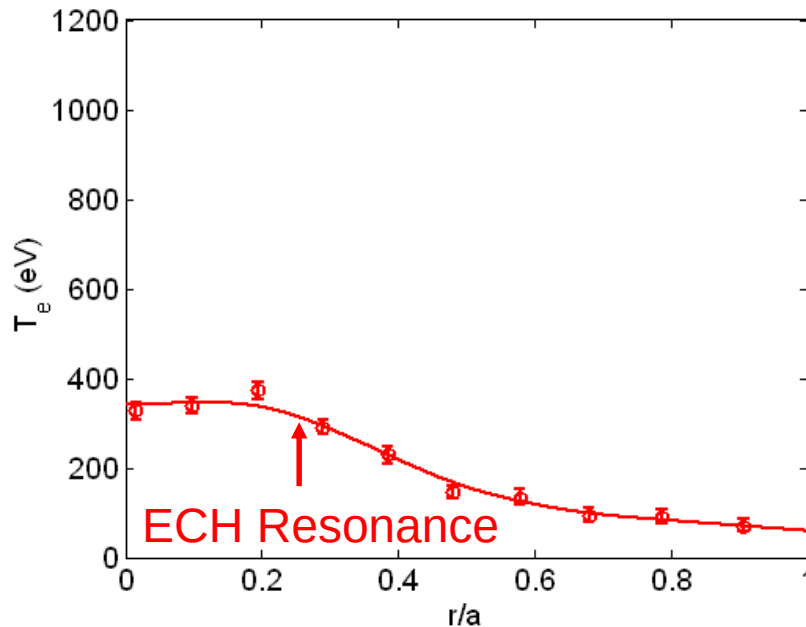
- The ∇T driven neoclassical flux is dominant

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



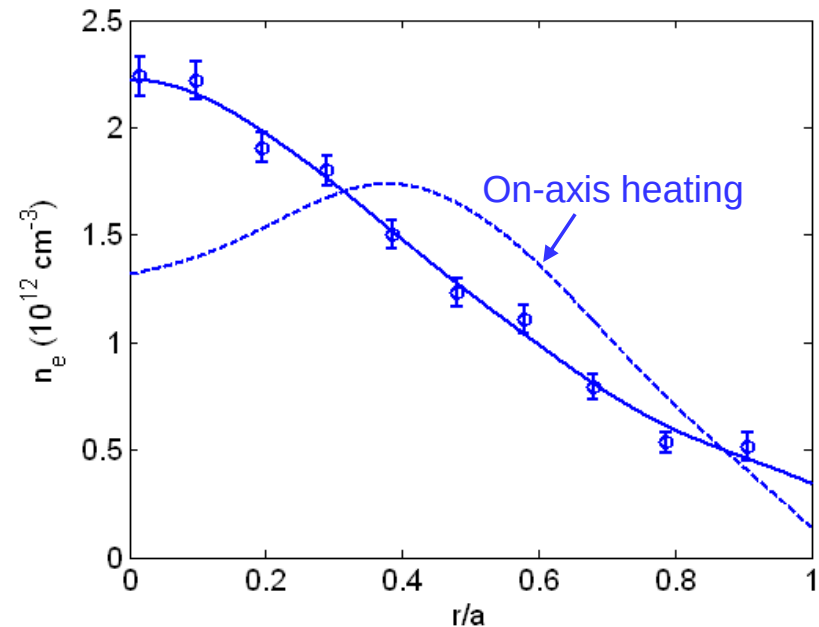
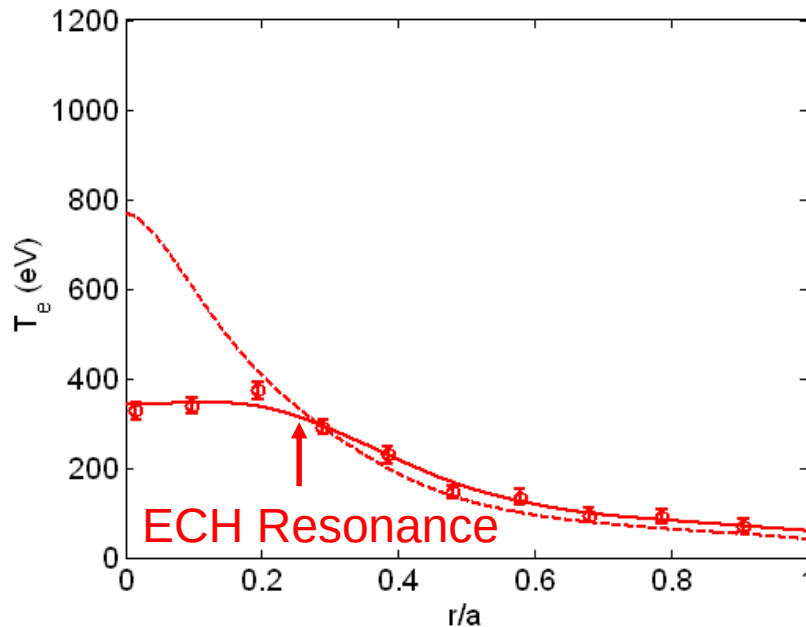
Off-axis Heating Confirms Thermodiffusive Flux in Mirror

- With off-axis heating, core temperature is flattened
- Mirror density profile becomes centrally peaked



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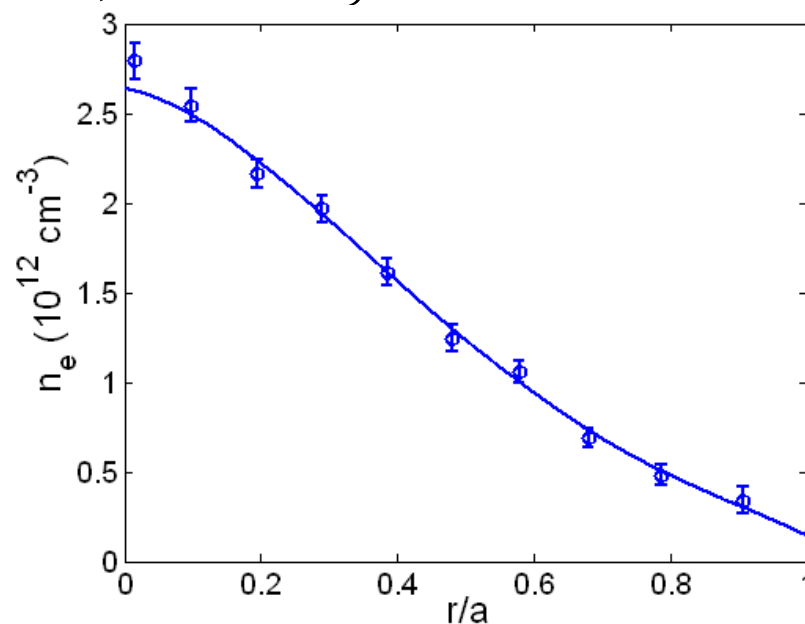
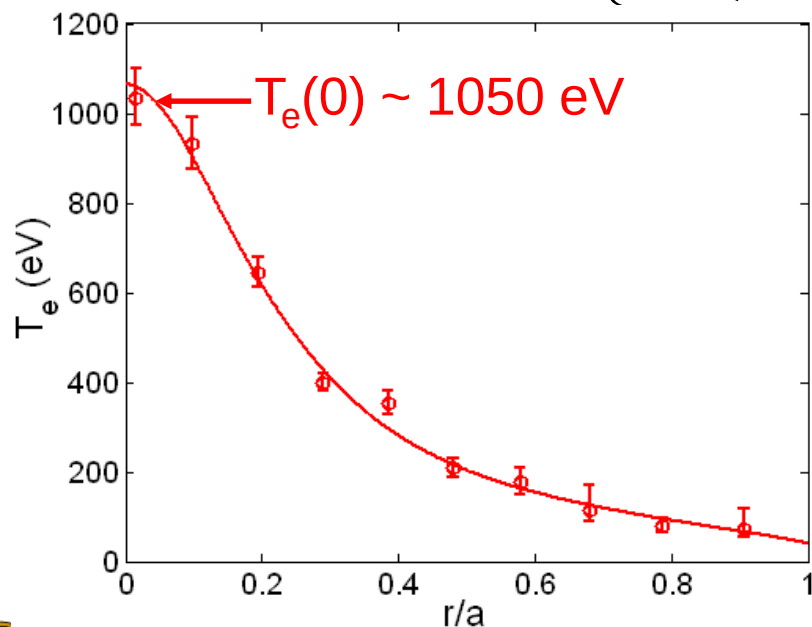


Quasisymmetric Configuration has Peaked Density Profiles with Central Heating

- 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

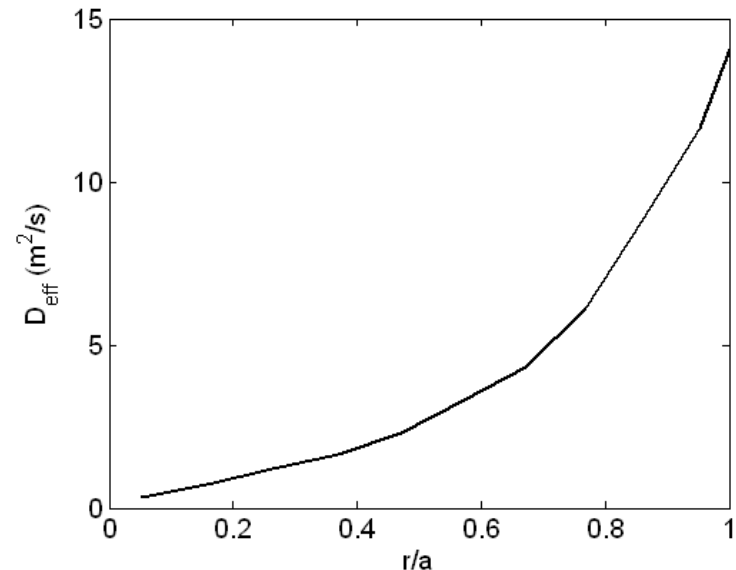
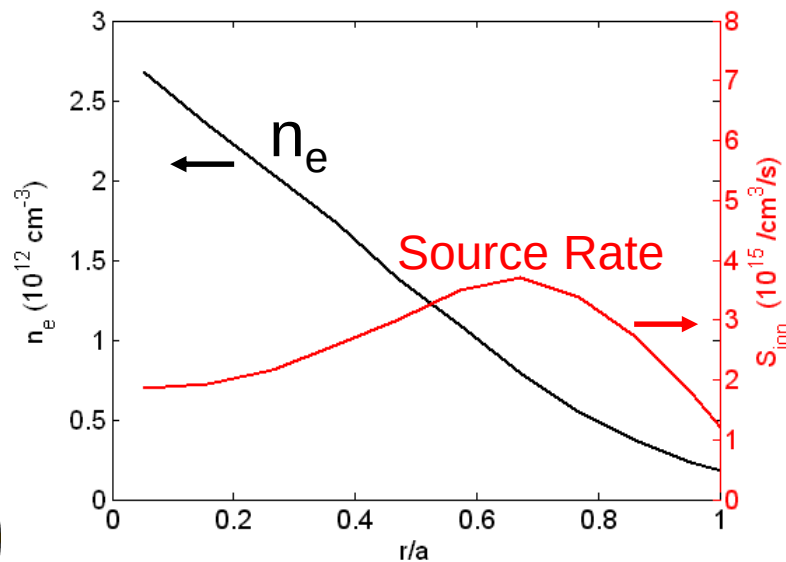
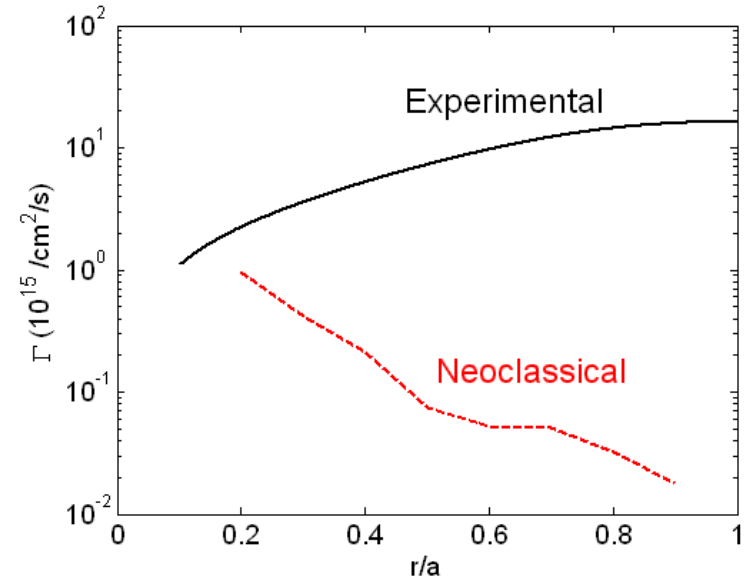
$$\Gamma = -n \left\{ D_{11} \left(\frac{n'}{n} - \frac{qE_r}{T} \right) + \cancel{D_{12} \frac{T'}{T}} \right\}$$

D_{12} is smaller due to quasi-symmetry



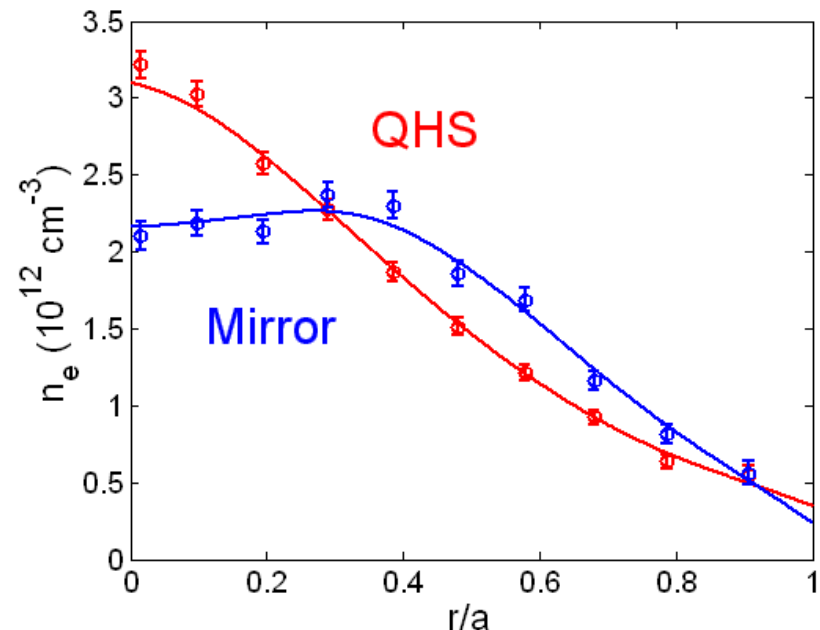
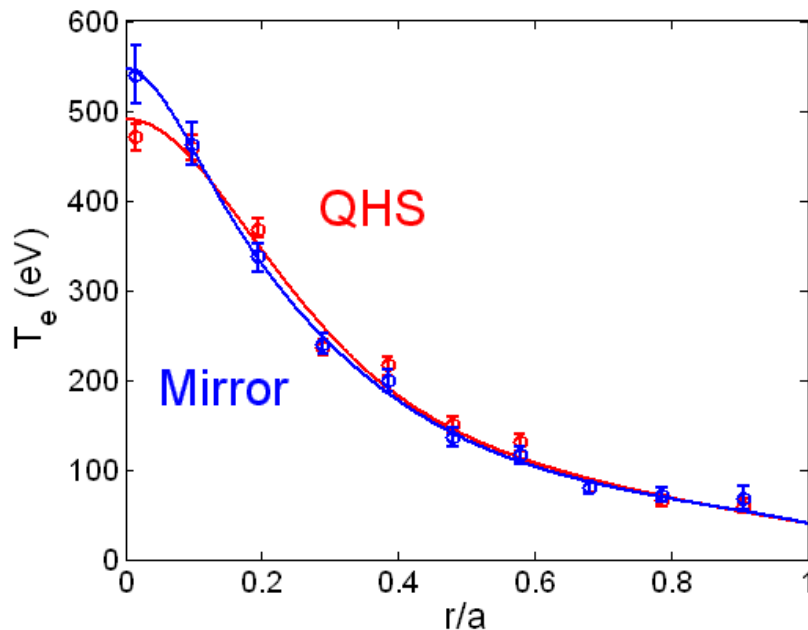
Neoclassical Particle Transport is Dominated by Anomalous in QHS

- Neoclassical particle flux now much less than experiment
 - Experiment 10 times larger than neoclassical at $r/a=0.3$
 - Core particle flux still large due to strong T_e and n_e gradients
- Large core fuelling $\Rightarrow$ inward convection not necessary for peaked profile



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 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)

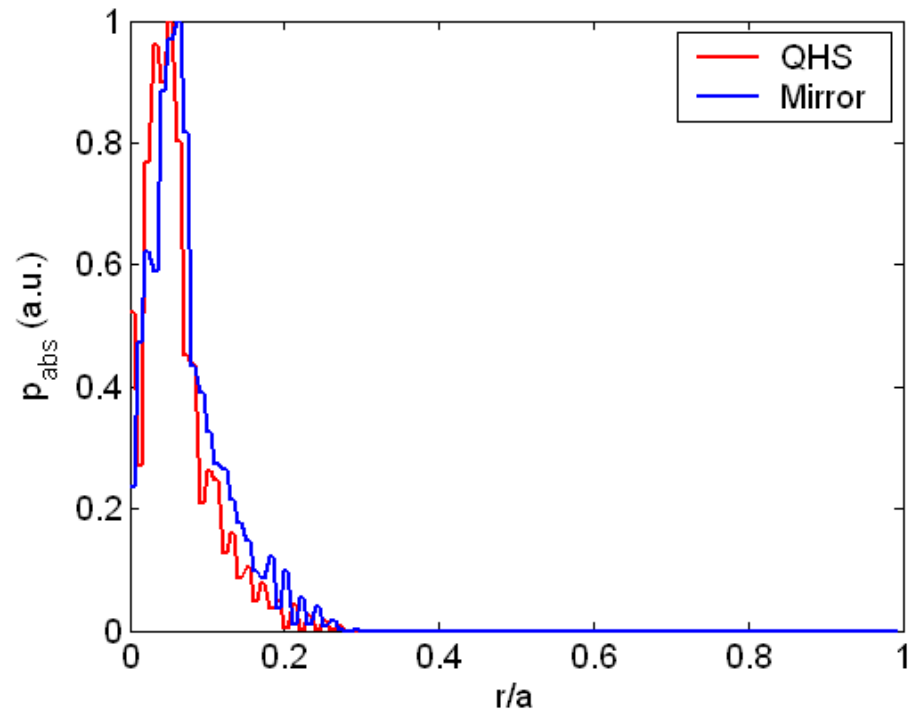
	QHS	Mirror
P_{inj}	26 kW	67 kW
P_{abs}	10 kW	15 kW
W_{kin}	17 J	17J

QHS has 50% improvement in confinement time: 1.7 vs. 1.1 ms



Transport Analysis has been Performed using Ray Tracing and Measured Power

- Total absorbed power is taken from Thomson scattering measurement
- 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 are negligible ($\sim 10\%$ of total loss inside $r/a \sim 0.6$)
- Effective electron thermal diffusivity is calculated



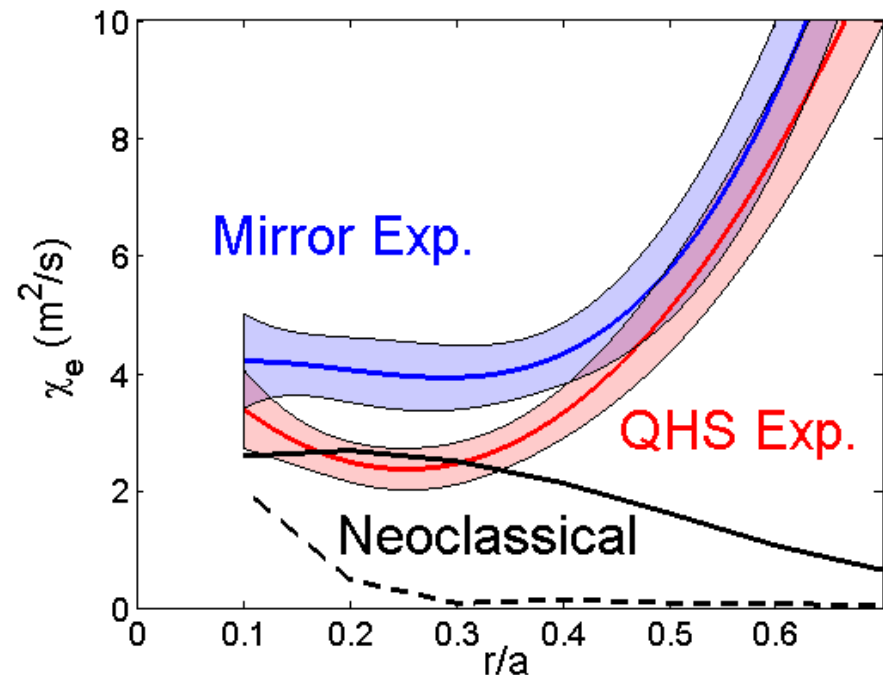
$$q_e = \frac{1}{r} \int_0^r r' p_{abs}(r') dr'$$

$$\chi_e = -\frac{q_e}{n \nabla T_e}$$



Thermal Diffusivity is Reduced in QHS

- QHS has lower core χ_e
 - At $r/a \sim 0.25$, χ_e is 2.5 m²/s in QHS, 4 m²/s in Mirror
 - Difference is comparable to neoclassical reduction (~ 2 m²/s)
- Two configurations have similar transport outside of $r/a \sim 0.5$



Conclusions

- Quasisymmetry has a large impact on plasma profiles
 - Density profiles are peaked with quasisymmetry, hollow when symmetry is broken
 - Quasisymmetry leads to higher electron temperatures
- These differences are due to reduced neoclassical transport with quasisymmetry
 - Hollow profile is due to thermodiffusion – reduced with quasisymmetry
 - Reduction in thermal diffusivity is comparable to neoclassical prediction

