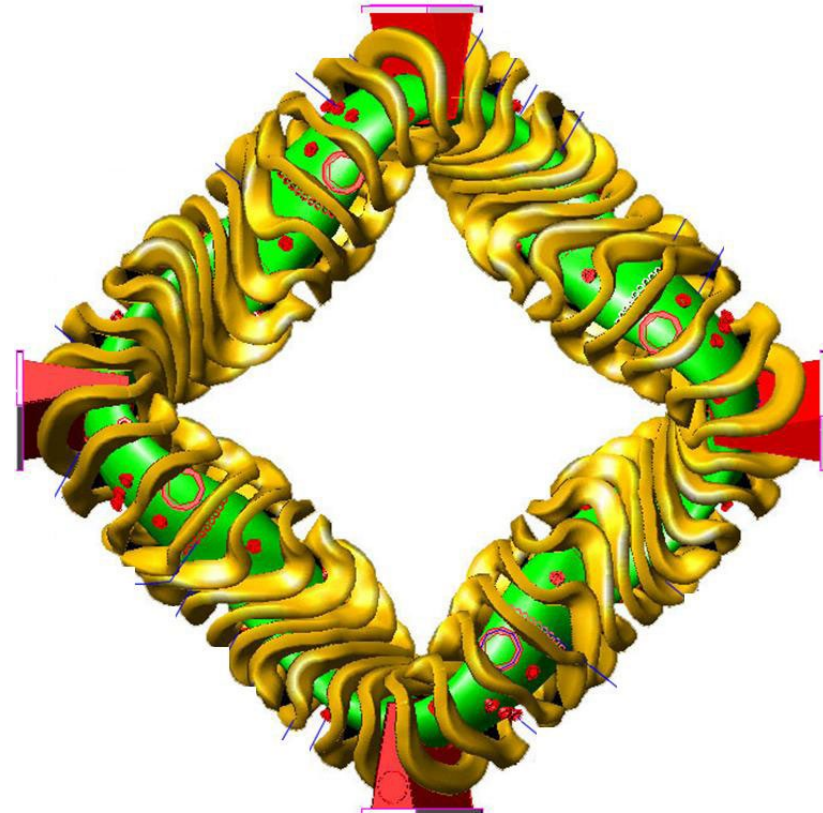
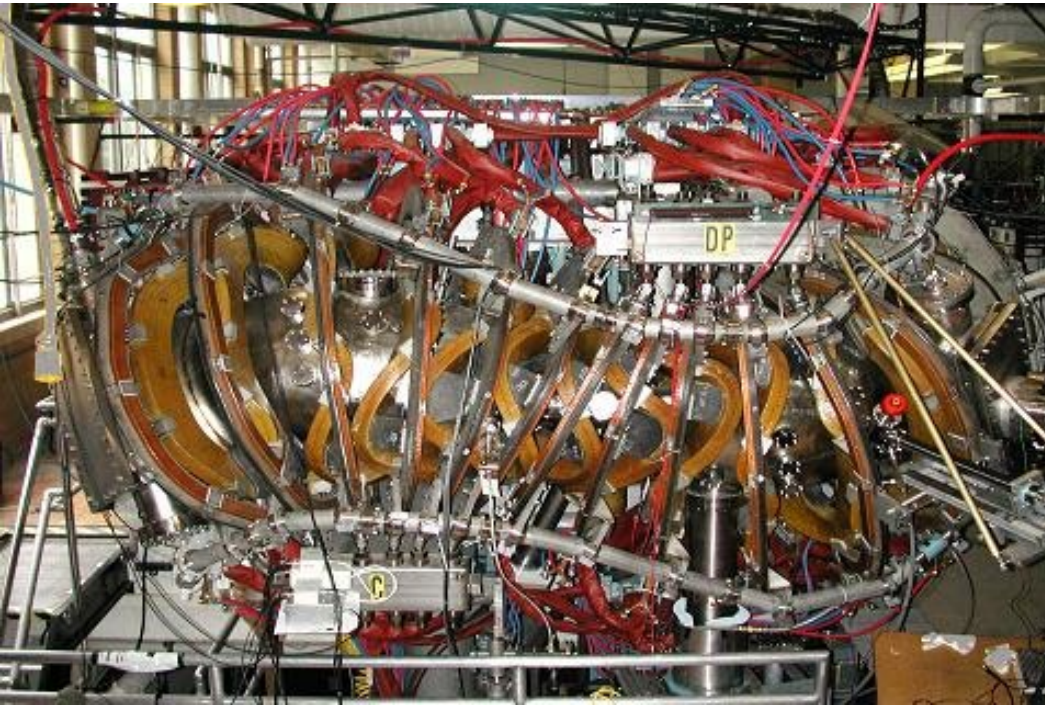


Neoclassically Driven Electron Transport Barrier in the HSX Stellarator



Jeremy Lore

University of Wisconsin-Madison

10/12/2009

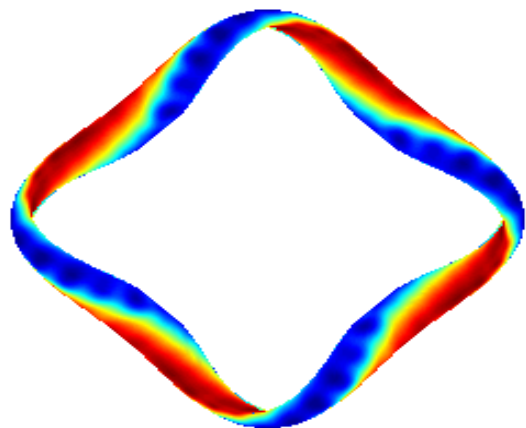
Special thanks to: Walter Guttenfelder (U. Warwick), Don Spong (ORNL), HSX Team



Outline

- Electron thermal transport barrier driven by neoclassical E_r
 - Peaked T_e profiles measured, large E_r with strong radial shear predicted
- 2D turbulent transport model well describes QHS anomalous transport
 - Core T_e profiles only reproduced when ExB shear included
- Density threshold for achieving transport barrier observed for fixed input power
 - Consistent with lack of NC electron root prediction
- Large parallel flow (10-25 km/s) predicted and measured for $r/a > 0.6$
 - This flow and associated fluxes are accounted for in momentum conserving NC analysis (PENTA) , neglected in “standard” stellarator NC calculations

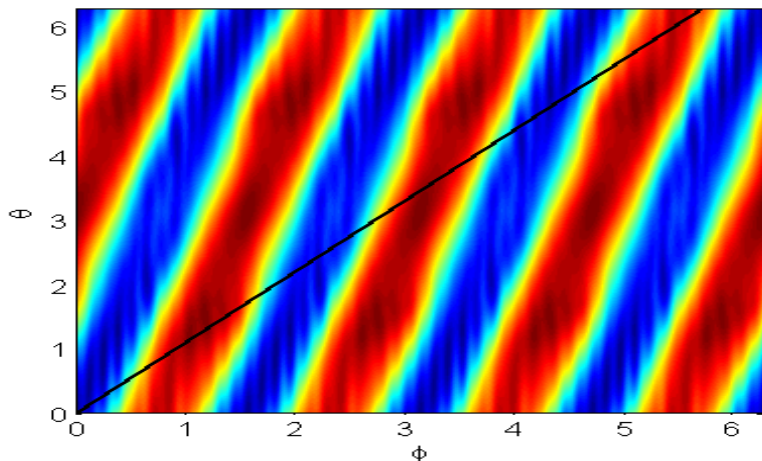
HSX is Quasi-Helically Symmetric



Tokamak: $B / B_0 = 1 - \varepsilon_t \cos t\phi$

QHS: $B / B_0 = 1 - \varepsilon_h \cos(n - m t)\phi$

$\iota_{\text{eff}} \sim 3$



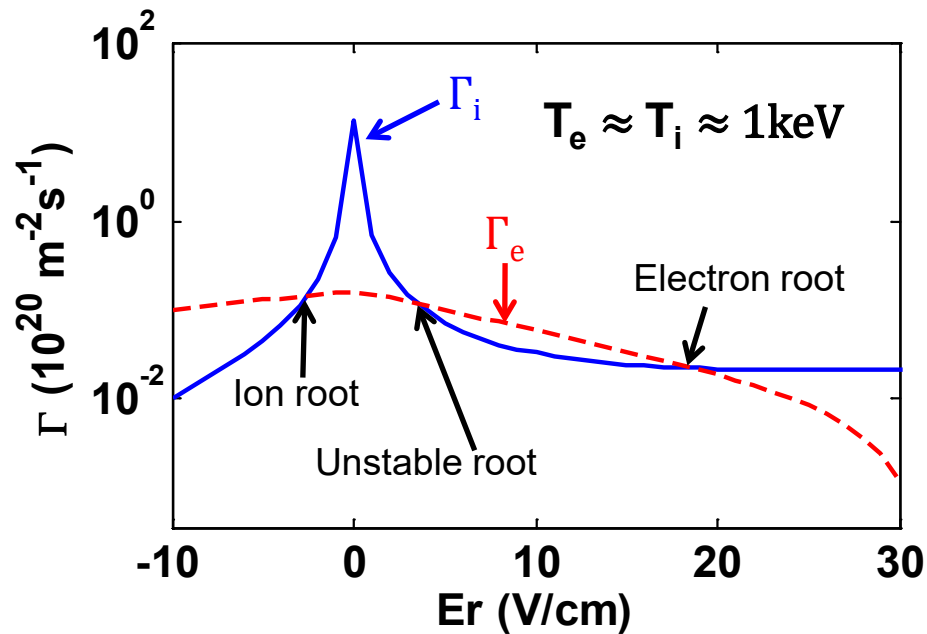
- QHS: helical direction of symmetry in $|B|$
- $|B|$ spectrum is dominated by a single $n=4, m=1$ helical term
- Effective transform is larger than physical transform

HSX Parameters

<R>	1.2 m
<a>	0.12 m
ι	1.05→1.12
B_0	0.5 -1.0 T
ECRH 28 GHz	<100 kW

Radial Electric Field is Determined by Enforcing Ambipolarity

- LMFP with $T_e \approx T_i$ results in three roots

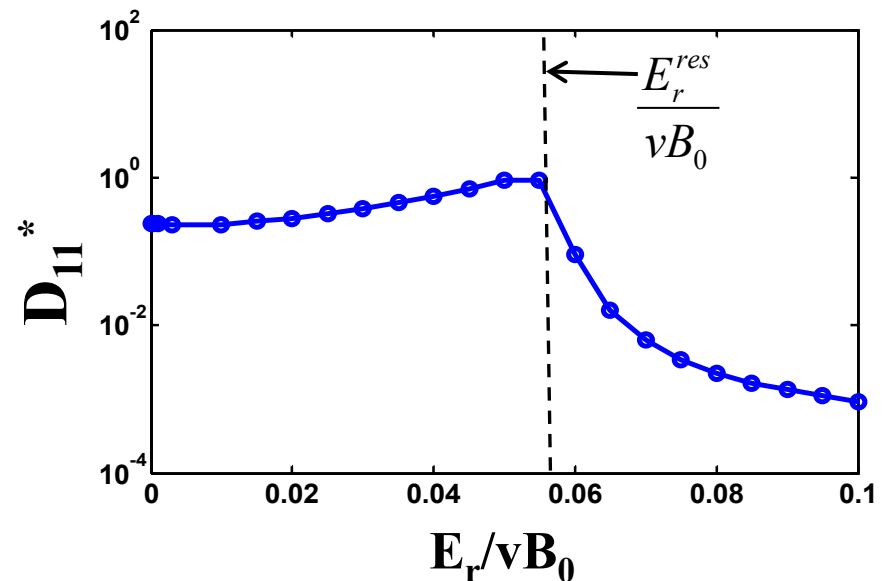
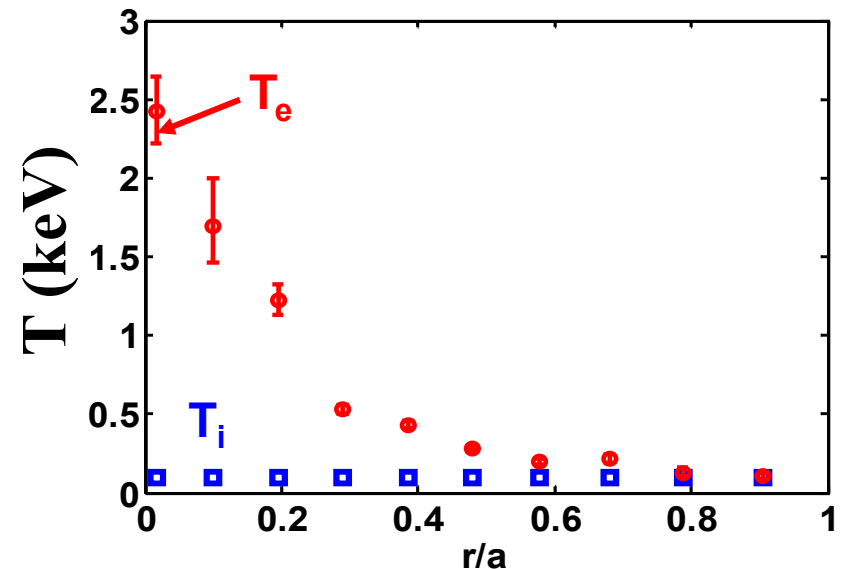


- Electron root can be reached by increasing Γ_e
- When $T_e \gg T_i$ the ion root solution may not exist near the core

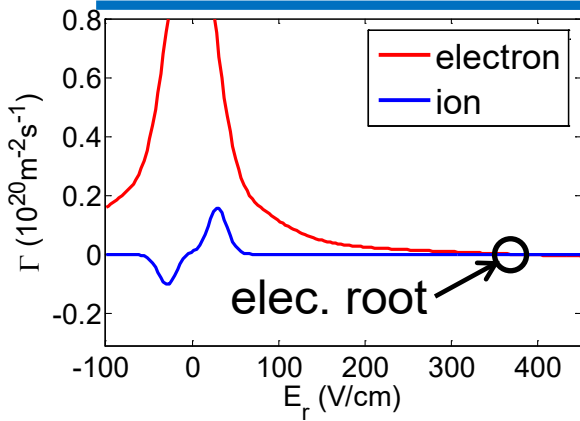
HSX Can Achieve Electron Root Because

$$T_e \gg T_i$$

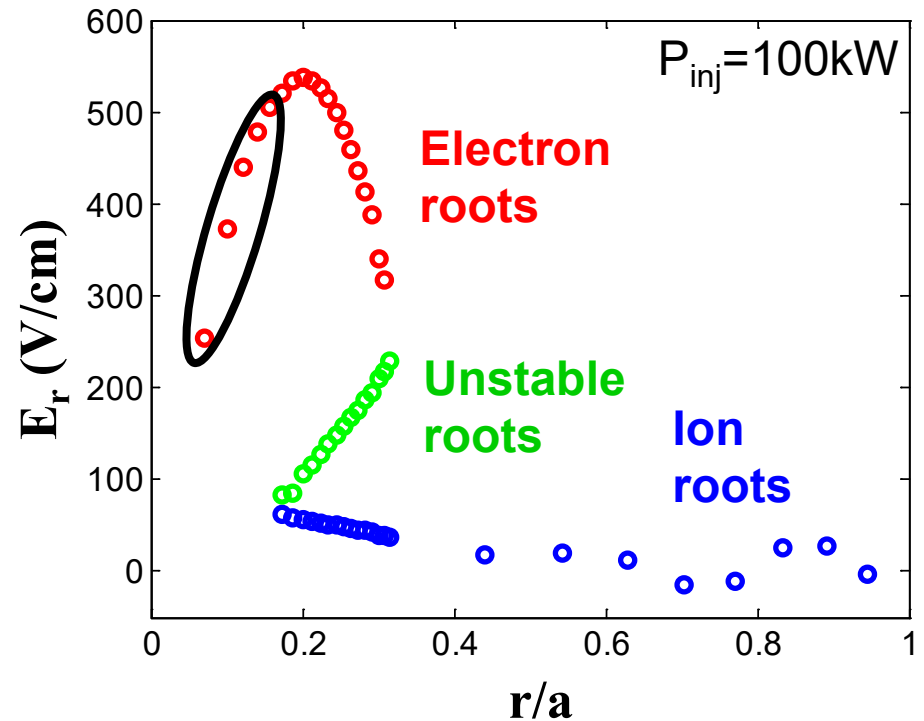
- In HSX $T_e \gg T_i$ over most of the plasma radius, with a strongly peaked T_e profile
- For $T_i \approx 100\text{eV}$, ions experience a resonance at modest E_r near plasma core
- The resonance occurs when poloidal velocity is canceled by the poloidal $\mathbf{E} \times \mathbf{B}$ drift
- Radial transport is increased near the resonance, and is strongly reduced for $E_r > E_r^{\text{res}}$



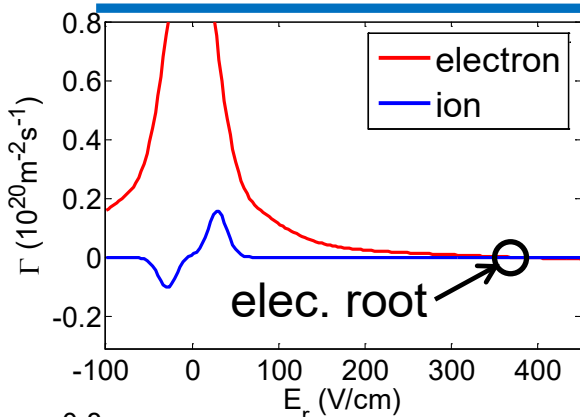
Radial Electric Field Roots in HSX



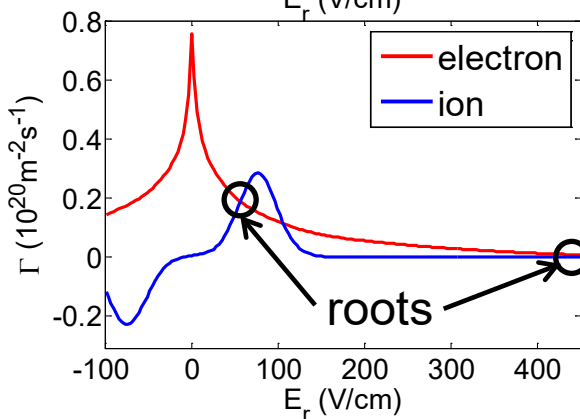
$\rho=0.1$
 $T_e=2\text{keV}$
 $T_i=70\text{eV}$



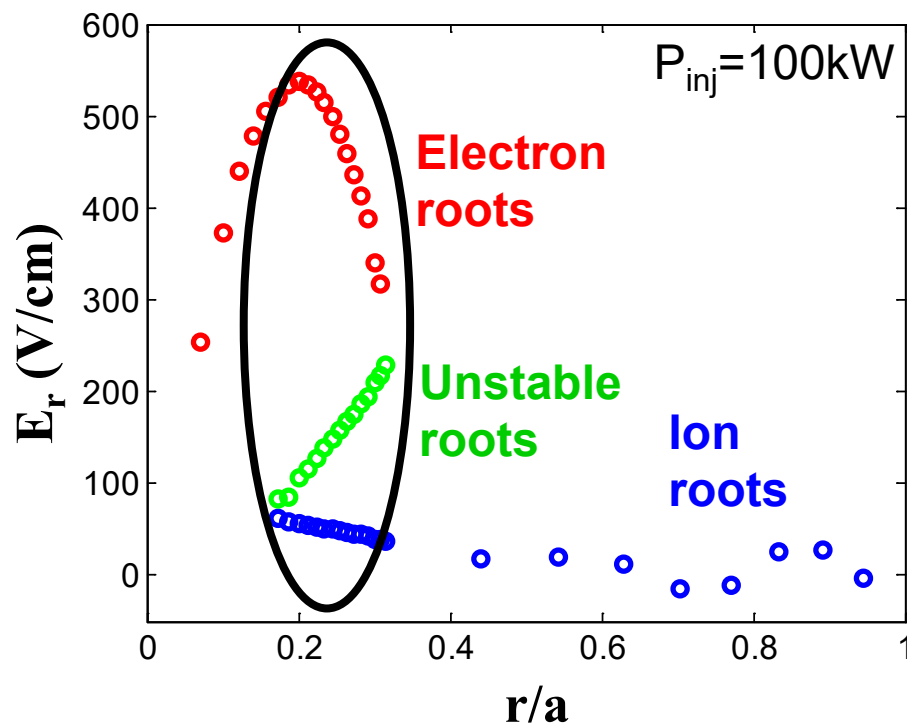
Radial Electric Field Roots in HSX



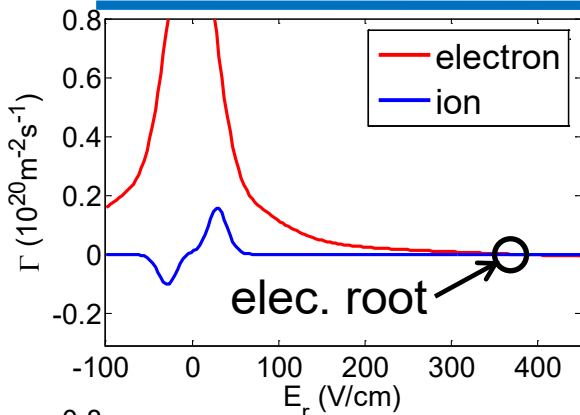
$\rho=0.1$
 $T_e=2\text{keV}$
 $T_i=70\text{eV}$



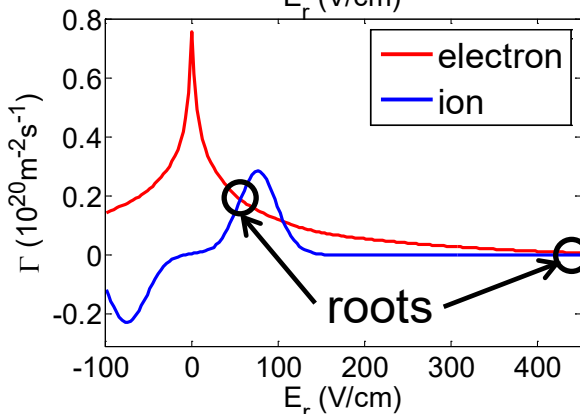
$\rho=0.3$
 $T_e=750\text{eV}$
 $T_i=60\text{eV}$



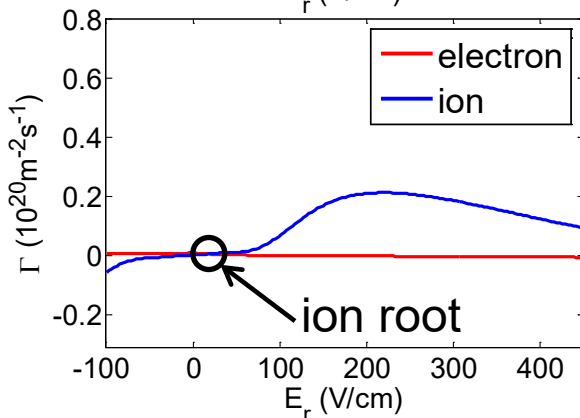
Radial Electric Field Roots in HSX



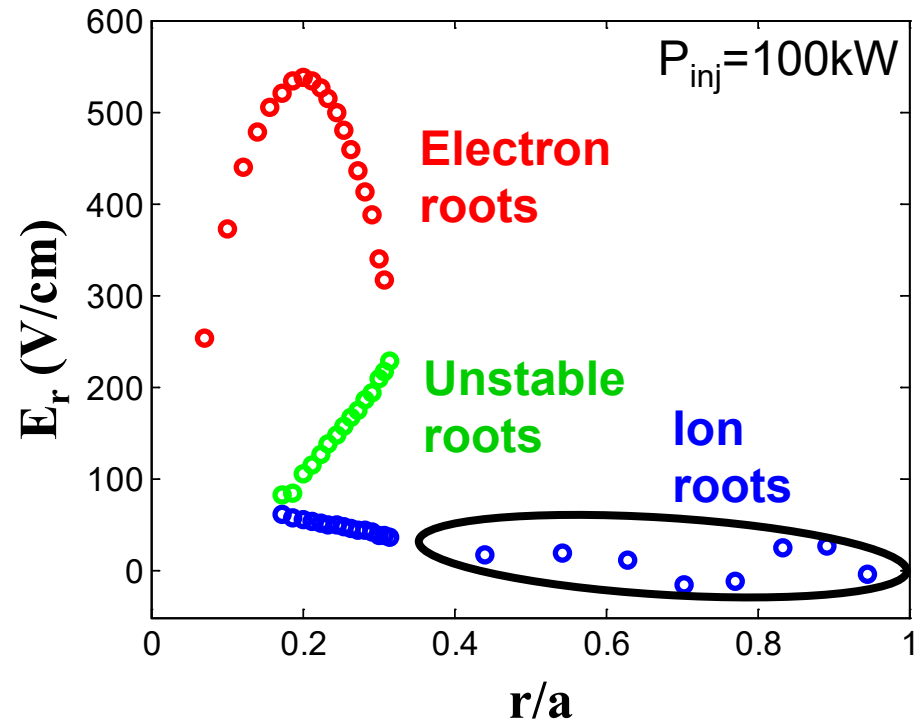
$\rho=0.1$
 $T_e=2\text{keV}$
 $T_i=70\text{eV}$



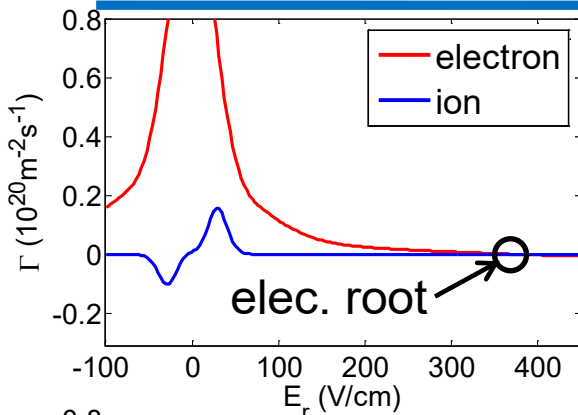
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 $T_e=750\text{eV}$
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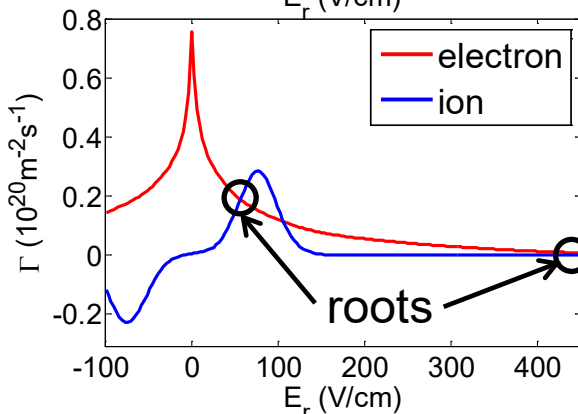
$\rho=0.5$
 $T_e=300\text{eV}$
 $T_i=55\text{eV}$



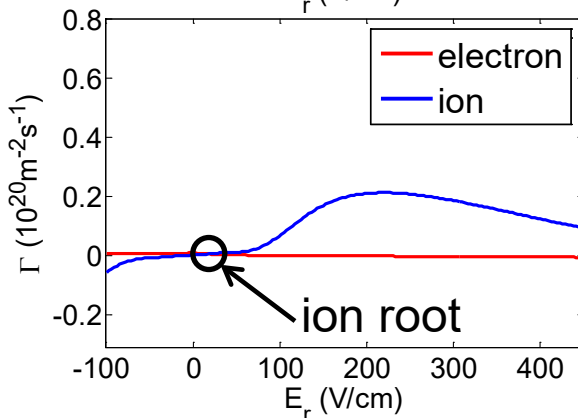
Radial Electric Field Roots in HSX



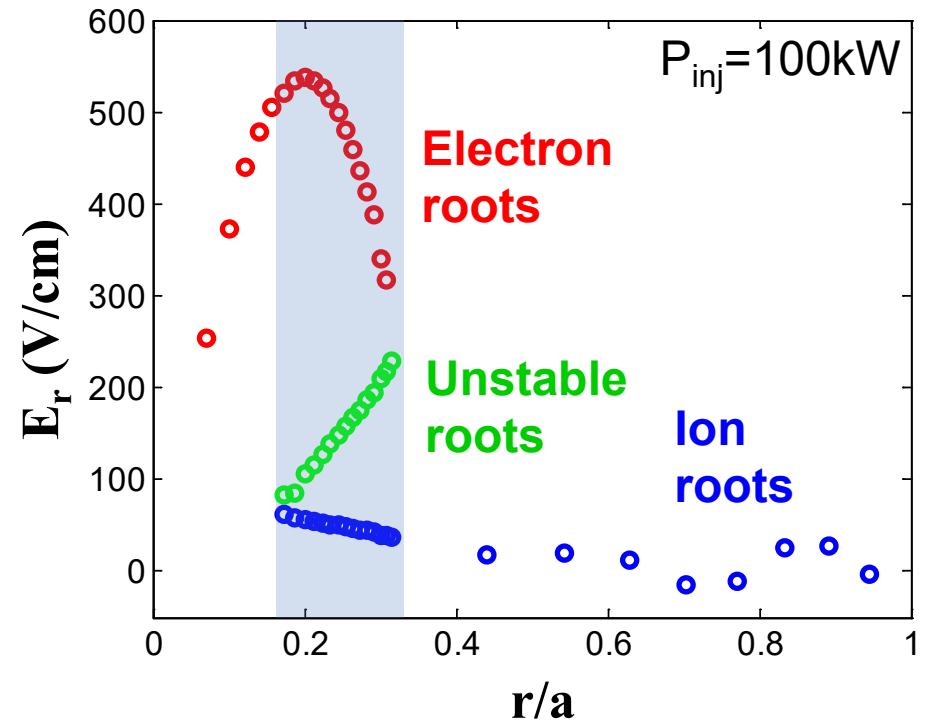
$\rho=0.1$
 $T_e=2\text{keV}$
 $T_i=70\text{eV}$



$\rho=0.3$
 $T_e=750\text{eV}$
 $T_i=60\text{eV}$



$\rho=0.5$
 $T_e=300\text{eV}$
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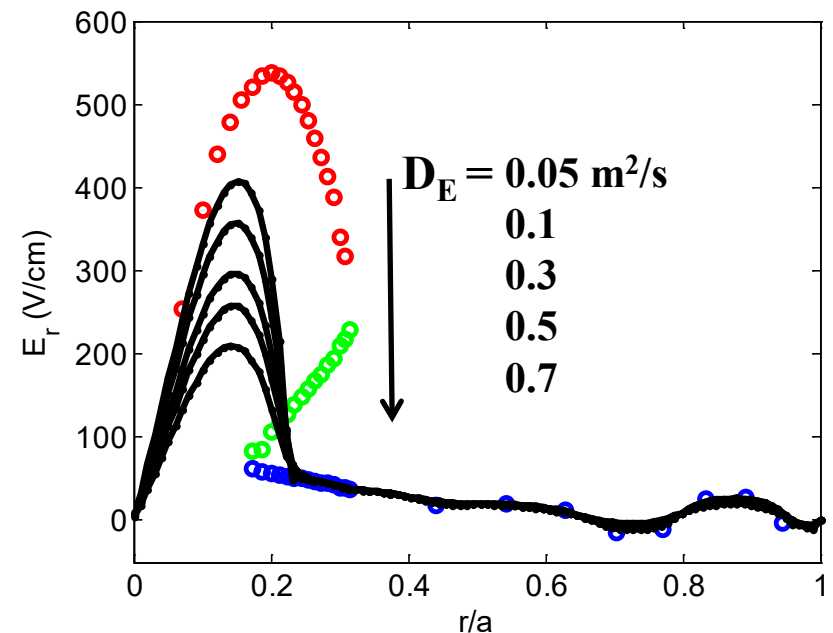


- **Only electron root in core, and only ion root towards edge**
 - Somewhere in three root region there is a transition, with strong E_r shear
 - Determining shear layer involves perpendicular viscosity

Solving the Diffusion Equation for E_r

- The radial electric field profile can be determined by solving a diffusion equation¹
- D_E (related to perpendicular viscosity) is generally not known
 - Solutions for different D_E show a region of strong E_r shear at $r/a \sim 0.25$

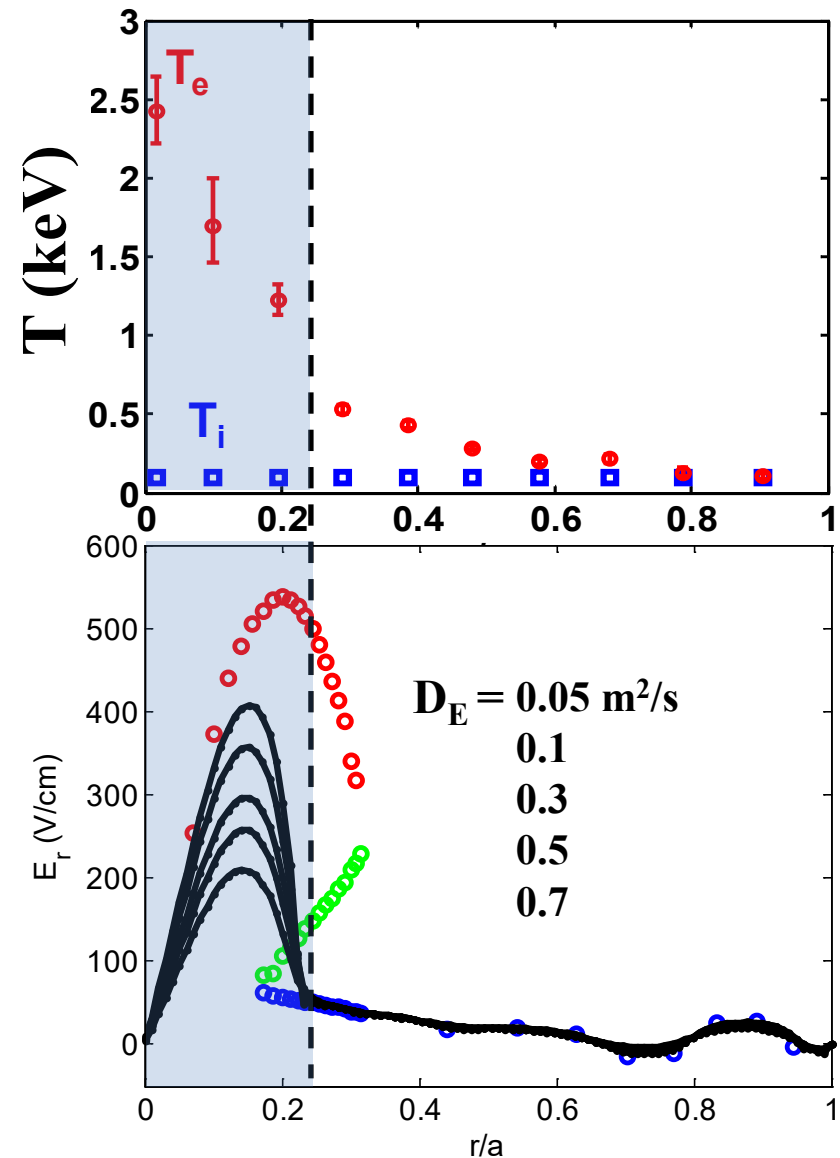
$$\frac{\partial E_r}{\partial t} - \frac{\partial}{\partial V} \left[\langle \nabla V \rangle D_E \left(\frac{\partial E_r}{\partial r} - \frac{E_r}{r} \right) \right] = \frac{e}{\varepsilon_{\perp}} (\Gamma_e - \Gamma_i)$$



1) Shaing and Callen (1983), Maassberg *et al* (1993).

Strong E_r Shear is Predicted in Region of Peaked T_e

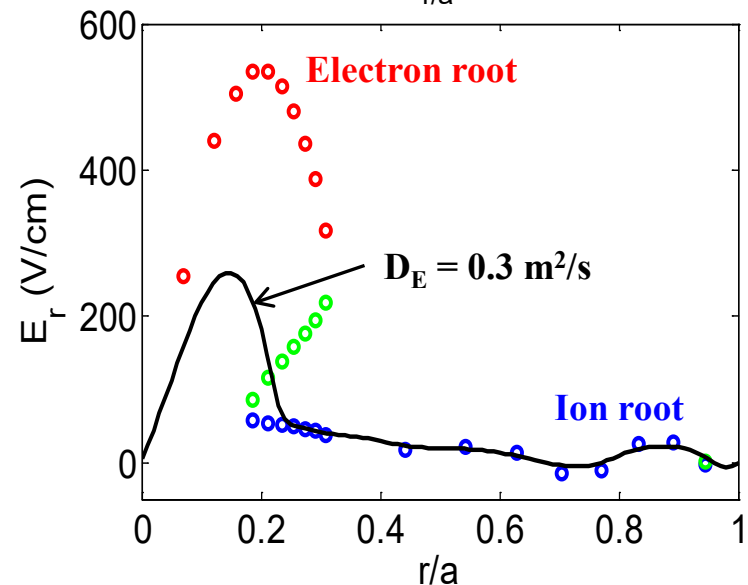
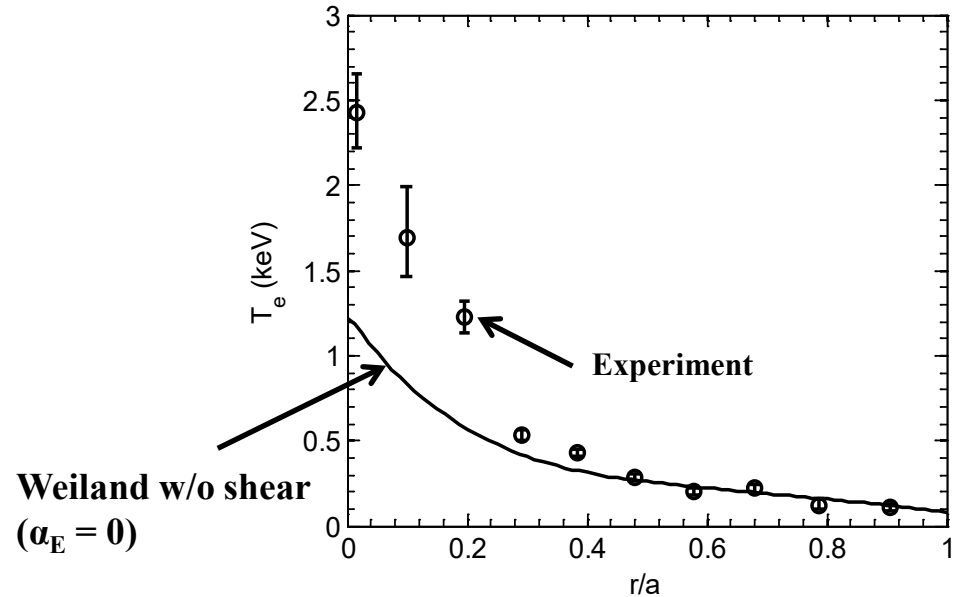
- The radial electric field profile can be determined by solving a diffusion equation¹
- D_E (related to perpendicular viscosity) is generally not known
 - Solutions for different D_E show a region of strong E_r shear at $r/a \sim 0.25$
- T_e peaking occurs within the strong E_r shear region
 - E_r shear can suppress turbulent transport



1) Shaing and Callen (1983), Maassberg *et al* (1993).

Applying a 2D Turbulent Transport Model to QHS

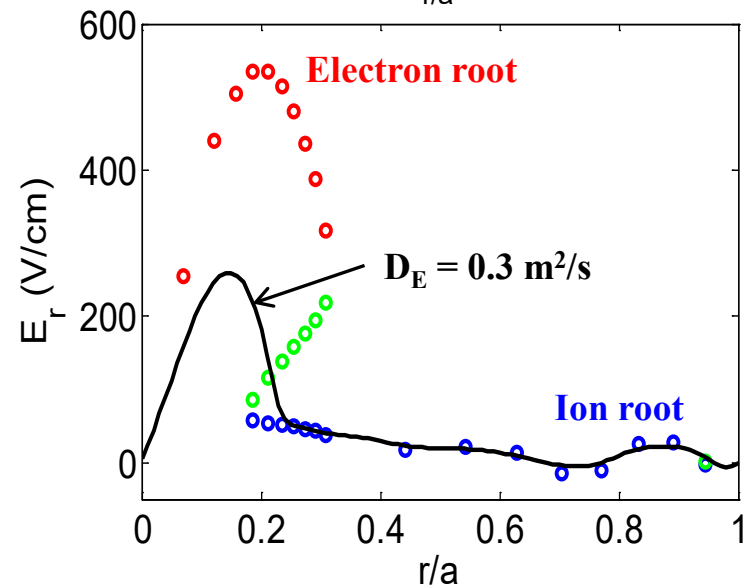
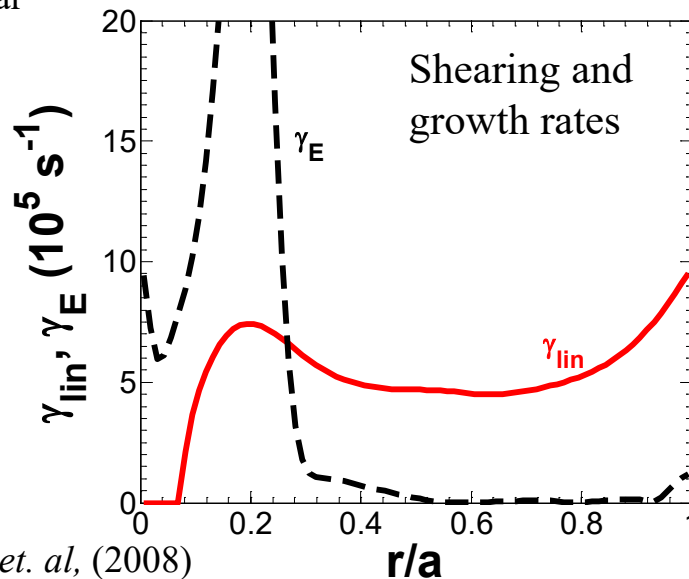
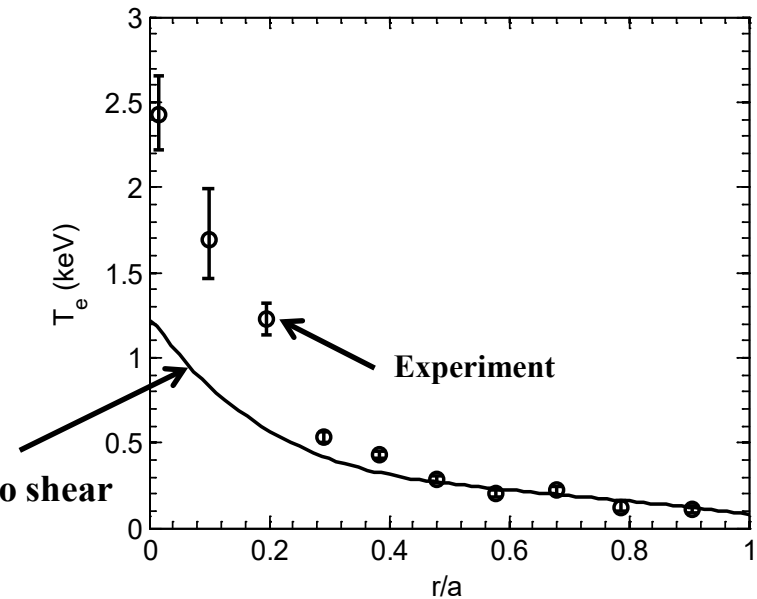
- The 2D quasi-linear Weiland model has been used to model turbulent transport for a 100kW QHS plasma
 - Like a tokamak, QHS has a single class of trapped particles.
 - With local geometry considerations, good agreement with 3D gyrokinetic GS2 growth rates.
- Predictive transport (NC + Turb.) simulations underestimate T_e in core
 - Turbulent transport can be suppressed via ExB flow shear



ExB Shearing Rate $\gg$ Linear Growth Rate for $r/a < 0.3$

- The 2D quasi-linear Weiland model has been used to model turbulent transport for a 100kW QHS plasma
 - Like a tokamak, QHS has a single class of trapped particles.
 - With local geometry considerations, good agreement with 3D gyrokinetic GS2 growth rates.
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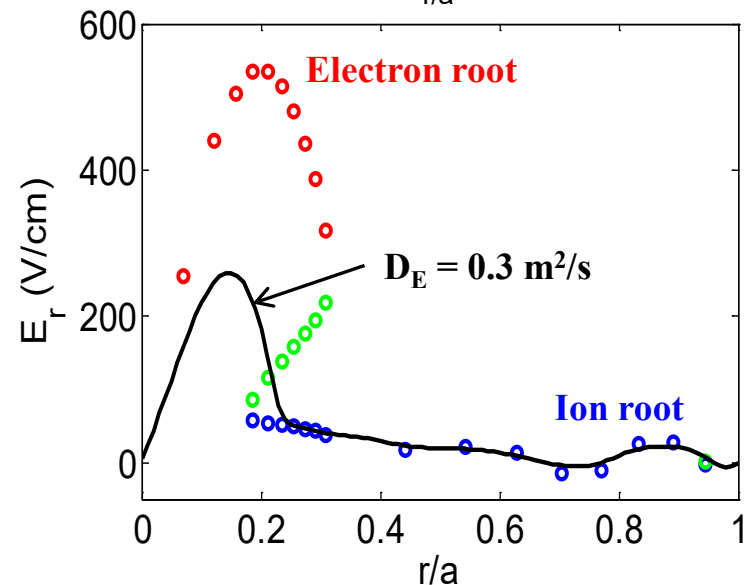
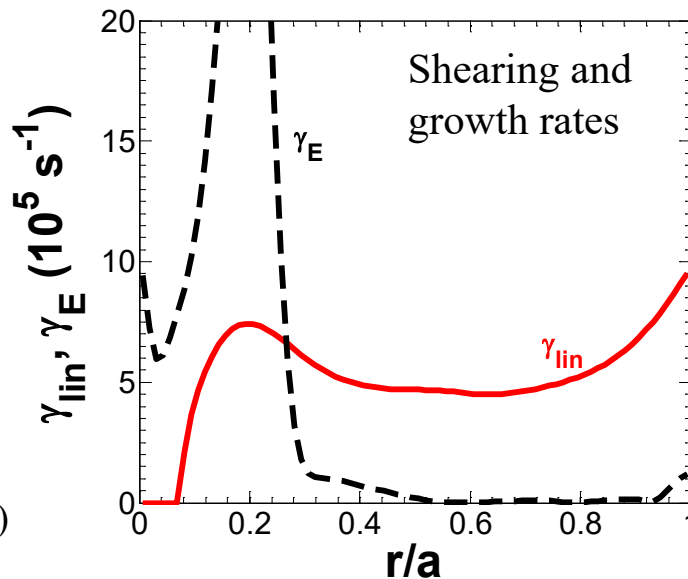
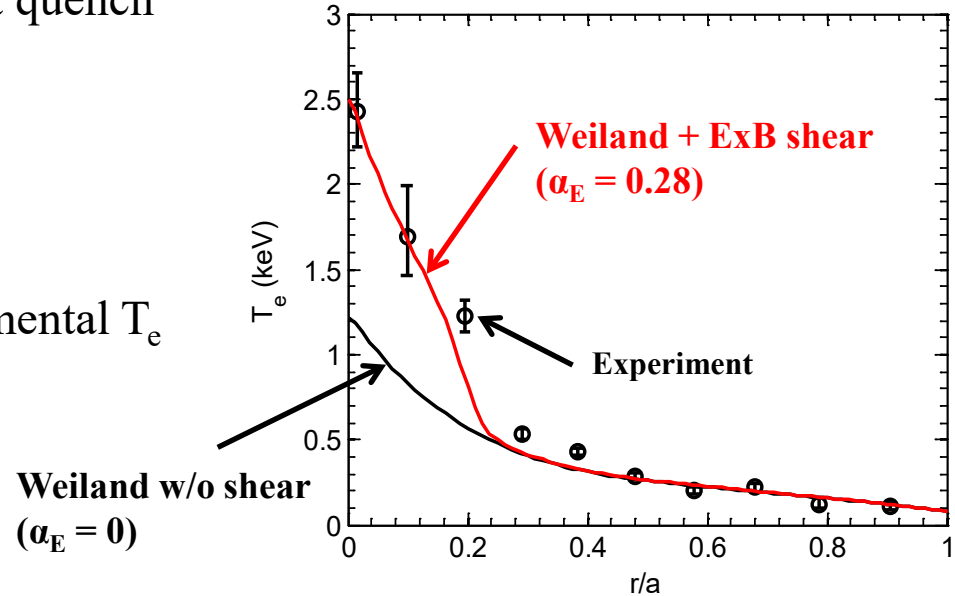
Weiland w/o shear
($\alpha_E = 0$)



Turbulence Suppression via ExB Shear can Reproduce Experimental Profiles

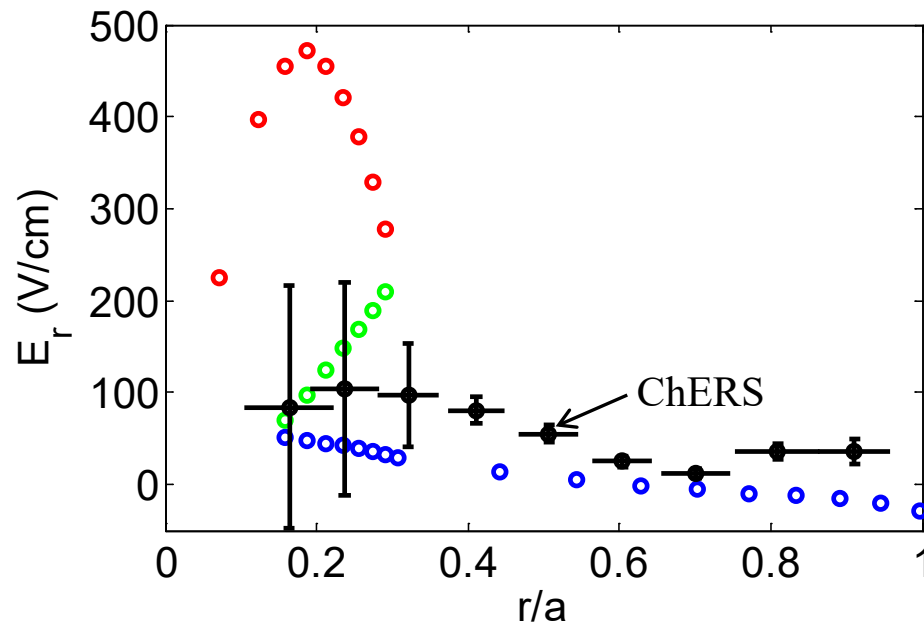
- ExB shear suppression is modeled using a quench rule:¹

$$D \Rightarrow D \cdot \max\left(1 - \alpha_E \frac{\gamma_E}{\gamma_{\max}}, 0\right)$$
 - γ_E = ExB shear rate
 - $\gamma_{\max}$ = maximum linear growth rate
- E_r shear can reproduce peaking of experimental T_e profile



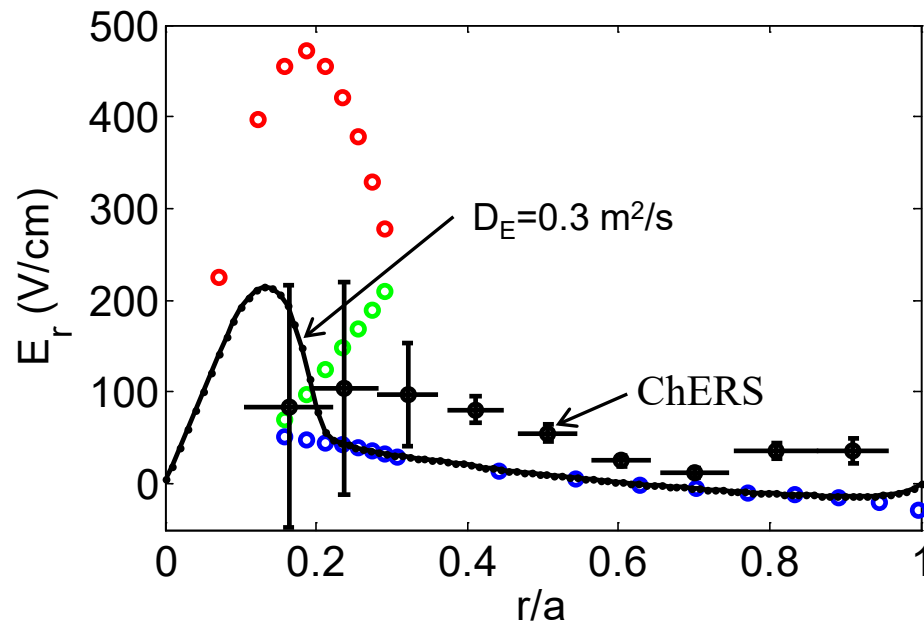
ChERS Measurements are Inconclusive in Plasma Core

- No measurements exist in region of electron root only solutions
- Edge measurements are consistent or larger than ion root



Most of Shear Region is Inside of Measurements

- No measurements exist in region of electron root only solutions
- Edge measurements are consistent or larger than ion root
- Only central measurement is within shear region, some smoothing may occur here due to radial extent of measurement
- See Briesemeister poster this afternoon (P01-04)



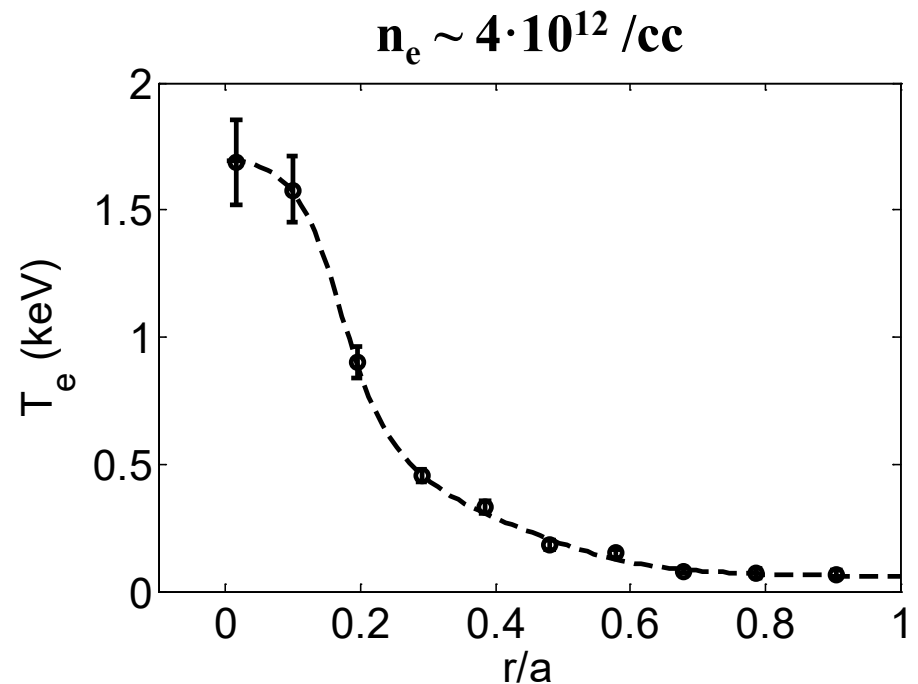
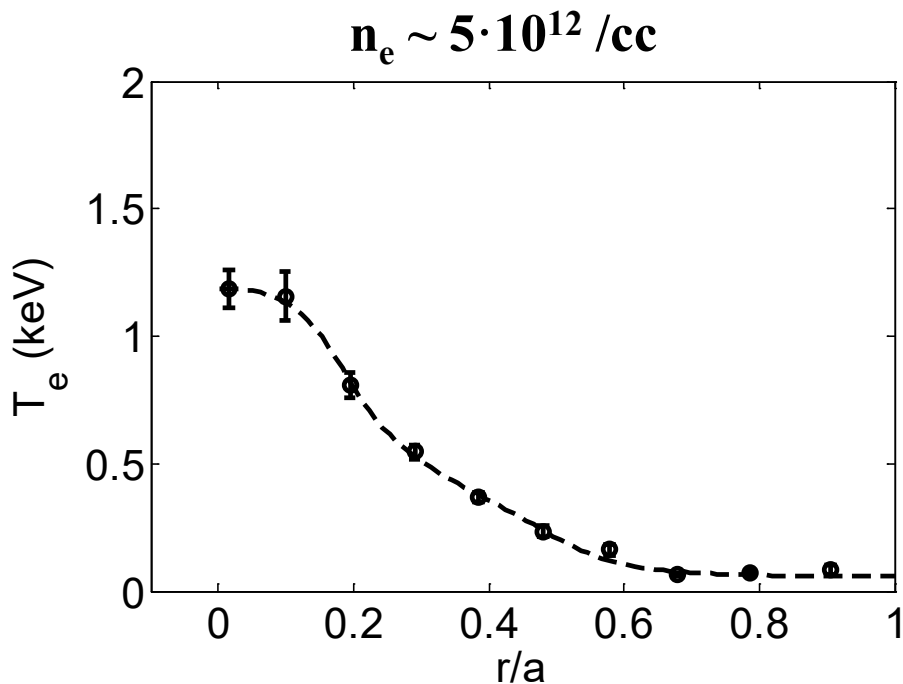
CERC Transport Barriers

- (Core Electron Root Confinement) CERC transport barriers have been observed in several other stellarators¹
 - Characterized by peaked T_e profiles, neoclassical electron root E_r
- One common feature is the existence of thresholds for achieving a CERC in P_{inj} and n_e
- Recent experiments suggest a threshold in QHS plasmas

1) Yokoyama, *et. al* (2006, 2007)

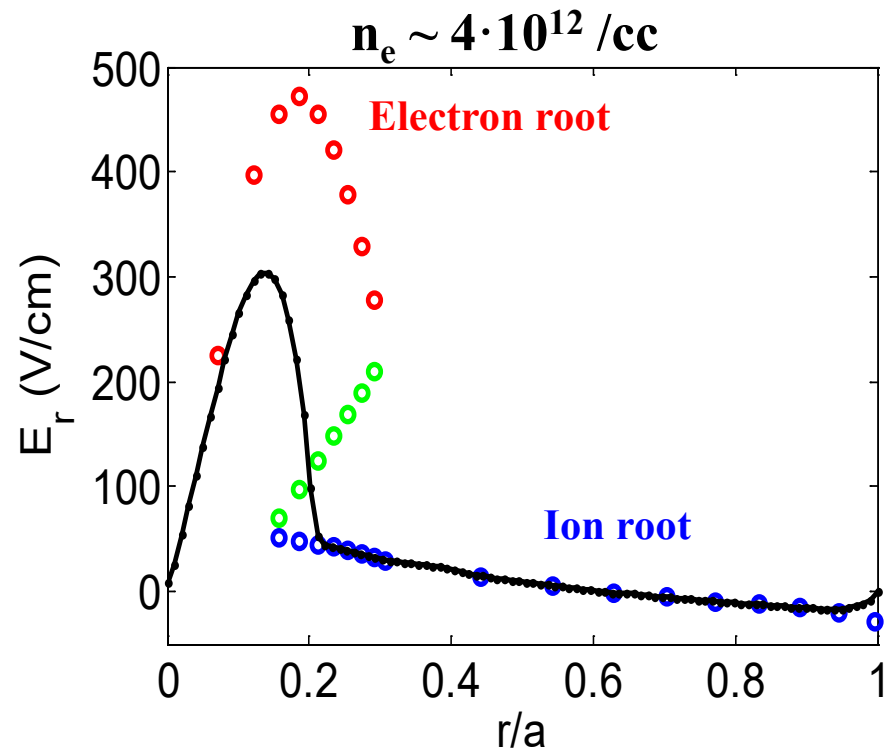
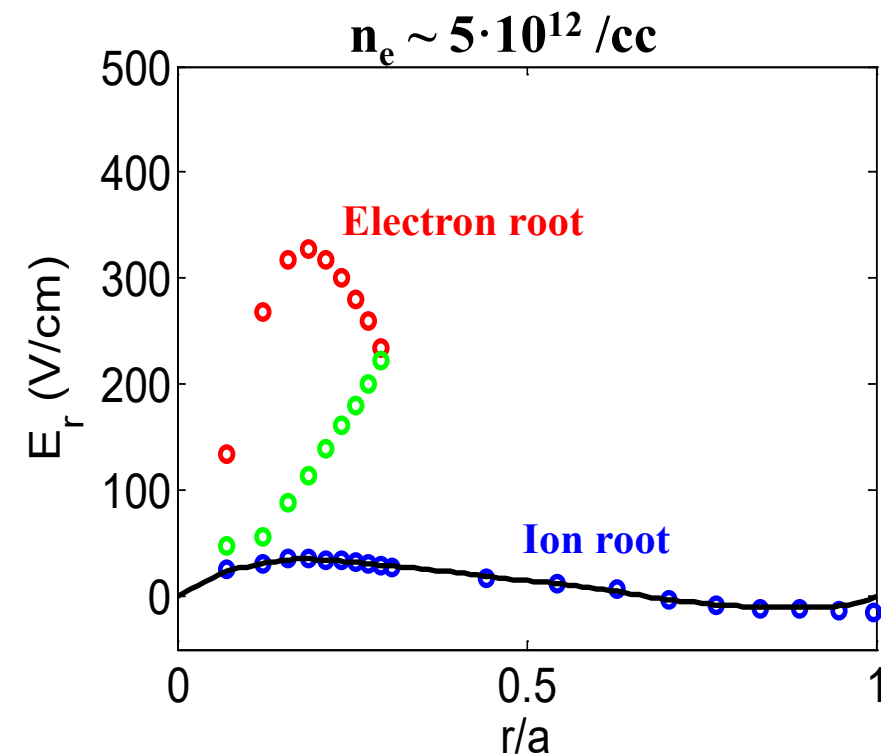
Recent Experiments Suggest a CERC Density Threshold

- For same input power, higher density results in less peaked T_e profile
- At higher density R/L_{Te} is 2x smaller near $r/a \sim 0.25$
- At $P_{inj} = 50\text{kW}$, threshold density $\sim 5 \cdot 10^{12} / \text{cc}$



Ion Root is Predicted Across the Plasma Radius at High Density

- The higher density case also results in ion root solutions across the entire plasma radius
 - Core ion root is caused by reduced T_e , $\nabla T_e \Rightarrow$ reduced electron flux
 - Without external drive the plasma would remain in the ion root
- Note that this threshold does not seem to require any additional fluxes (e.g. ECRH driven)



Neoclassical Calculations Conserve Parallel Momentum

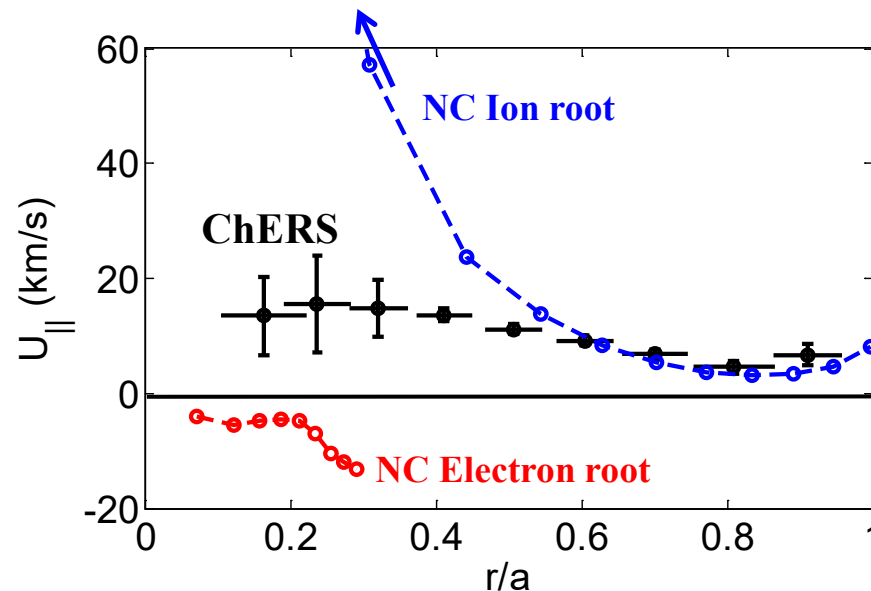
- Neoclassical calculations are performed using the PENTA¹ code
 - Based on the parallel momentum conserving moments method of Sugama and Nishimura²
 - Modified version of PENTA can include impurity transport (see Clark P01-08)
- Unlike calculations which only consider pitch angle scattering, the effects of interspecies collisions and parallel flow are included
- In principle, this method can be applied to the full range of configurations:

tokamaks → rippled tokamaks → quasi-symmetric → conventional stellarators

Increasing effective ripple →

Momentum Conserving Calculations may be Important in Quasi-Symmetric Configurations

- Standard NC calculations assume $U_{\parallel} = 0$
 - Justified in conventional stellarators, because no $|B|$ symmetry leads to strong flow damping in all directions
 - Parallel flow may be large in quasi-symmetric configurations
- Large (~ 10 - 25 km/s) parallel flow measured in QHS
 - In agreement with PENTA predictions for $r/a > 0.6$
 - Very large ion root flows are inconsistent with assumption $U \ll v_{Ti}$
- Change in transport small in electron root, ion root E_r changes by $\sim 2x$



Conclusions

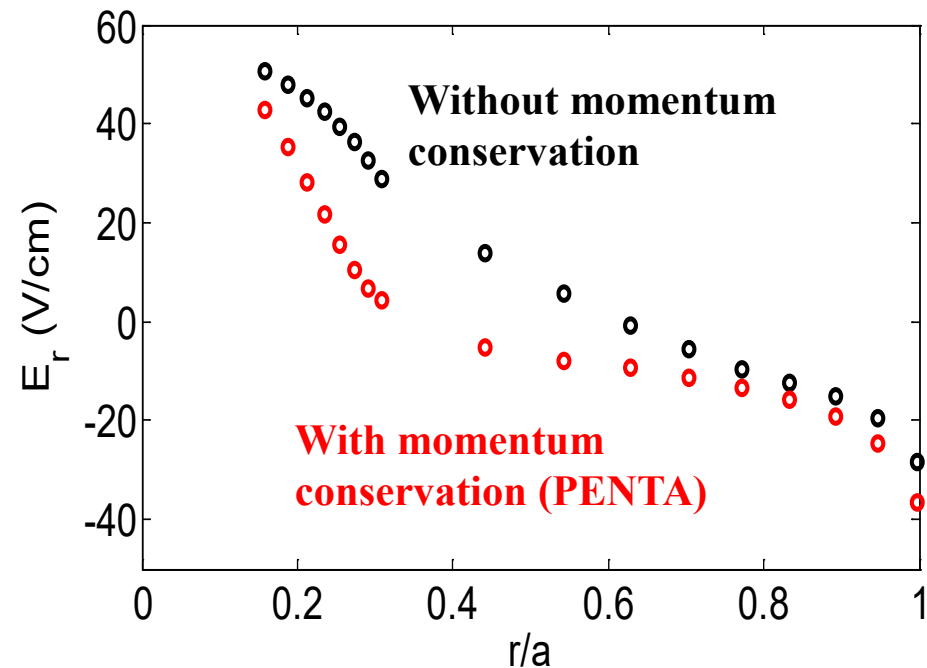
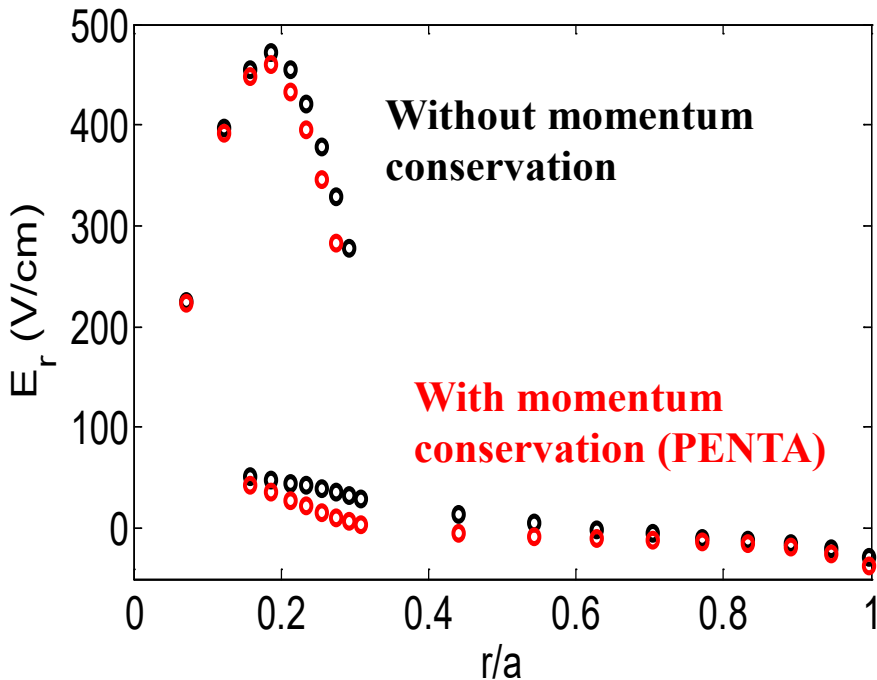
- Evidence of a neoclassically driven transport barrier in QS device
 - Peaked T_e profiles measured, large E_r with strong shear predicted
- 2D tokamak turbulent transport model well describes QHS anomalous transport
 - Core T_e profiles only reproduced when ExB shear included
- Density threshold for achieving CERC observed for fixed input power
 - Consistent with lack of NC electron root prediction
- Large parallel flow (10-25 km/s) predicted and measured at plasma edge
 - This flow and associated fluxes are accounted for in momentum conserving NC analysis (PENTA) , neglected in “standard” stellarator NC calculations

Questions?

Additional slides

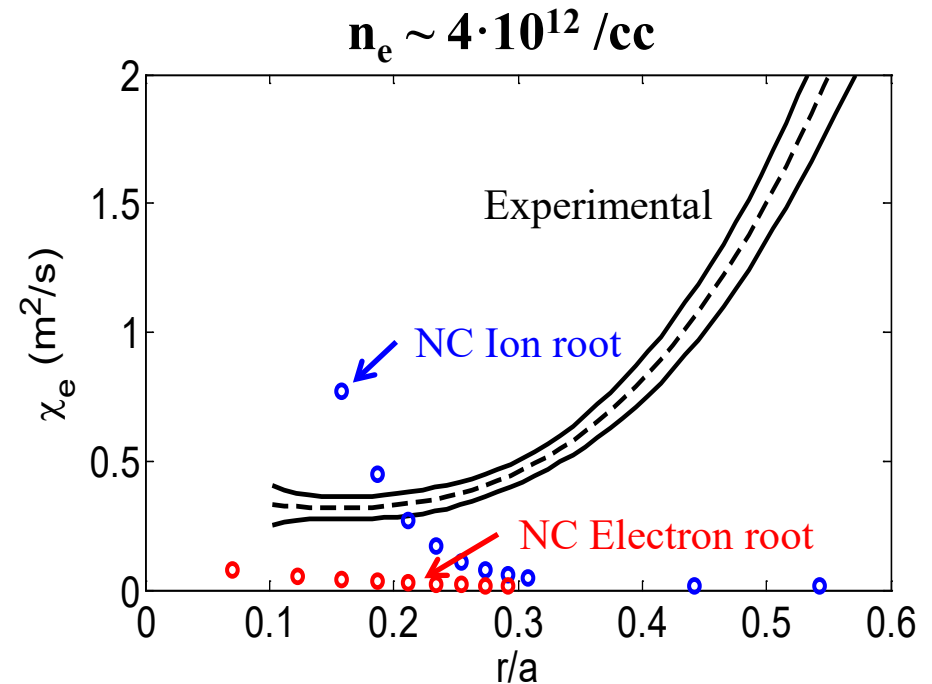
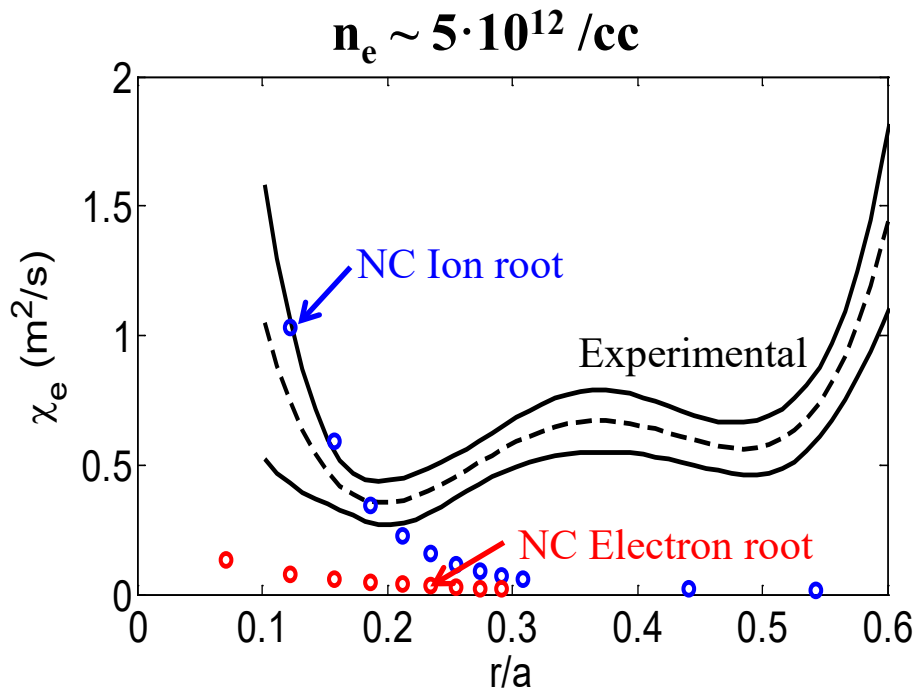
Momentum Conservation Changes Neoclassical E_r

- Momentum conservation changes the neoclassical fluxes, which modifies the ambipolar roots
- For HSX parameters, change in E_r is modest, but effects may be greater for larger T_i
- Change in ion root E_r may be important for ion confinement



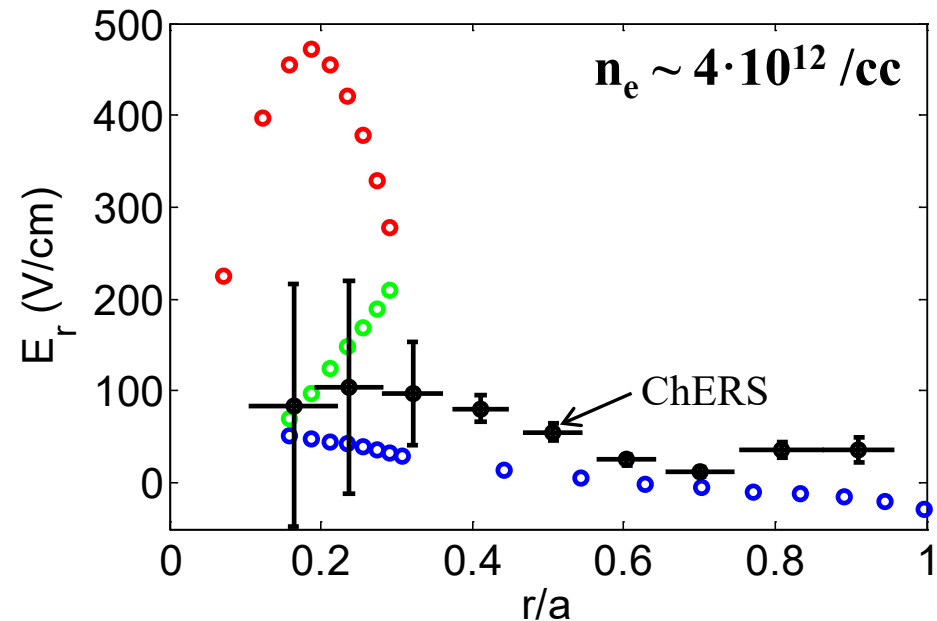
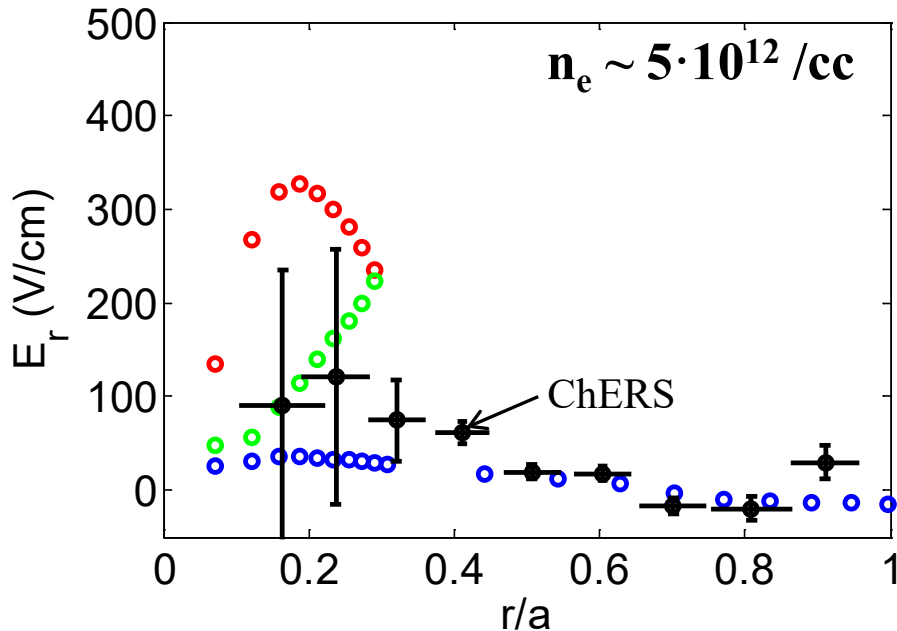
Experimental Thermal Diffusivity is Consistent with Ion Root at High Density

- In the higher density case the neoclassical χ_e in the ion root is consistent with the experimental χ_e
 - At the lower density the neoclassical level is larger than the experimental



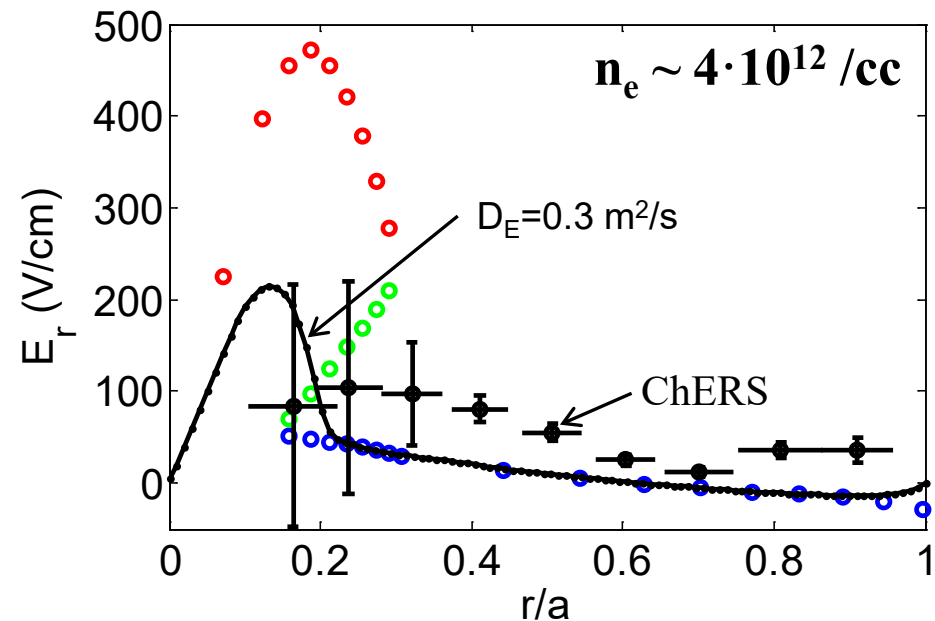
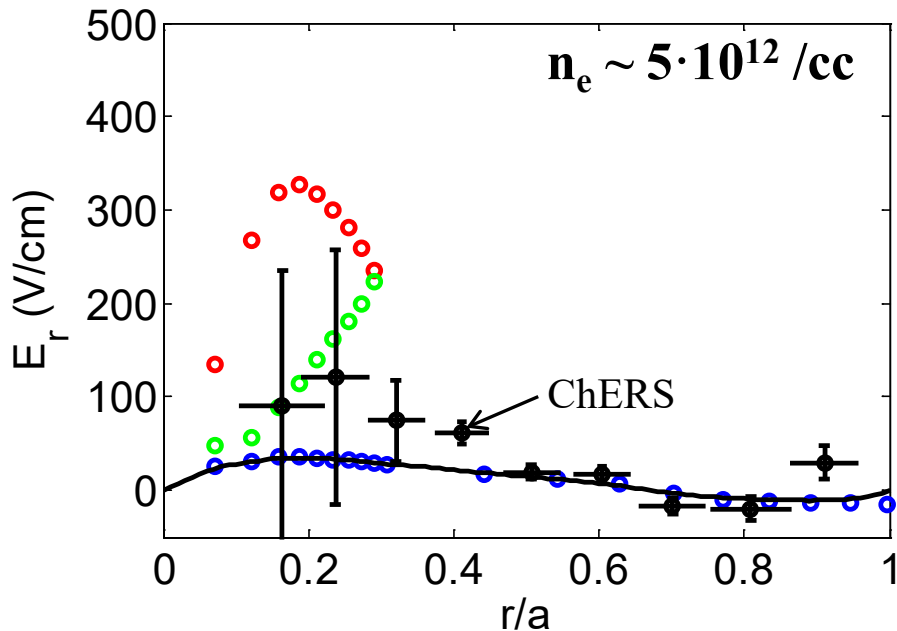
ChERS Measurements are Inconclusive in Plasma Core

- No ChERS measurements exist in region with only electron root predictions
- Edge measurements are consistent with ion root predictions at high density, larger than ion root at low density
- See Briesemeister poster this afternoon (P01-04)



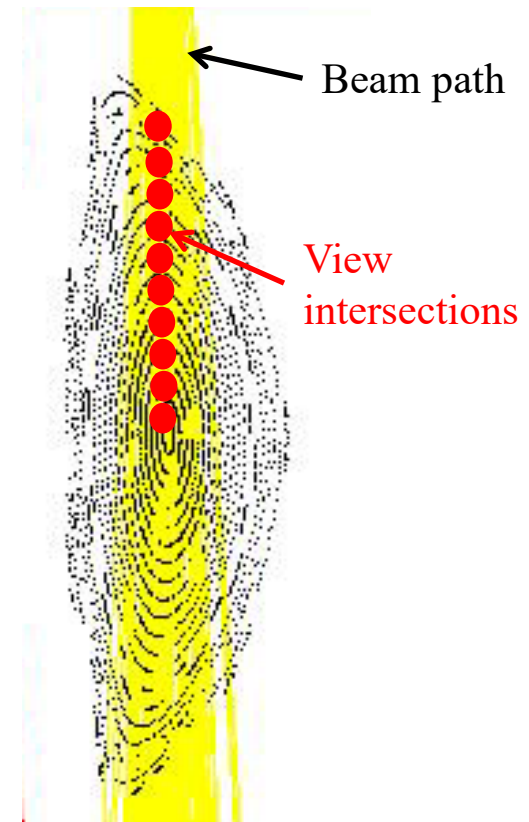
Most of Shear Region is Inside of Measurements

- No ChERS measurements exist in region with only electron root predictions
- Edge measurements are consistent with ion root predictions at high density, larger than ion root at low density
- Only central measurement is within shear region



ChERS Measurements are Complicated Near Plasma Core

- The strong flux surface shaping and the beam width complicate the ChERS analysis, particularly near the core
 - These effects may result in a smoothing of the measured E_r profile
- Work is proceeding on a synthetic diagnostic and an improved analysis technique¹ to better quantify errors
- See Briesemeister poster this afternoon (P01-04)

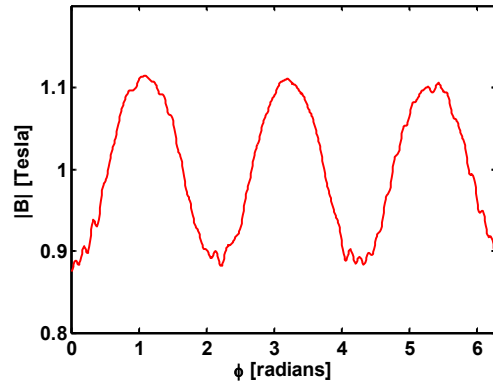


1) Conway, Carolan and Tournianski (1998)

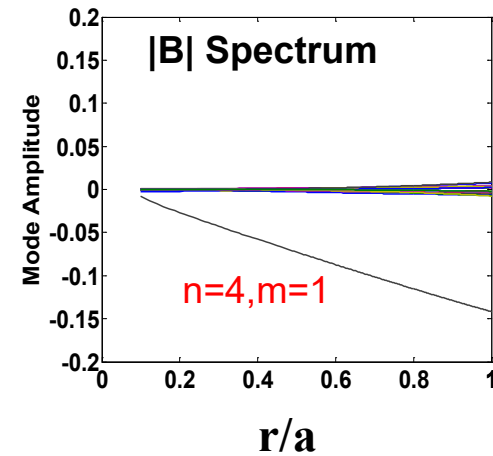
HSX can operate in QHS or as a conventional stellarator

QHS

|B| along field line

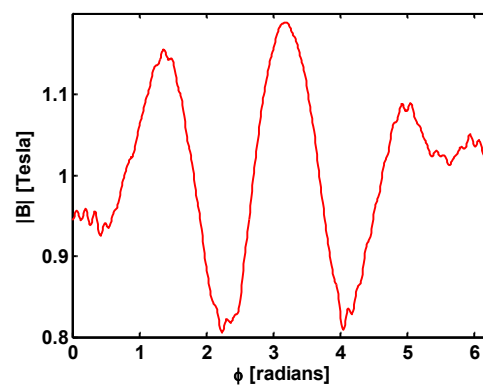


|B| Spectrum

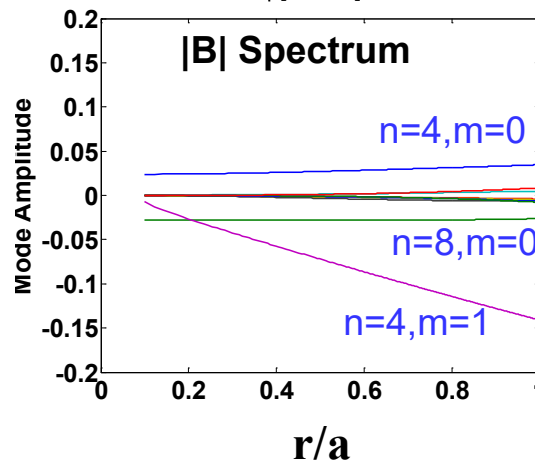


Mirror

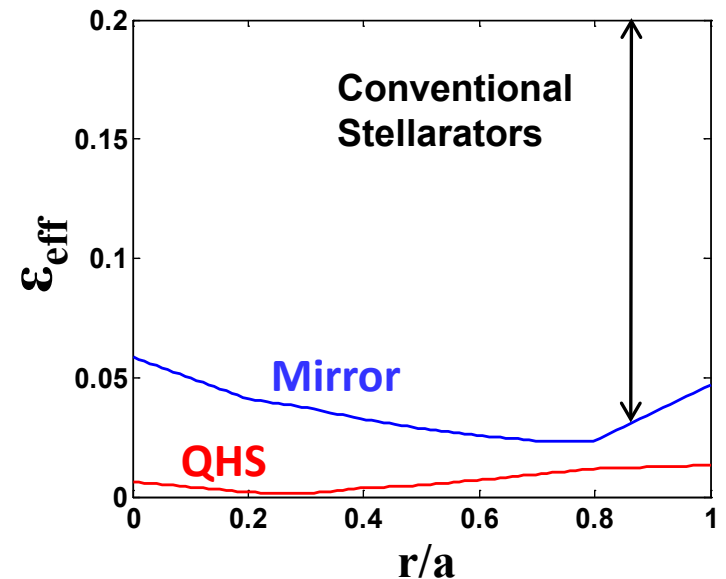
|B| along field line



|B| Spectrum

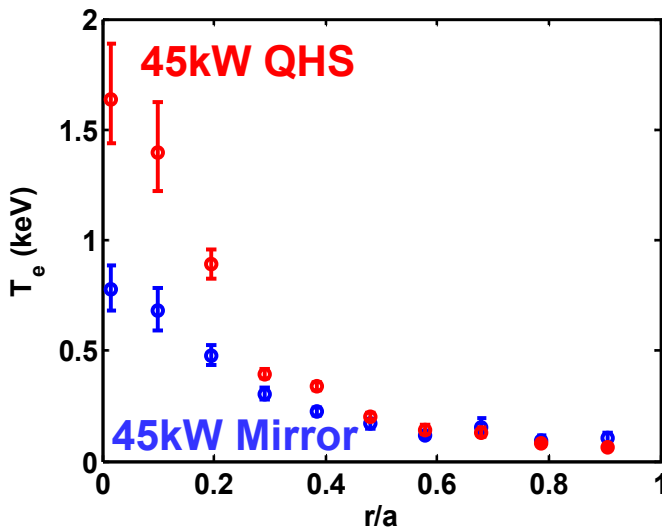


- The quasi-helical symmetry (QHS) of HSX can be spoiled by a set of auxiliary coils
- This symmetry breaking configuration (Mirror) changes the transport properties towards the level of a conventional stellarator
- The level of symmetry breaking can be represented by the effective ripple



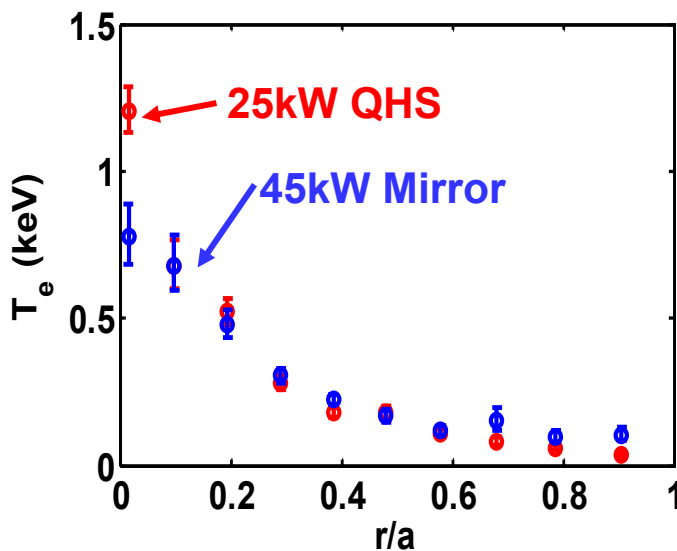
Symmetry breaking at edge < 1%

Electron Thermal Transport

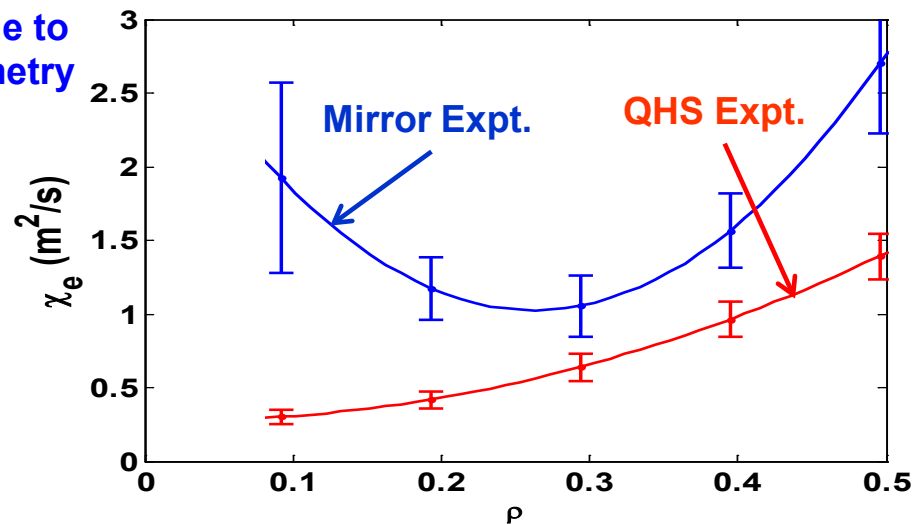


- For the same injected power, core T_e in QHS is much greater than Mirror.
- QHS profiles are very peaked, with sharp radial transition in ∇T_e .
- Experimental thermal transport analyzed via matching T_e profiles by varying injected power.
- Anomalous transport of interest due to LHD results where reducing NC transport also reduces anomalous.
- Anomalous transport is inferred by difference in experimental and NC levels.

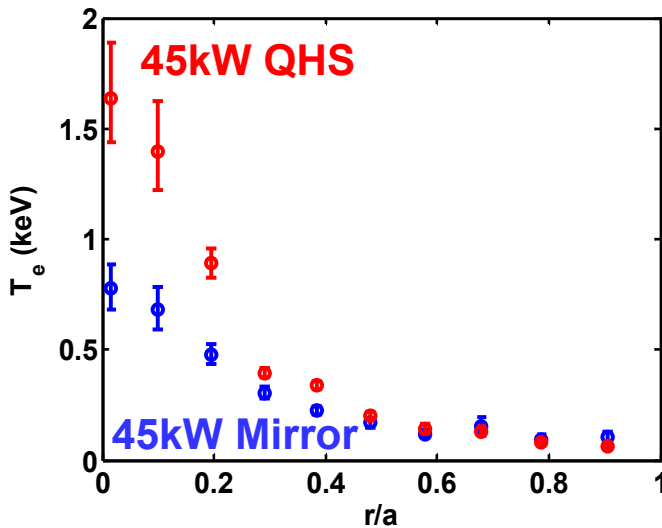
$$\chi_{anom} = \chi_{exp} - \chi_{neo}$$



Transport
reduced due to
quasisymmetry

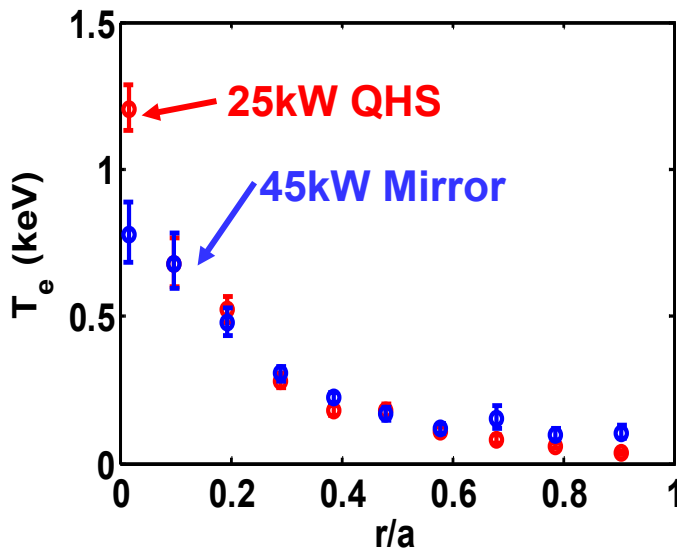


Electron Thermal Transport

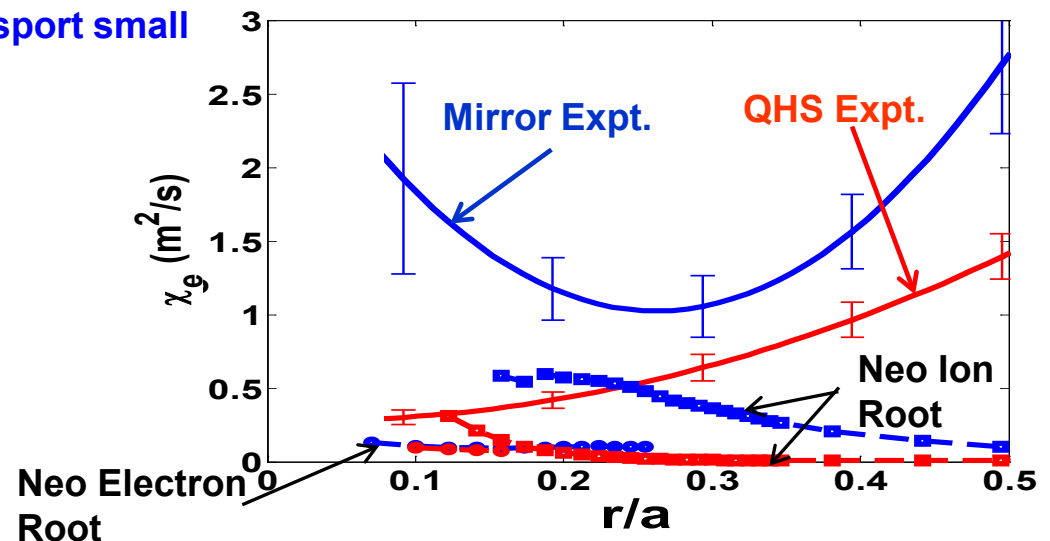


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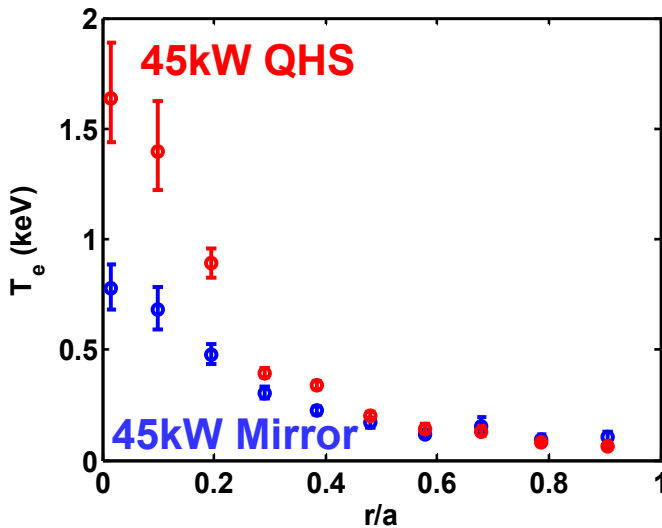
$$\chi_{anom} = \chi_{exp} - \chi_{neo}$$



Neoclassical
transport small

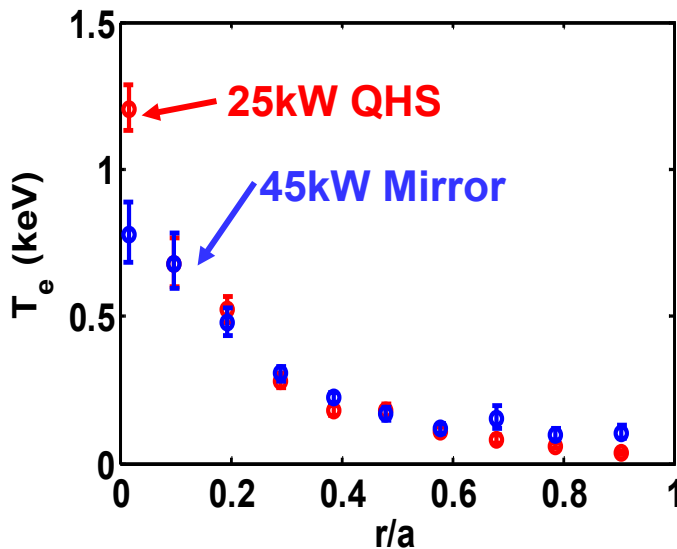


Electron Thermal Transport

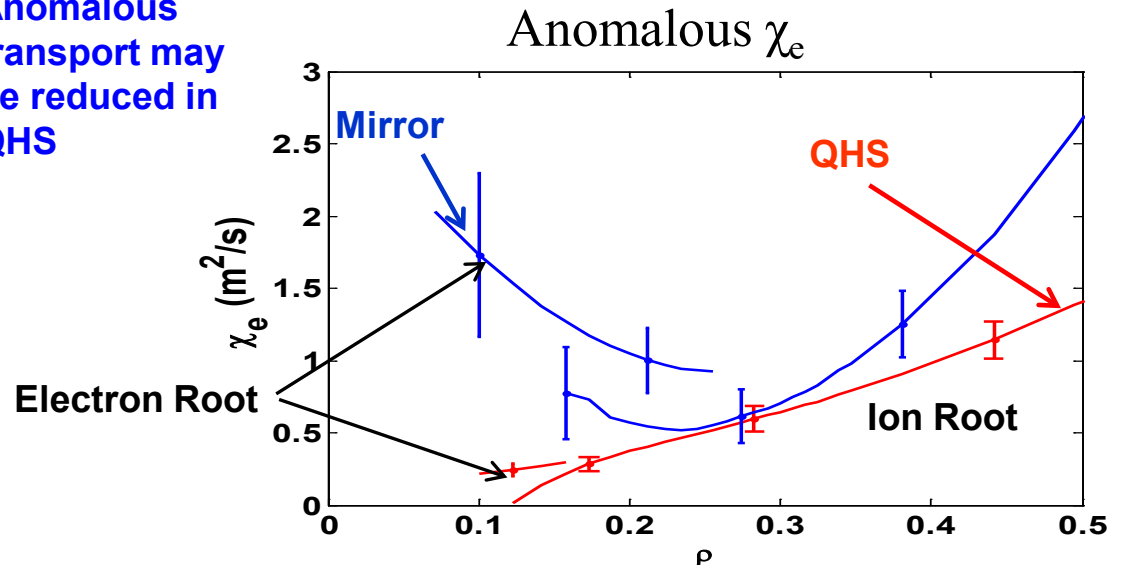


- For the same injected power, core T_e in QHS is much greater than Mirror.
- QHS profiles are very peaked, with sharp radial transition in ∇T_e .
- Experimental thermal transport analyzed via matching T_e profiles by varying injected power.
- Anomalous transport of interest due to LHD results where reducing NC transport also reduces anomalous.
- Anomalous transport is inferred by difference in experimental and NC levels.

$$\chi_{anom} = \chi_{exp} - \chi_{neo}$$

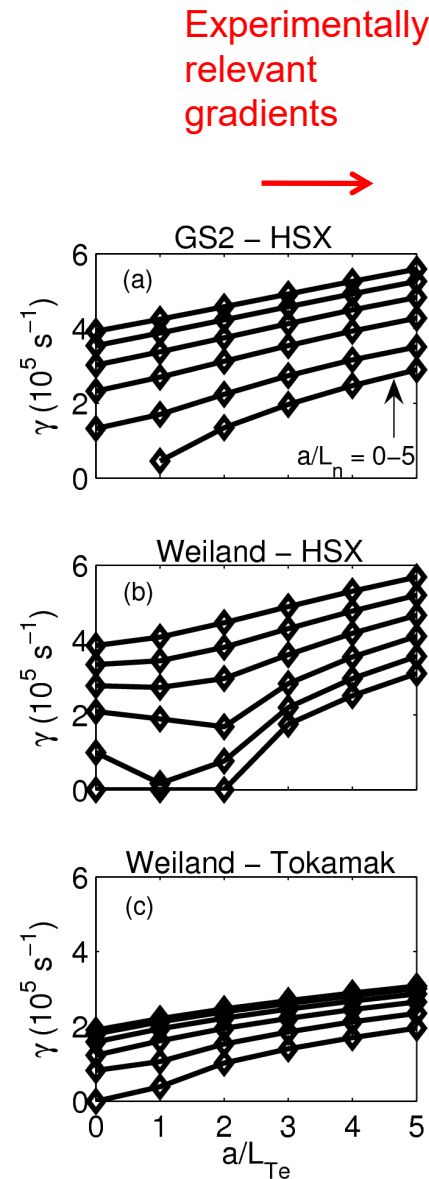


Anomalous transport may be reduced in QHS



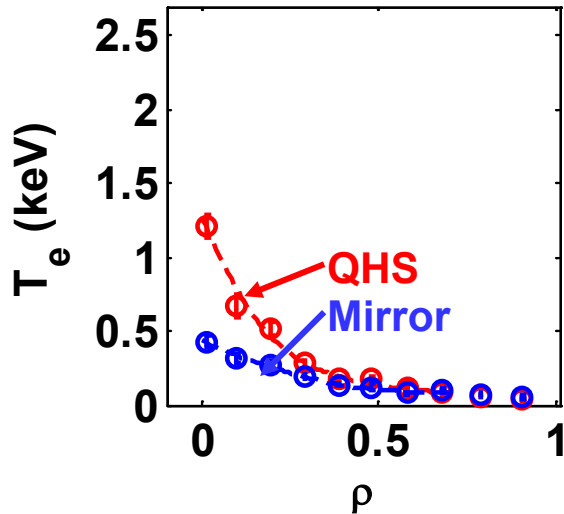
GS2 and Weiland Growth Rates

- Agreement within 30% for experimentally relevant gradients

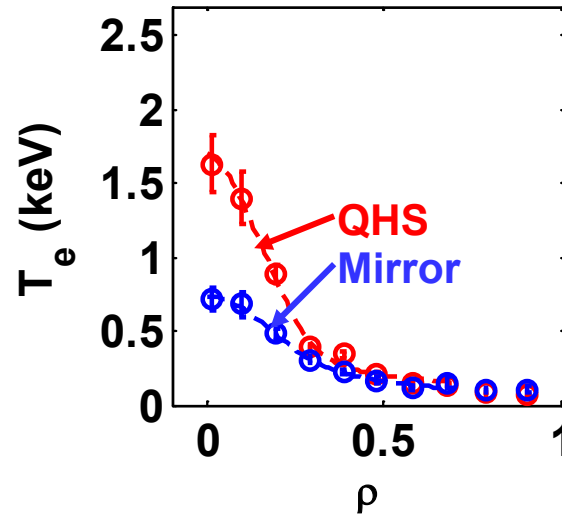


Electron Thermal Transport

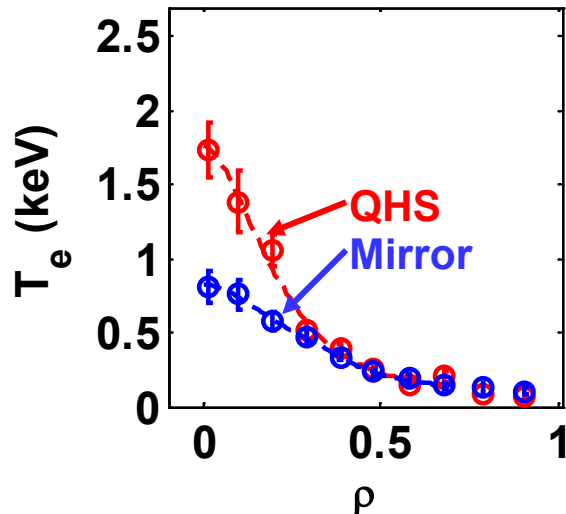
26kW



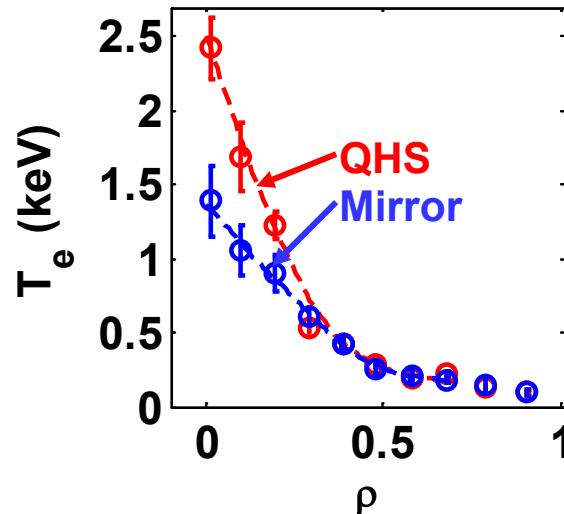
44kW



70kW

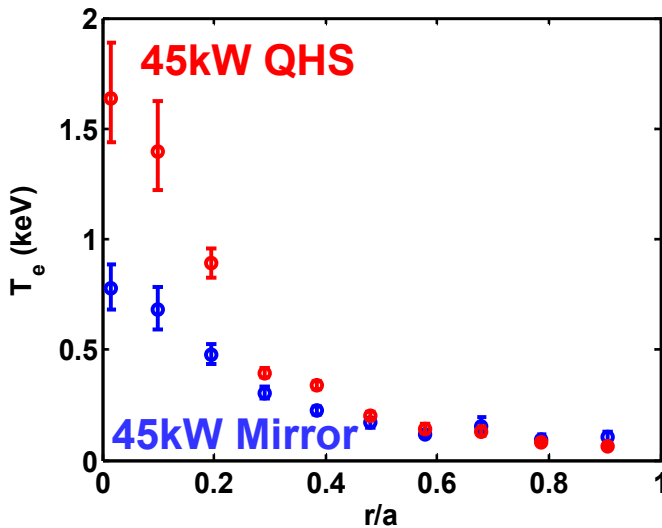


100kW

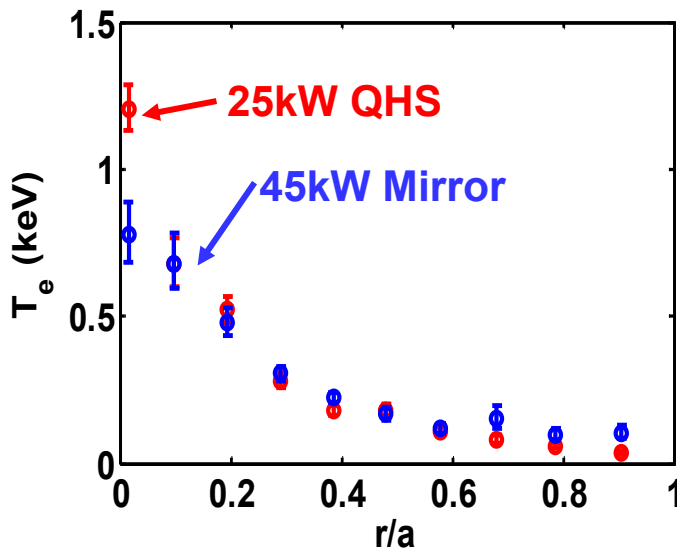


- For every injected power, T_e in QHS is much greater than Mirror.
- This indicates improved electron thermal transport in QHS.
- Note also that QHS profiles have sharp radial transition in ∇T_e .

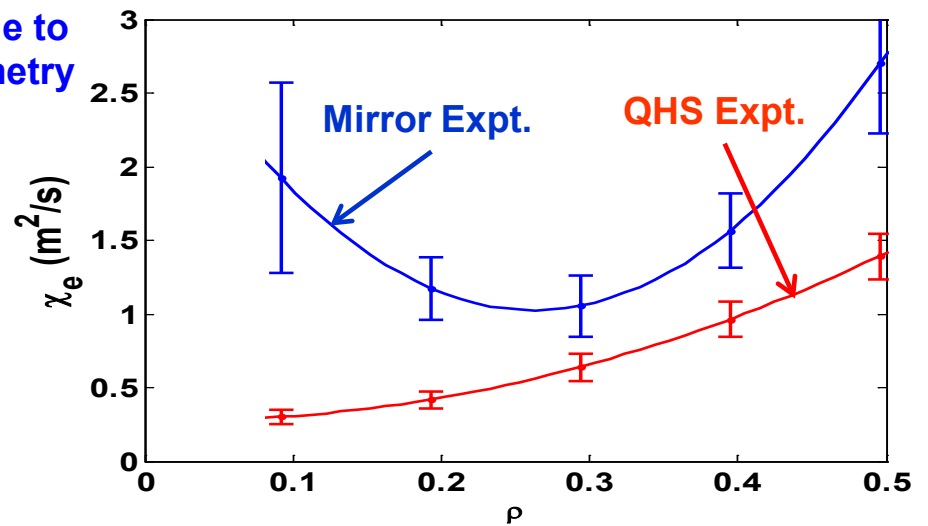
Electron Thermal Transport



- For the same injected power, core T_e in QHS is much greater than Mirror.
- QHS profiles are very peaked, with sharp radial transition in ∇T_e .
- Experimental thermal transport analyzed via matching T_e profiles by varying injected power.



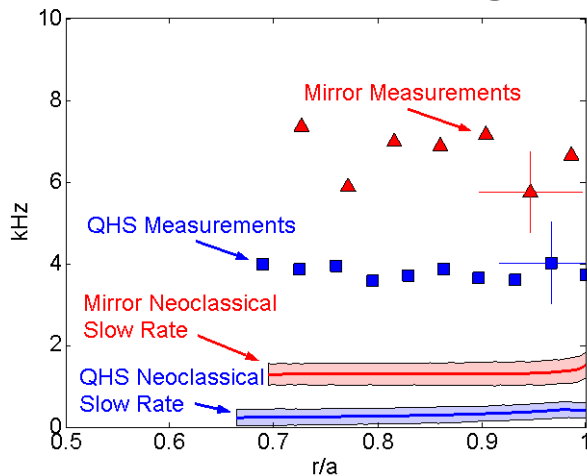
Transport reduced due to quasisymmetry



HSX has demonstrated benefits of quasi-symmetry at B=0.5T

- Reduction in flow damping, particle and heat transport demonstrated at B=0.5T
- Neoclassical is reduced; anomalous contribution dominates
- All other results in this talk for B=1T

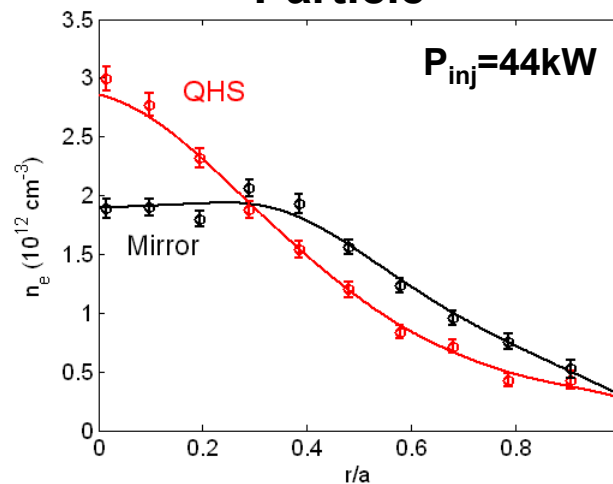
Flow Damping



Larger flows in QHS with equivalent torque

→ Lower parallel viscous damping

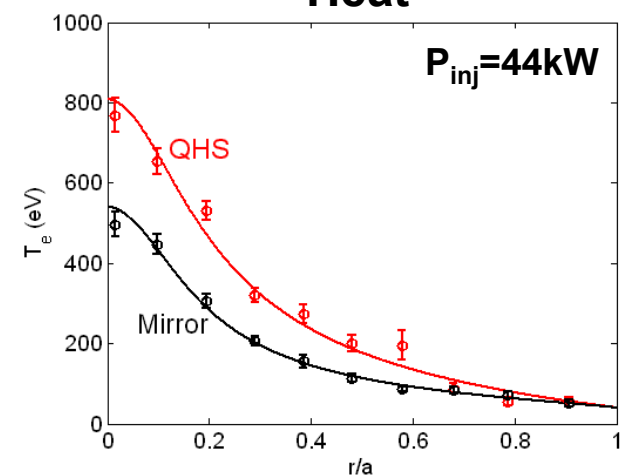
Particle



Peaked density profiles in QHS

→ Reduced thermodiffusion

Heat



Higher T_e in QHS with same absorbed power

→ Lower χ_e

→ For same absorbed power χ_e in core reduced from 4 to 2.5 m^2/s , comparable to NC reduction

Neoclassical Calculations can Conserve Parallel Momentum

- Neoclassical heat and particle fluxes, bootstrap current and flows are calculated using an enhanced version of the PENTA¹ code
 - What I added to
- PENTA is based on the parallel momentum conserving moments method of Sugama and Nishimura²
 - Unlike calculations which only consider pitch angle scattering, the effects of interspecies collisions and parallel flow are included

$$\Gamma^{SN} \cong \underbrace{-D_{11}A_1 - D_{12}A_2}_{\text{Pitch angle scattering}} - \underbrace{D_{11}^{corr}A_1 - D_{12}^{corr}A_2 + \sum_{j=1}^{j_{\max}} \{N^* L_j^{(3/2)}(K)\}_K U_{\parallel j}}_{\text{Momentum restoring}}$$

$$A_1 \sim \nabla p, \nabla \Phi$$

$$A_2 \sim \nabla T$$