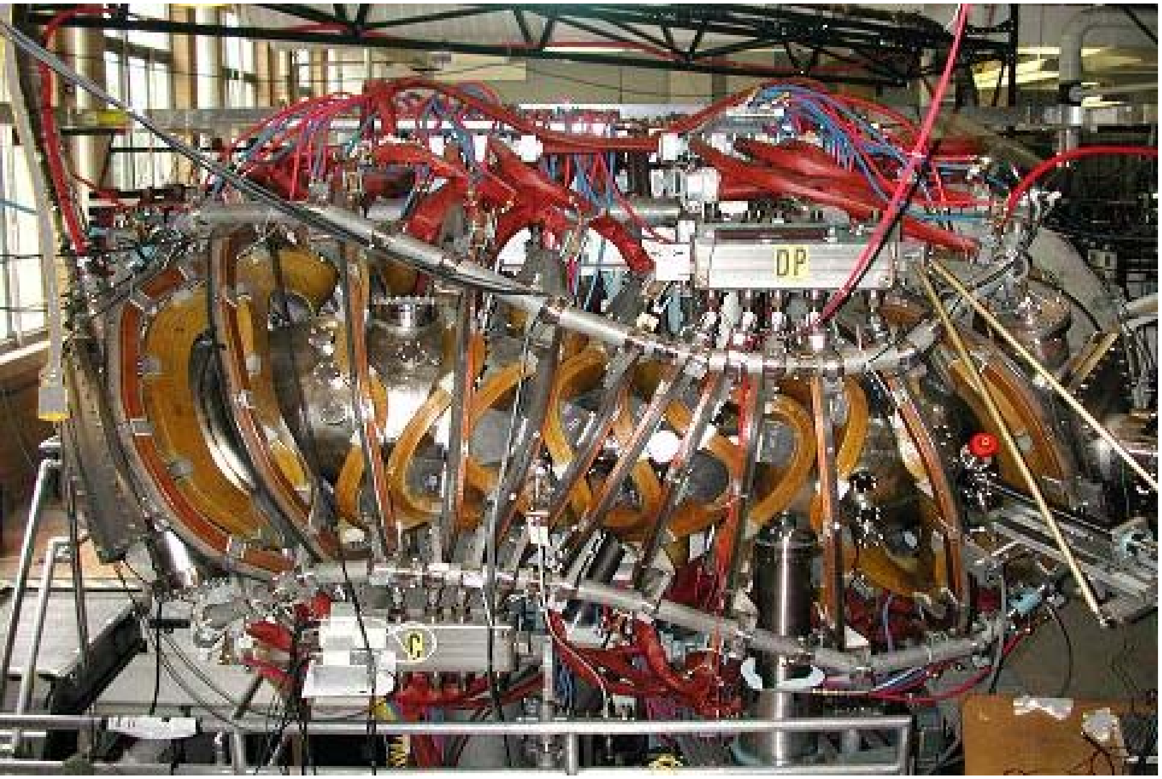
Neoclassically Driven Electron Transport Barrier in the HSX Stellarator



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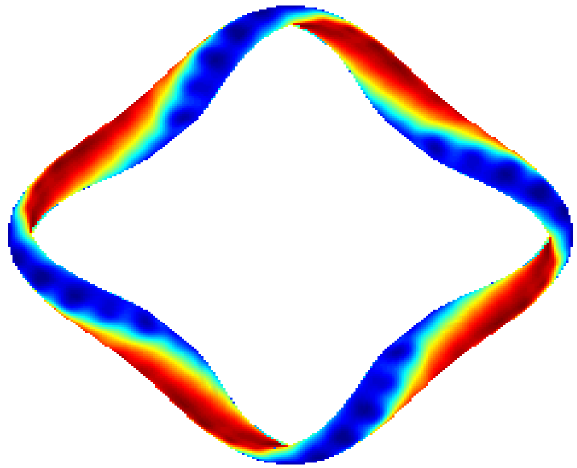
Special thanks to: Walter Guttenfelder (U. Warwick), Don Spong (ORNL), HSX Team

Outline

- Description of the HSX stellarator
- Evidence of electron transport barrier driven by neoclassical E_r profile
  - Peaked T_e profiles measured, electron root E_r with strong radial shear predicted
- 2D turbulent transport model used to describe anomalous transport
  - Peaked T_e profiles only reproduced when ExB shear included
- Density threshold for achieving transport barrier observed for fixed input power
  - Consistent with neoclassical ion root predictions
- Large parallel flow measured and predicted (10-25 km/s)
  - This flow and associated fluxes are accounted for in momentum conserving NC analysis (PENTA)

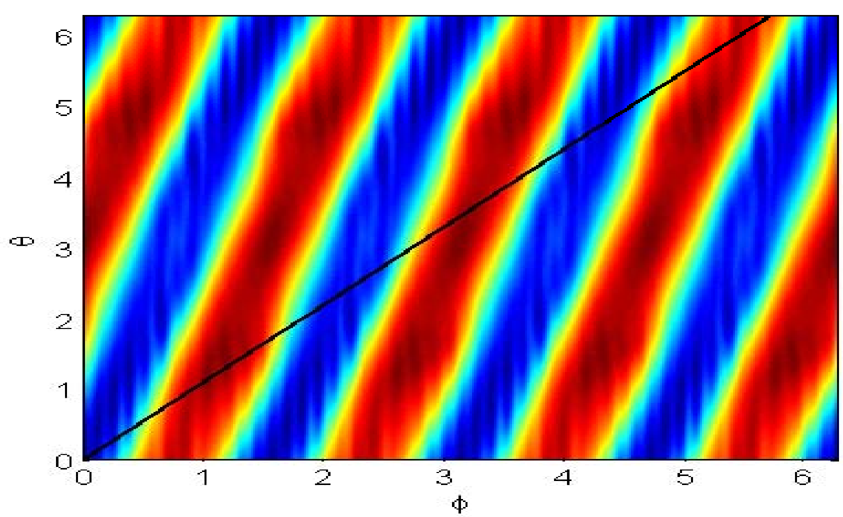
HSX is Quasi-Helically Symmetric



- QHS: helical direction of symmetry in |B|
- Effective transform is larger than physical transform
- Symmetry breaking < 1% at edge

Tokamak: $B/B_0 \cong 1-\varepsilon_t \cos \iota\phi$

QHS: $B/B_0 \cong 1-\varepsilon_h \cos \underbrace{(n-m\iota)}_{\iota_{\mathrm{eff}} \sim 3}\phi$

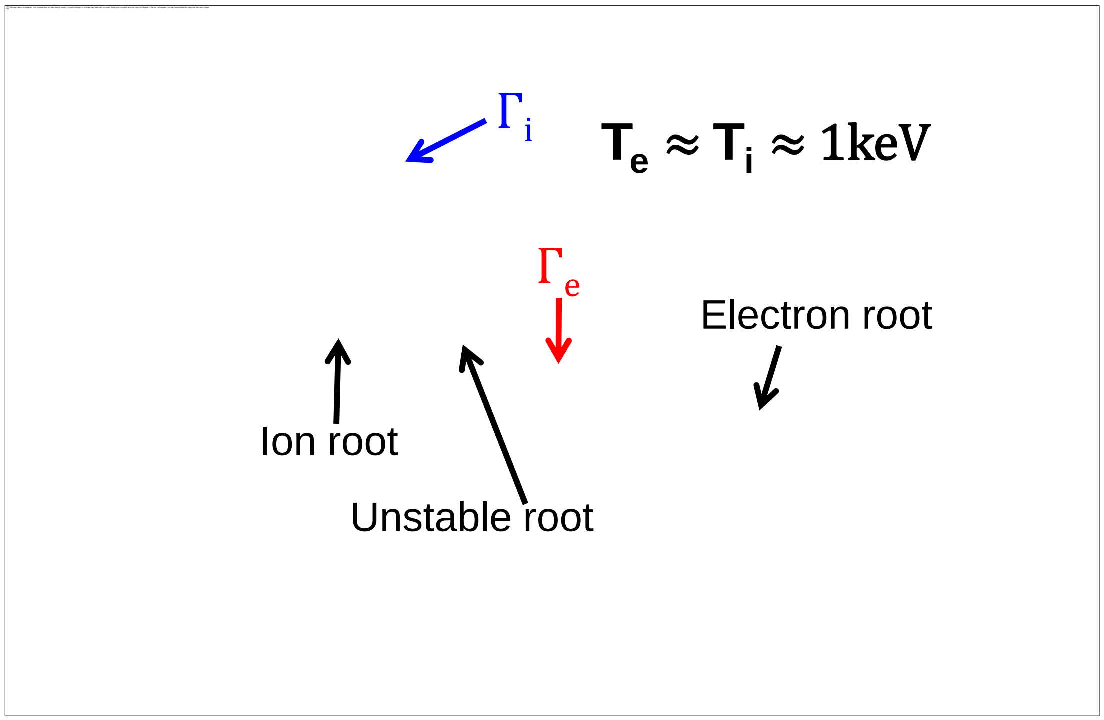


HSX Parameters

<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**

Calculating the Radial Electric Field

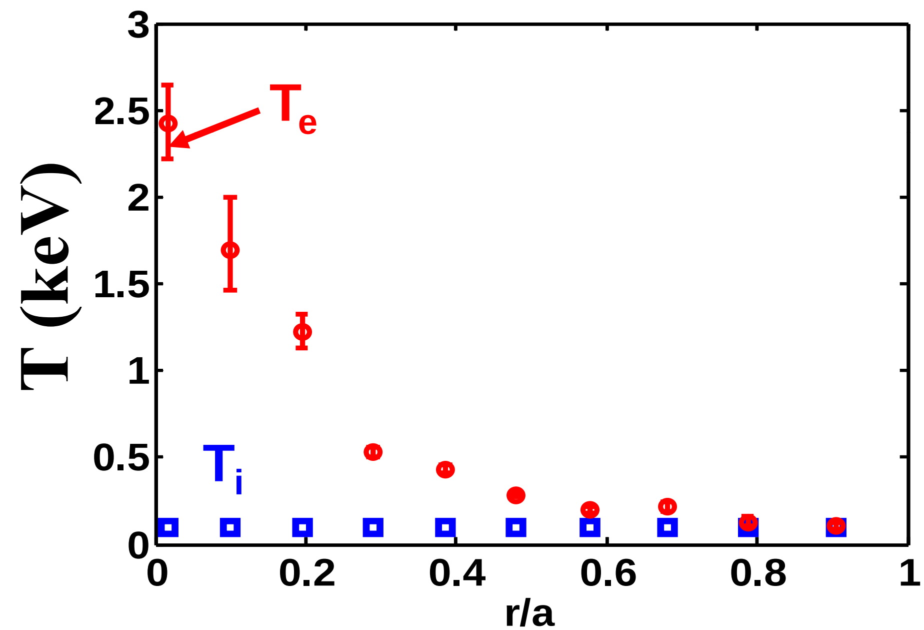
- E_r is determined by enforcing ambipolarity
- LMFP with $T_e \approx T_i$ results in three roots

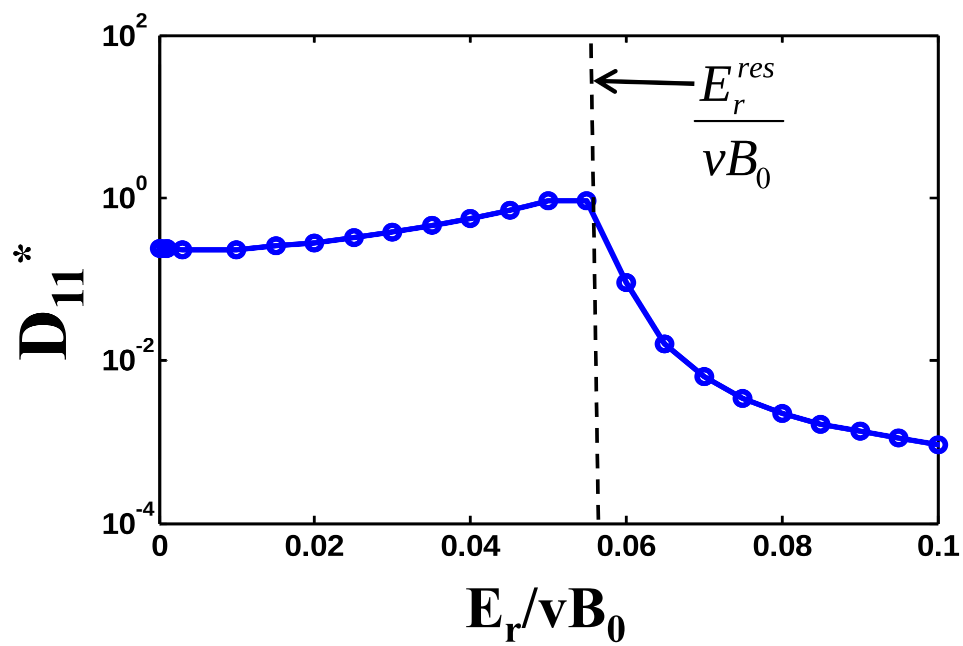


- Electron root can be reached by increasing Γ_e
- When $T_e >> T_i$ the ion root solution may not exist near the core

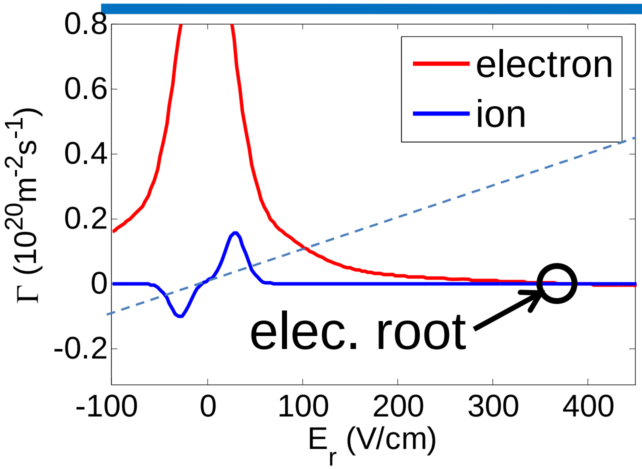
HSX Can Achieve Electron Root Because $T_e >> T_i$

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

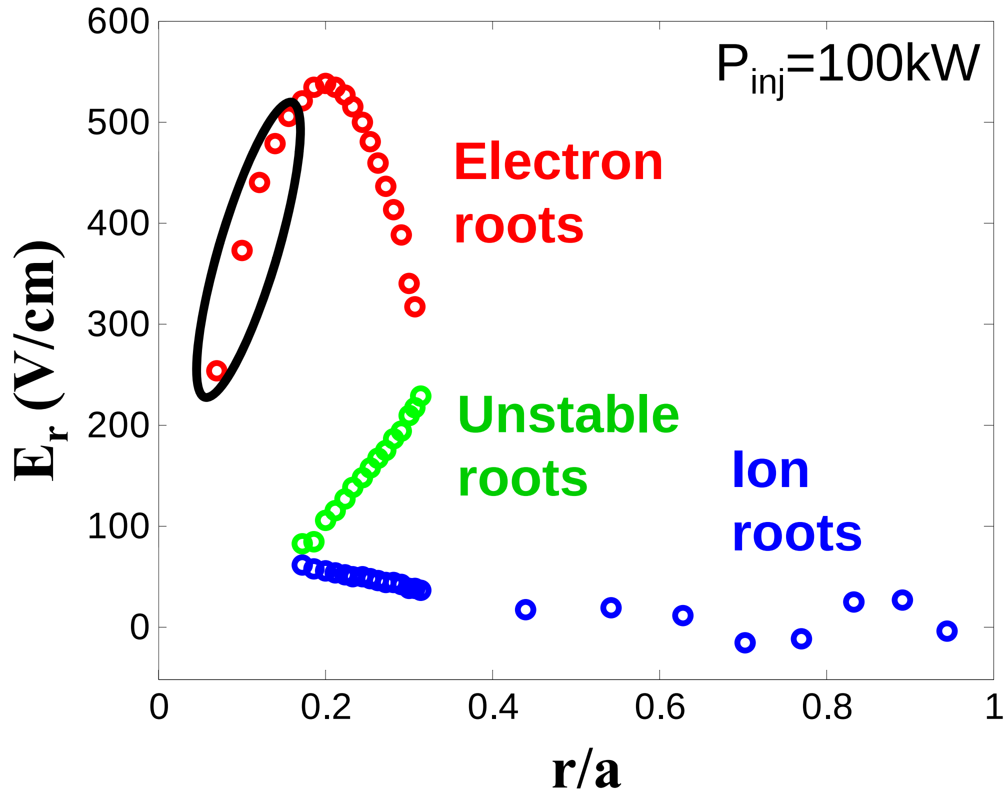




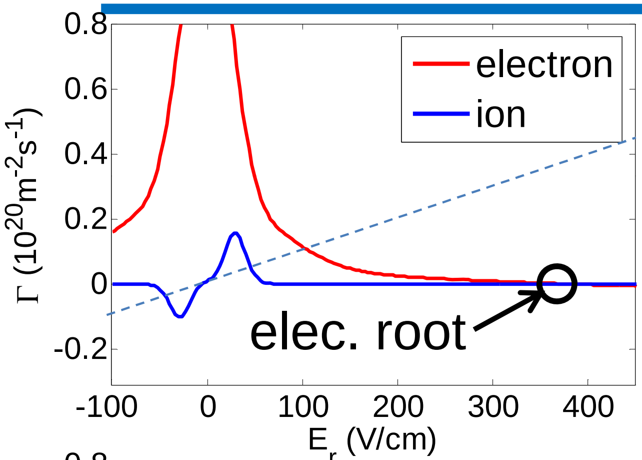
Radial Electric Field Roots in HSX



ρ=0.1
T_e=2keV
T_i=70eV



Radial Electric Field Roots in HSX



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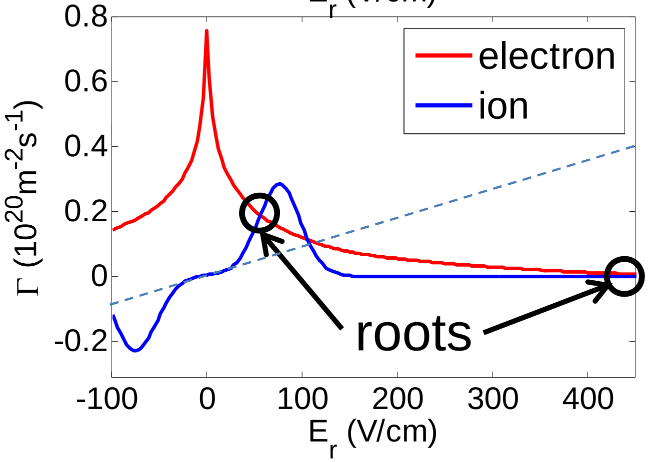
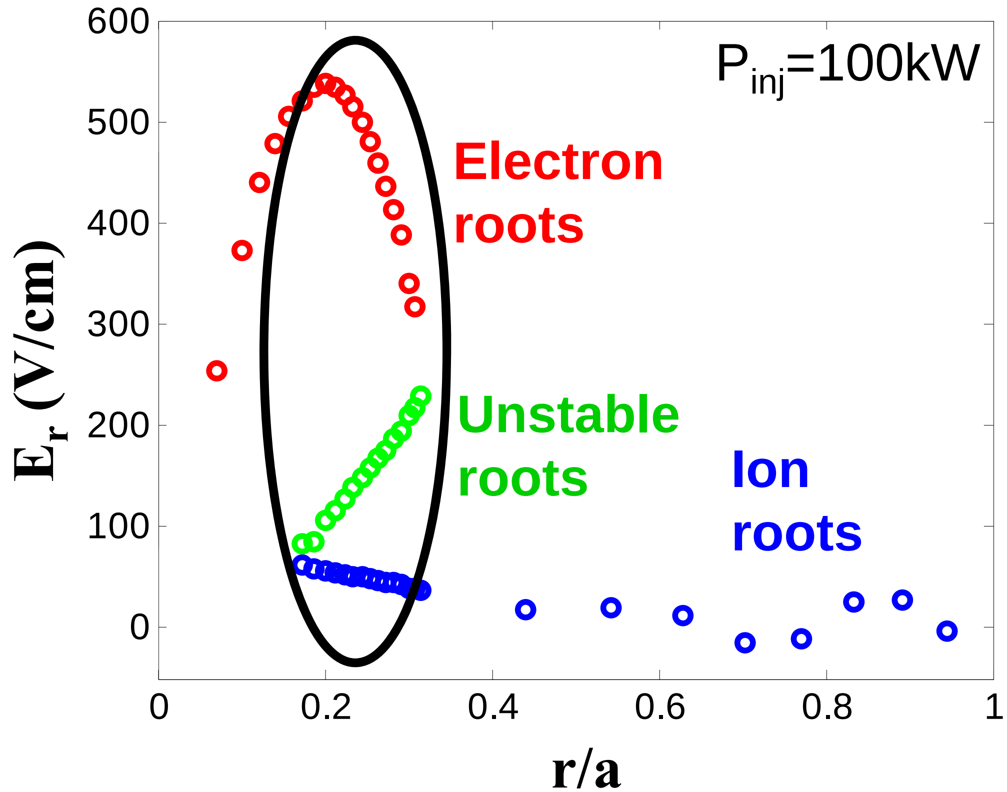


ρ=0.3
T_e=750eV
T_i=60eV



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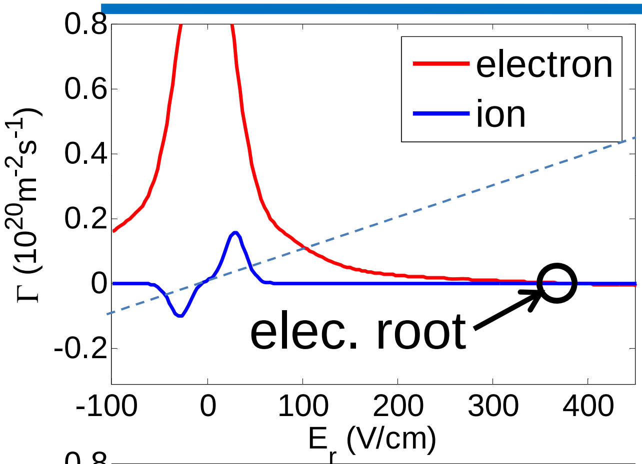

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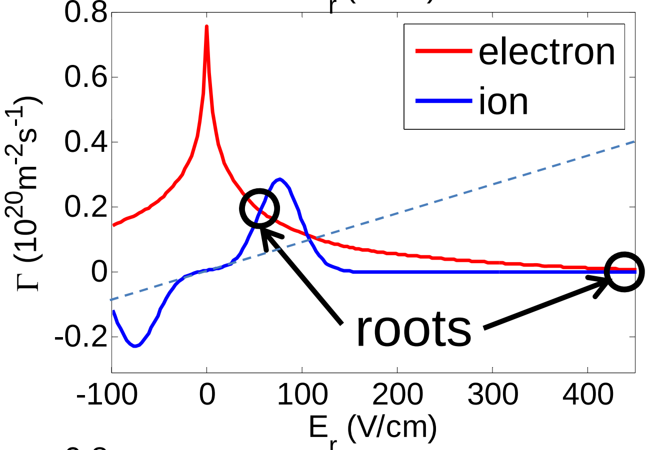

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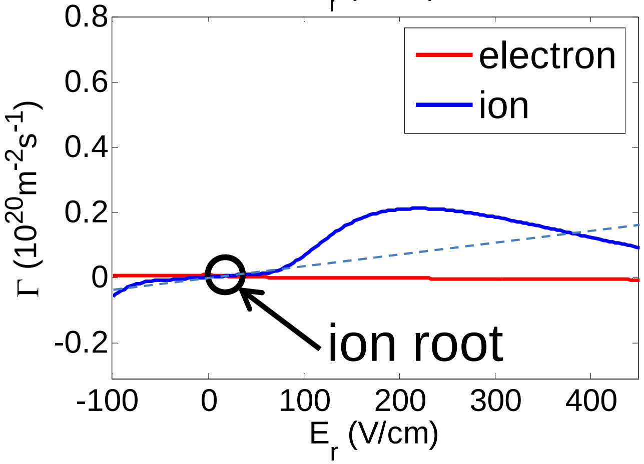
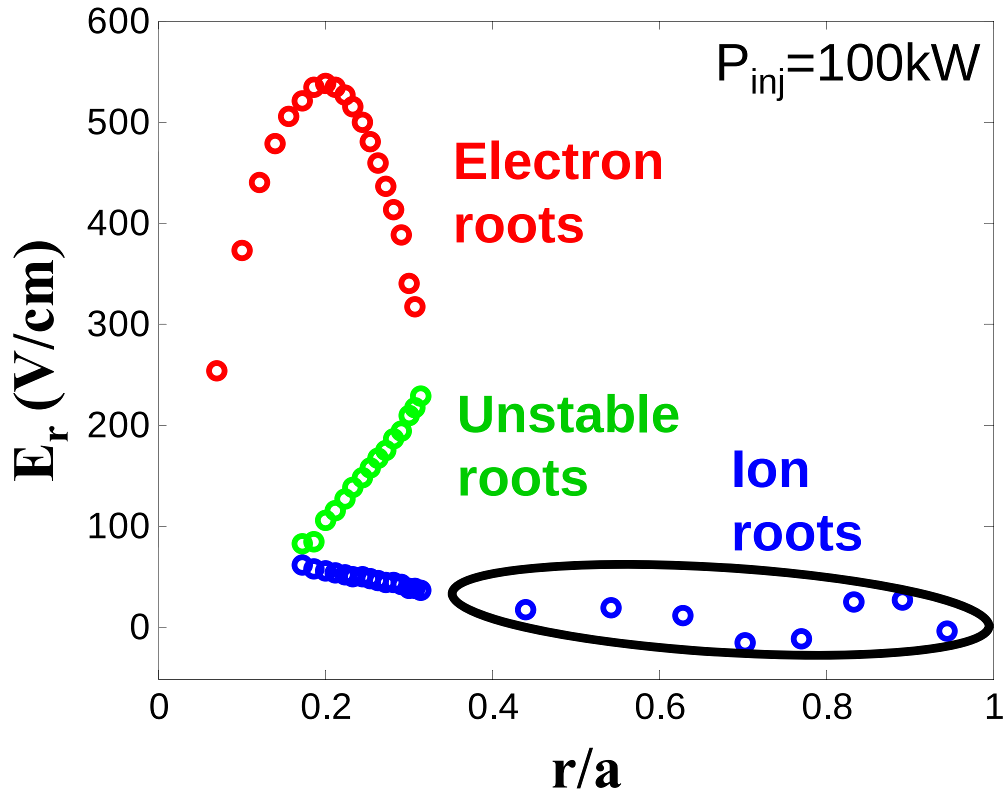
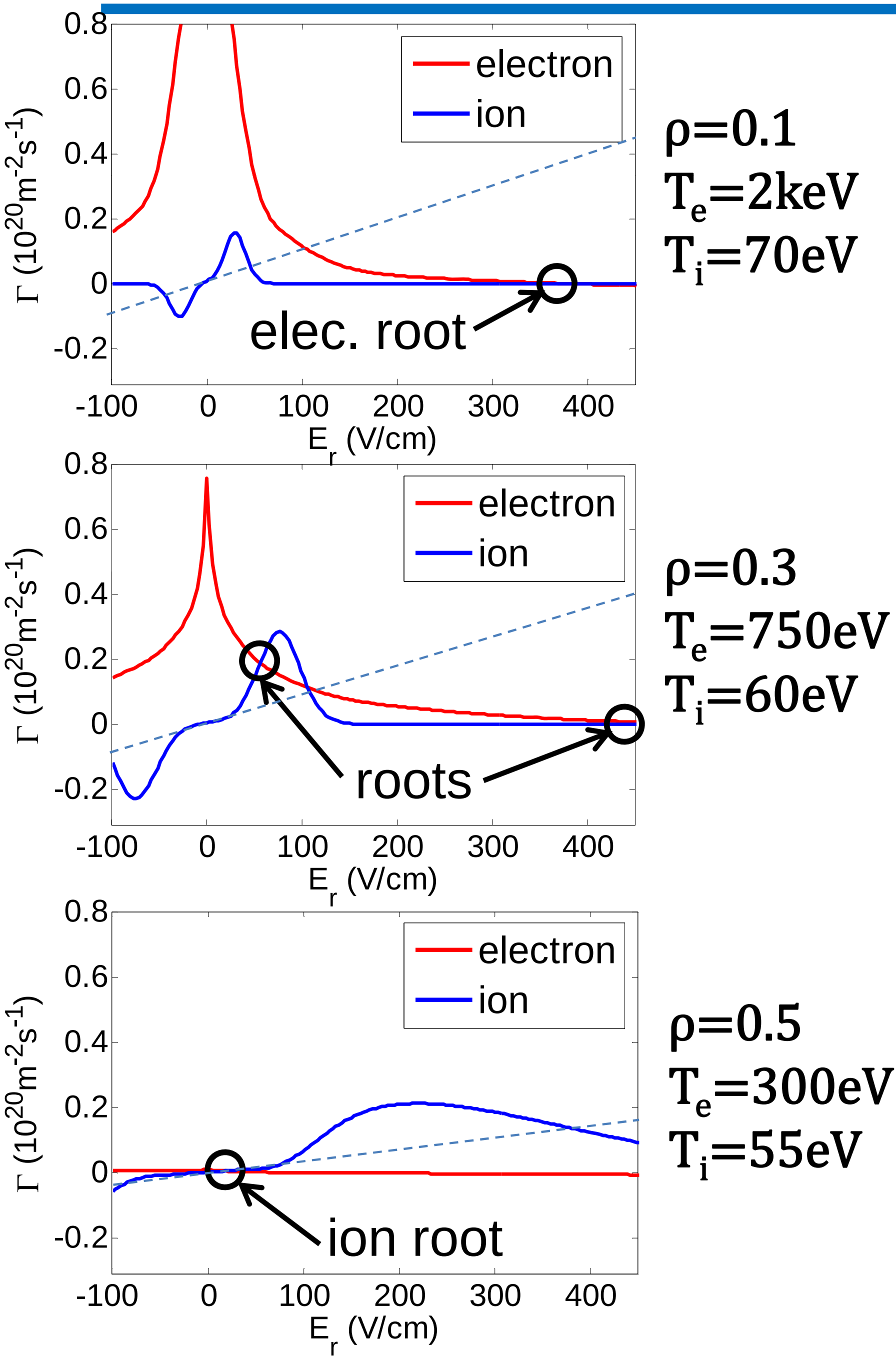
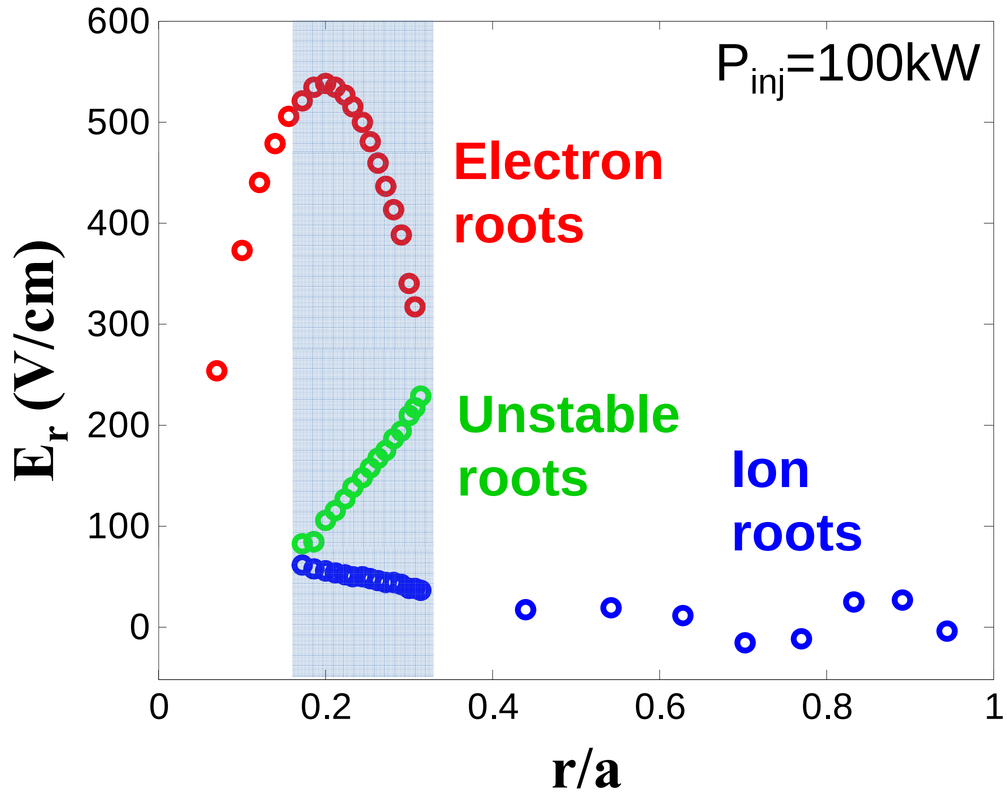


ρ=0.5
T_e=300eV
T_i=55eV



Radial Electric Field Roots in HSX



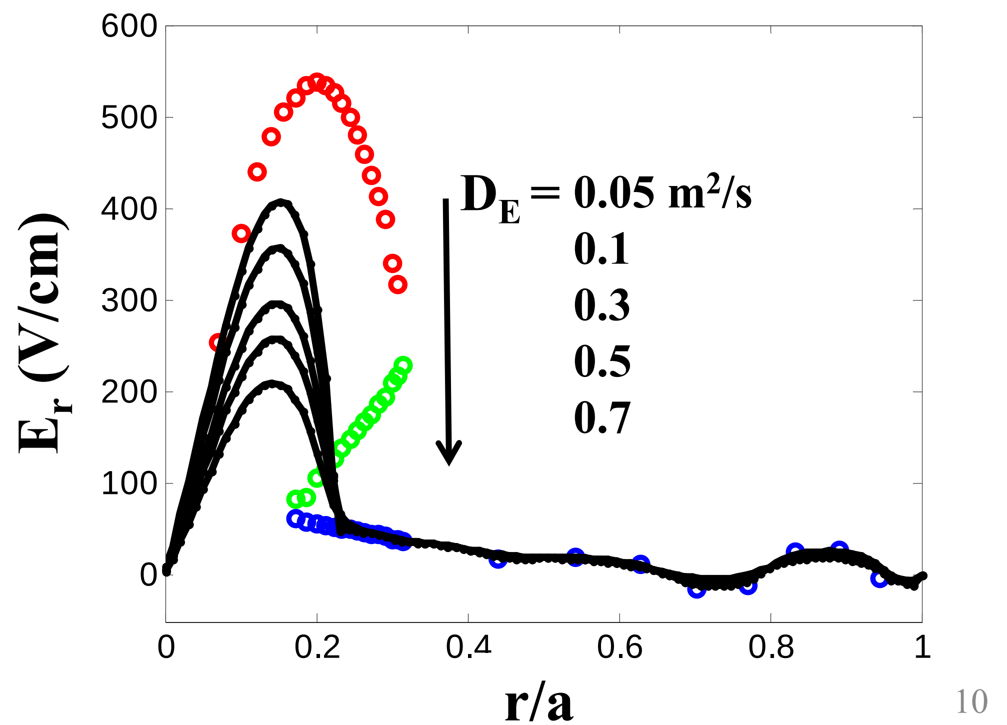


- **Only electron root in core, and only ion root towards edge**
  - Somewhere in three root region there is a transition, with strong E_r shear
  - Determining shear layer involves perpendicular viscosity

Solving the Diffusion Equation for E_r

- The radial electric field profile can be determined by solving a diffusion equation[1]
- 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~0.25

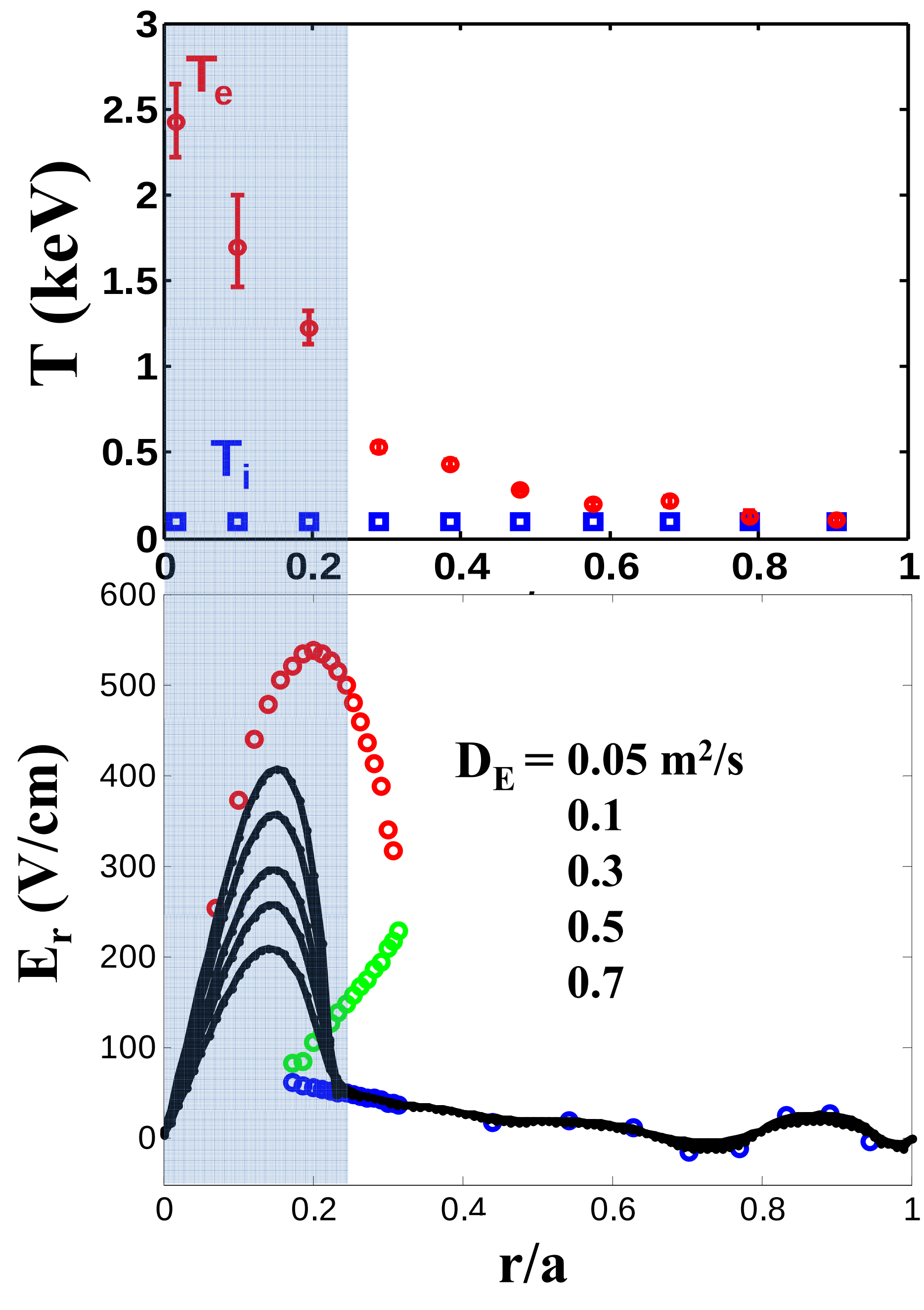
$$\frac{\partial E_r}{\partial t} - \frac{\partial}{\partial V}\left[\langle \nabla V \rangle D_E \left(\frac{\partial E_r}{\partial r} - \frac{E_r}{r}\right)\right] = \frac{e}{\varepsilon_\perp}\left(\Gamma_e - \Gamma_i\right)$$



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

Strong E_r Shear is Predicted in Region of Peaked T_e

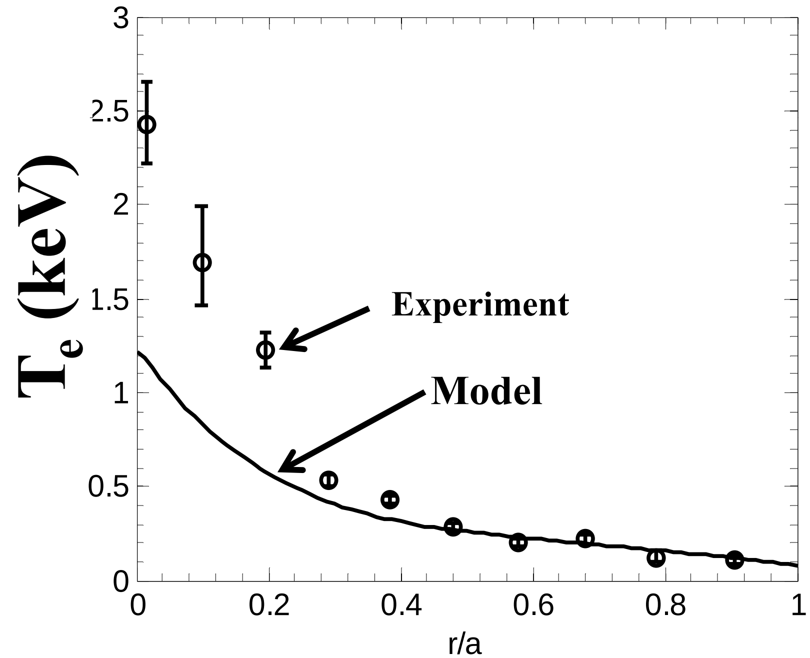
- The radial electric field profile can be determined by solving a diffusion equation[1]
- D_E (related to perpendicular viscosity) is generally not known
  - Solutions for different D_E show a region of strong E_r shear at r/a~0.25
- T_e peaking occurs within the strong E_r shear region
  - E_r shear 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 in QHS
  - Like a tokamak, QHS has a single class of trapped particles.
  - With local geometry considerations, good agreement with 3D gyrokinetic GS2 growth rates.
  - Stored energy and confinement times predicted within 10%
- Predictive transport (NC + Turb.) simulations underestimate T_e in core
  - Turbulent diffusivity in this region is 10x experimental
  - Transport can be reduced via ExB shear



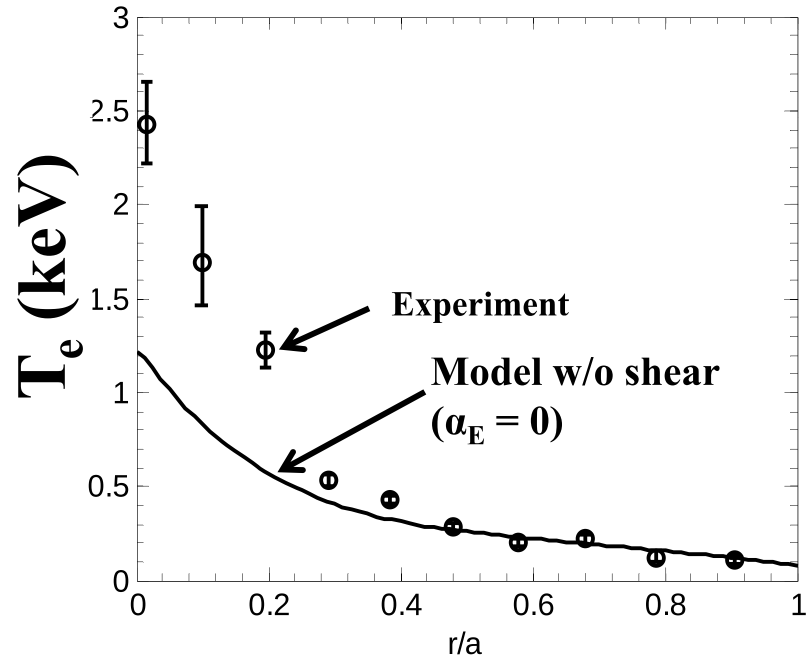
Guttenfelder, Lore, *et. al,* (2008)

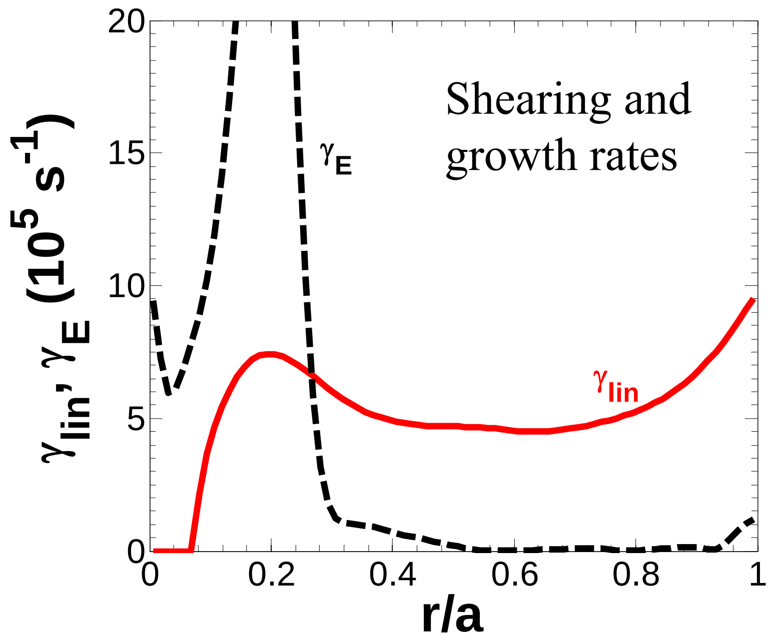
ExB Shearing Rate >> Linear Growth Rate for r/a < 0.3

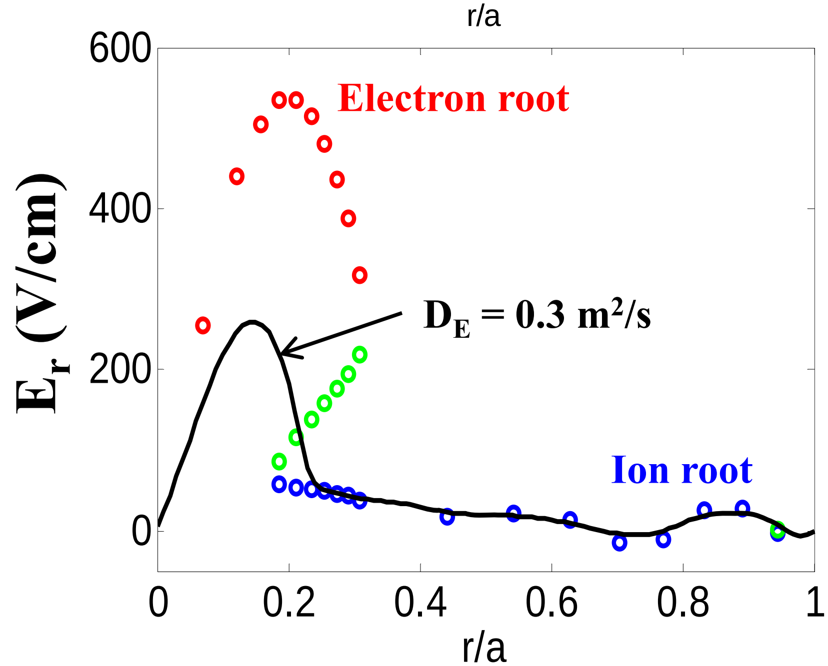
- ExB shear suppression is modeled using a linear quench rule:[1]

$$D \Rightarrow D \cdot \max\left(1 - \alpha_E \frac{\gamma_E}{\gamma_{max}}, 0\right)$$

  - γ_E = ExB shear rate
  - γ_{max} = maximum linear growth rate
- Shear suppression expected inside of r/a = 0.3







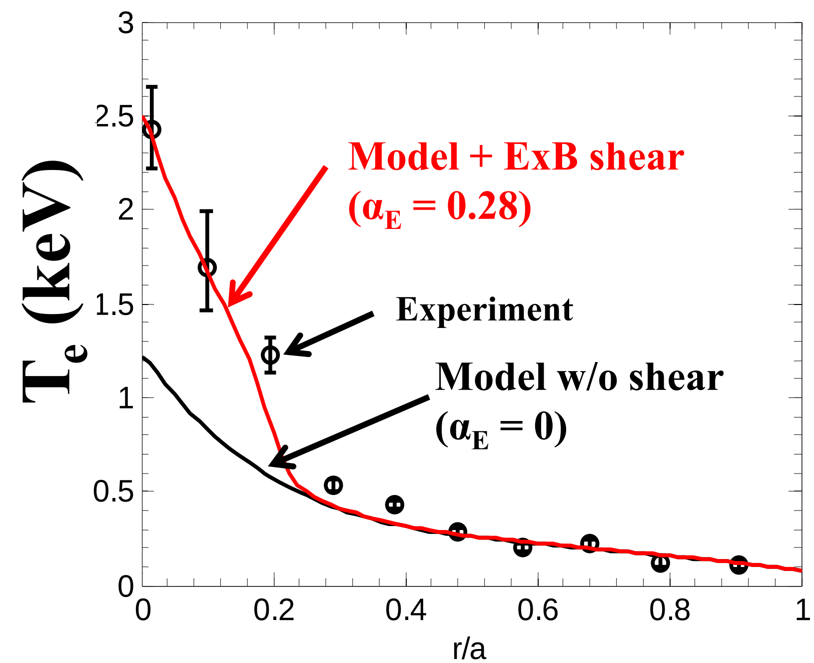
Guttenfelder, Lore, *et. al*, (2008), 1) Kinsey (2005)

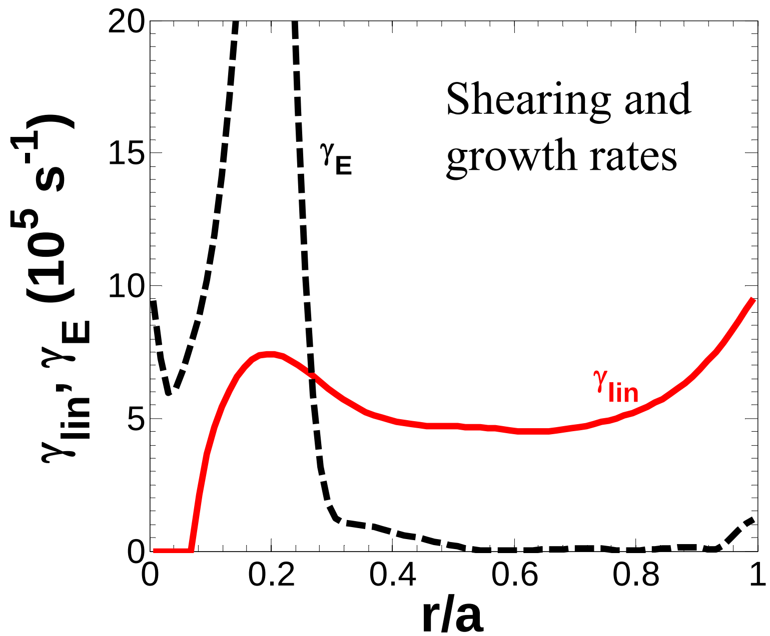
Turbulence Suppression via ExB Shear can Reproduce Experimental Profiles

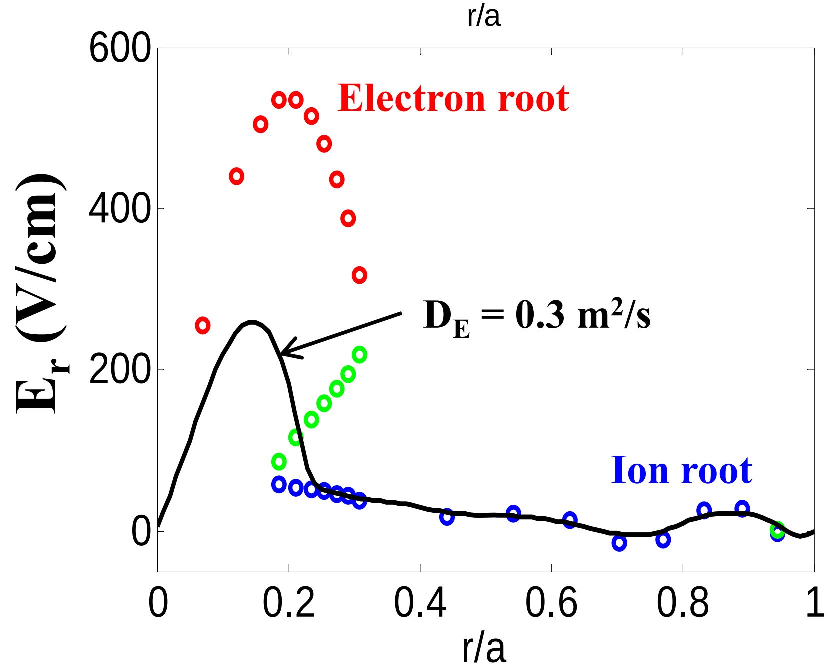
- ExB shear suppression is modeled using a quench rule:[1]

$$D \Rightarrow D \cdot \max\left(1 - \alpha_E \frac{\gamma_E}{\gamma_{\max}}, 0\right)$$

  - γ_E = ExB shear rate
  - γ_{max} = maximum linear growth rate
- E_r shear required to reproduce peaking of experimental T_e profile
- **Coupled turbulent and NC transport model can self-consistently explain measured T_e profiles**



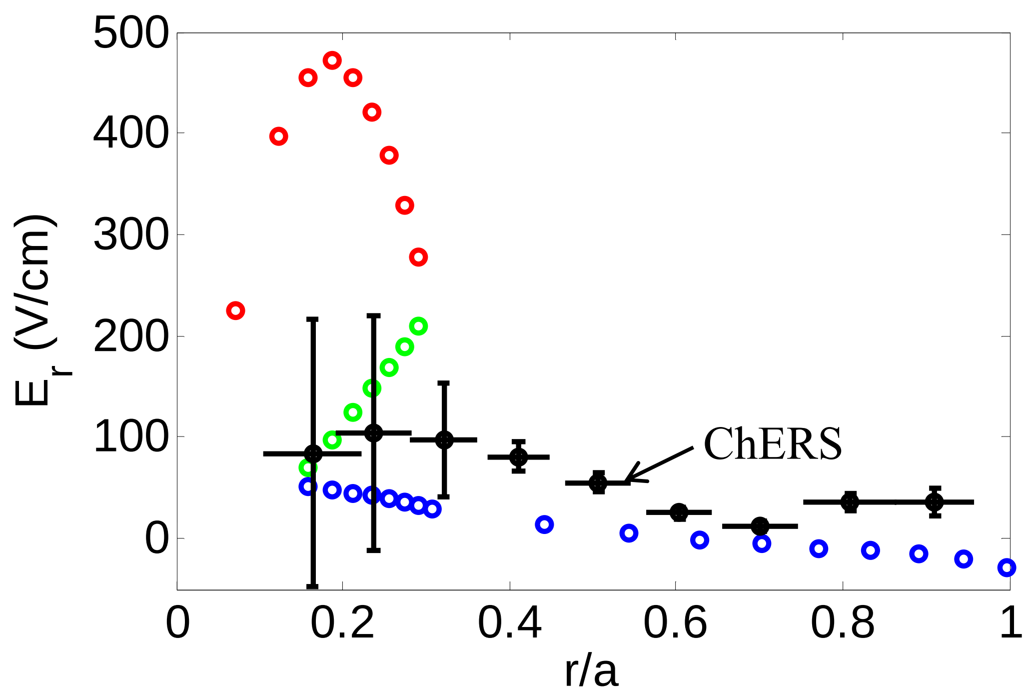




Guttenfelder, Lore, *et. al*, (2008), 1) Kinsey (2005)

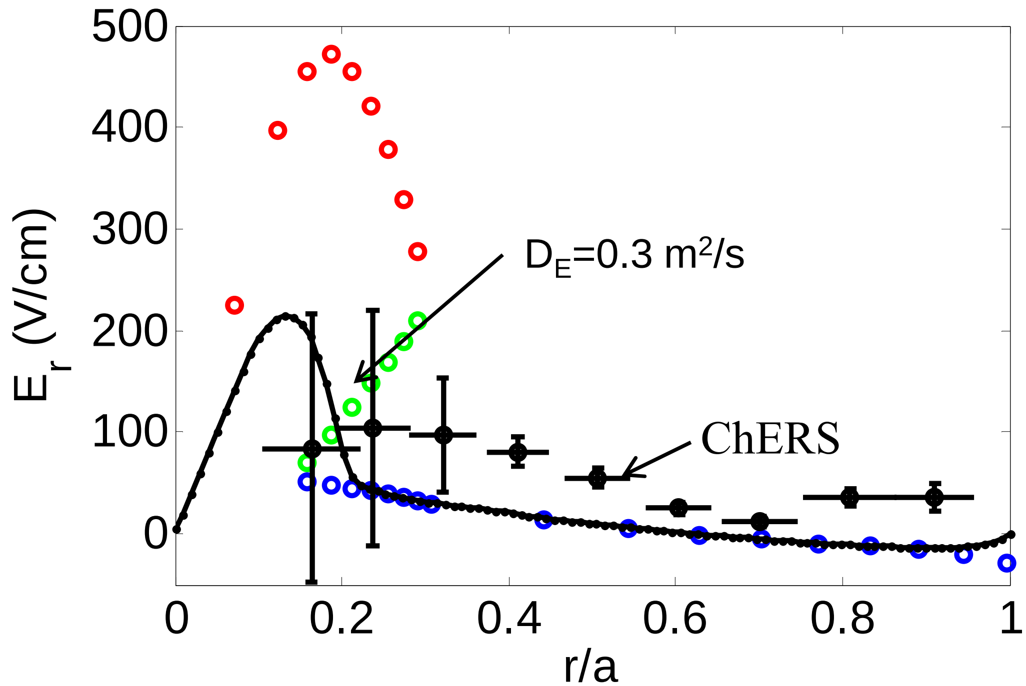
ChERS Measurements are Inconclusive in Plasma Core

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



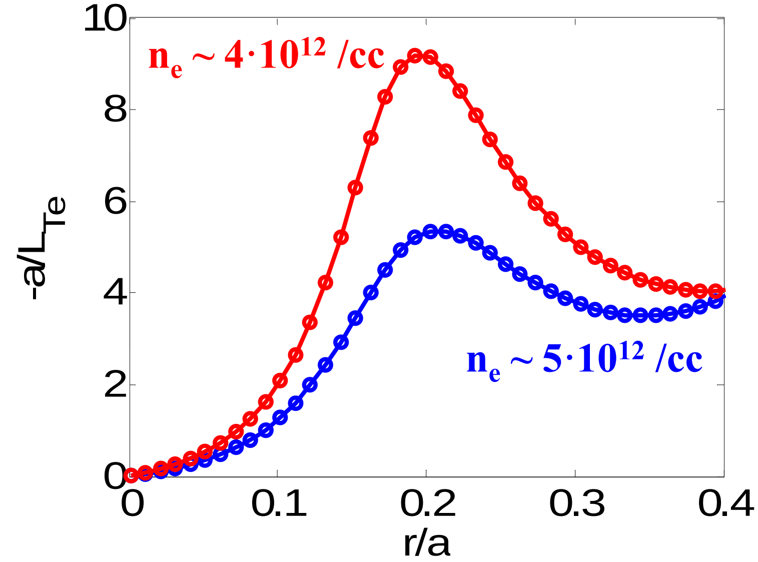
CERC Transport Barriers

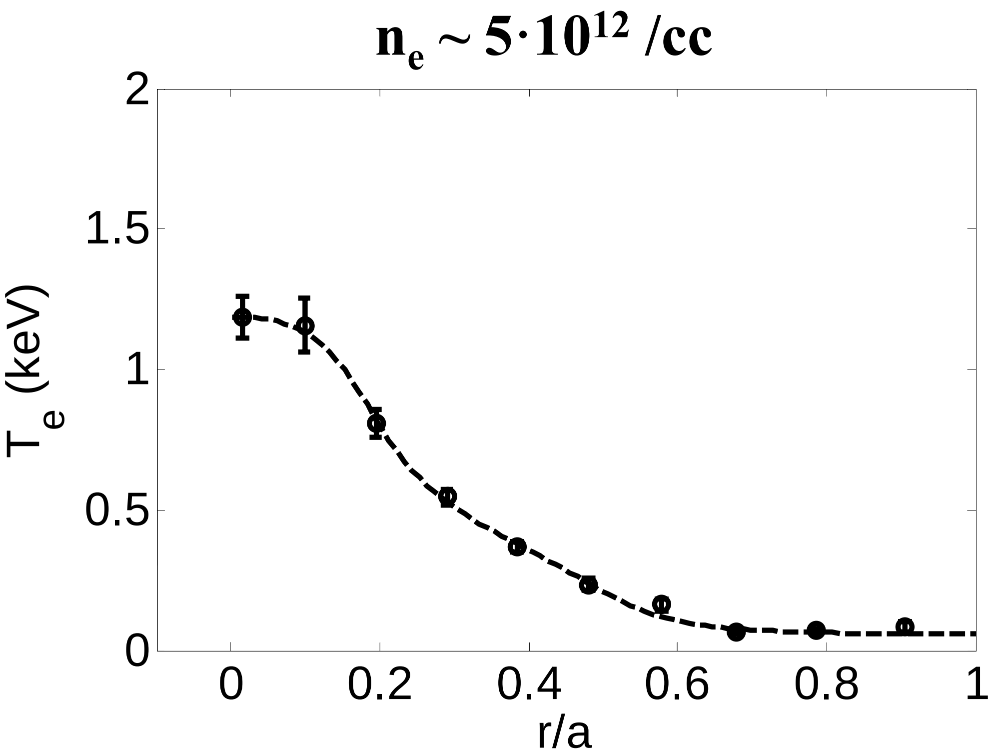
- CERC (Core Electron Root Confinement) transport barriers have been observed in several other stellarators[1]
  - Characterized by peaked T_e profiles, neoclassical electron root E_r
- One common feature is the existence of thresholds for achieving a CERC in P_{inj} and density
  - Thresholds often attributed to ECRH effects (conv. fluxes)
- Recent experiments indicate a threshold in QHS plasmas

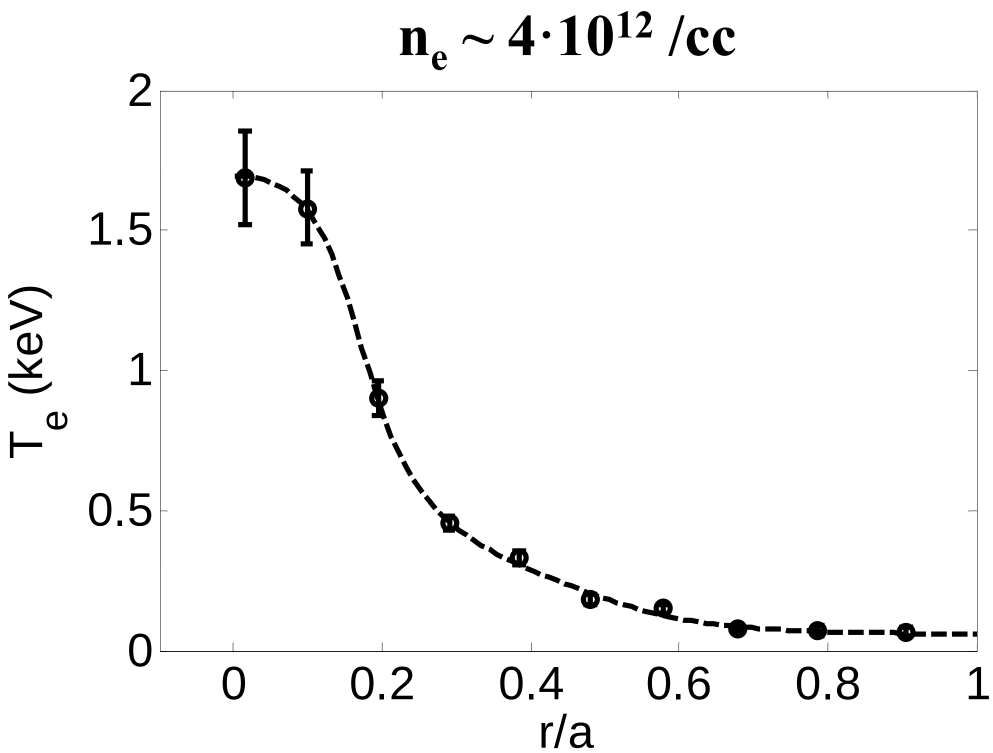
1) Yokoyama, *et. al* (2006, 2007)

Recent Experiments Suggest a CERC Density Threshold

- For same input power, higher density results in less peaked T_e profile
  - $P_{inj} = 50kW$
- At higher density a/L_{Te} is 2x smaller in core

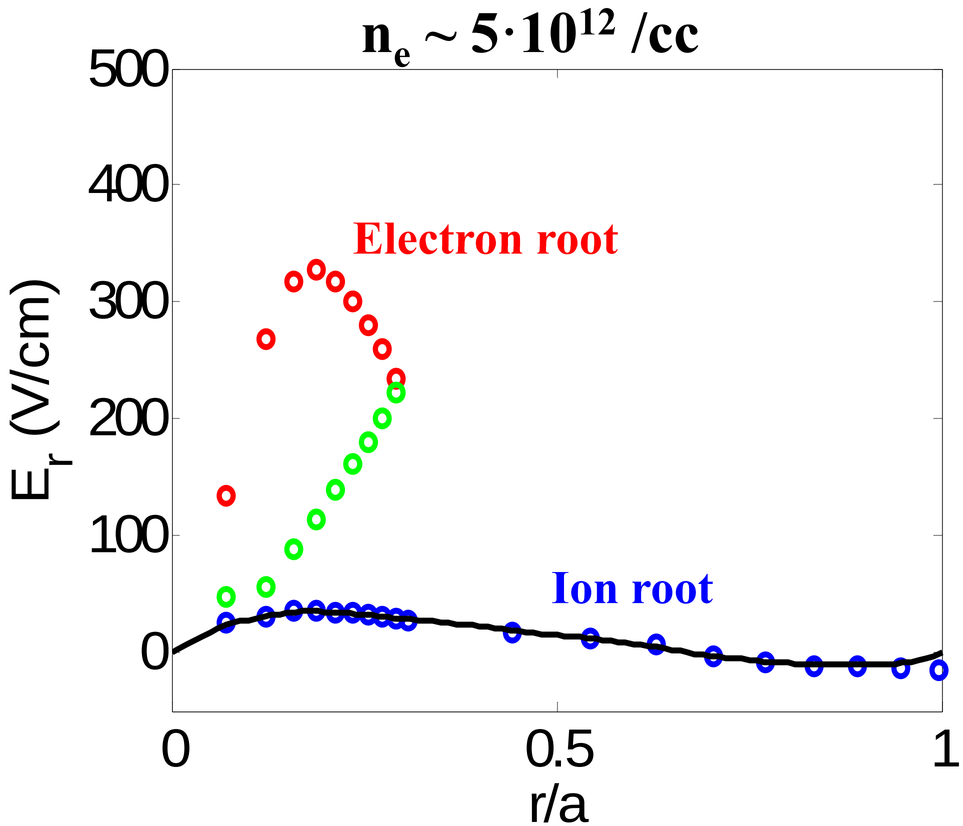


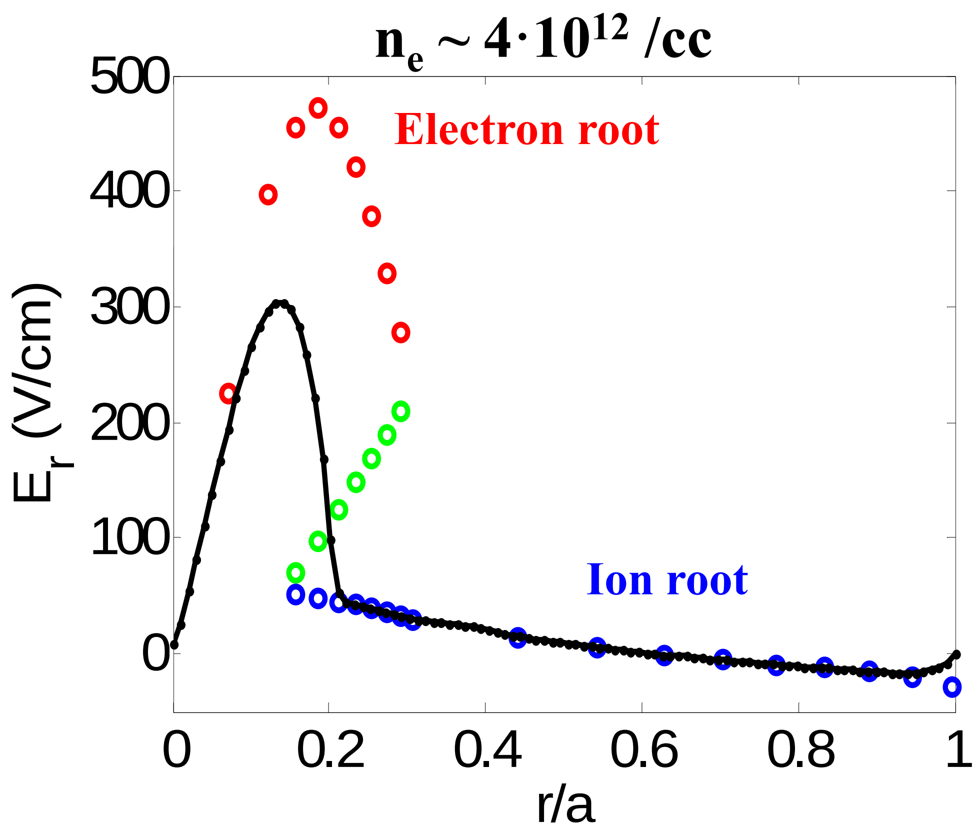




Ion Root is Predicted Across the Plasma Radius at High Density

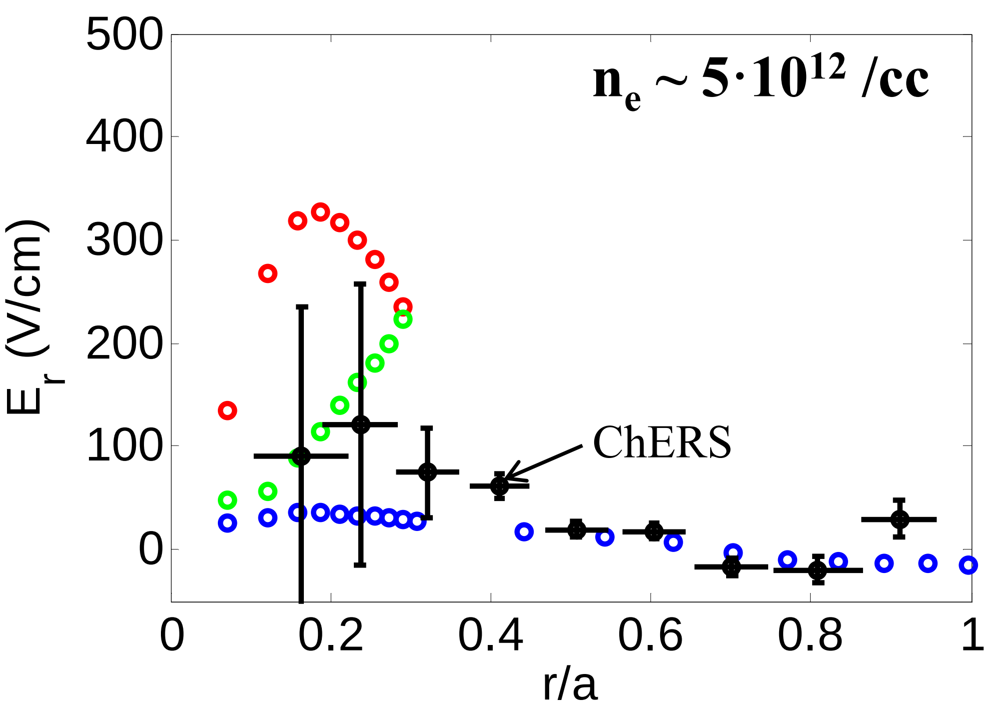
- The higher density case results in ion root solutions across the entire plasma radius
  - Core ion root is caused by reduced T_e, ∇T_e => reduced electron flux
  - Without external drive the plasma would remain in the ion root
- Note that this threshold does not seem to require any additional fluxes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

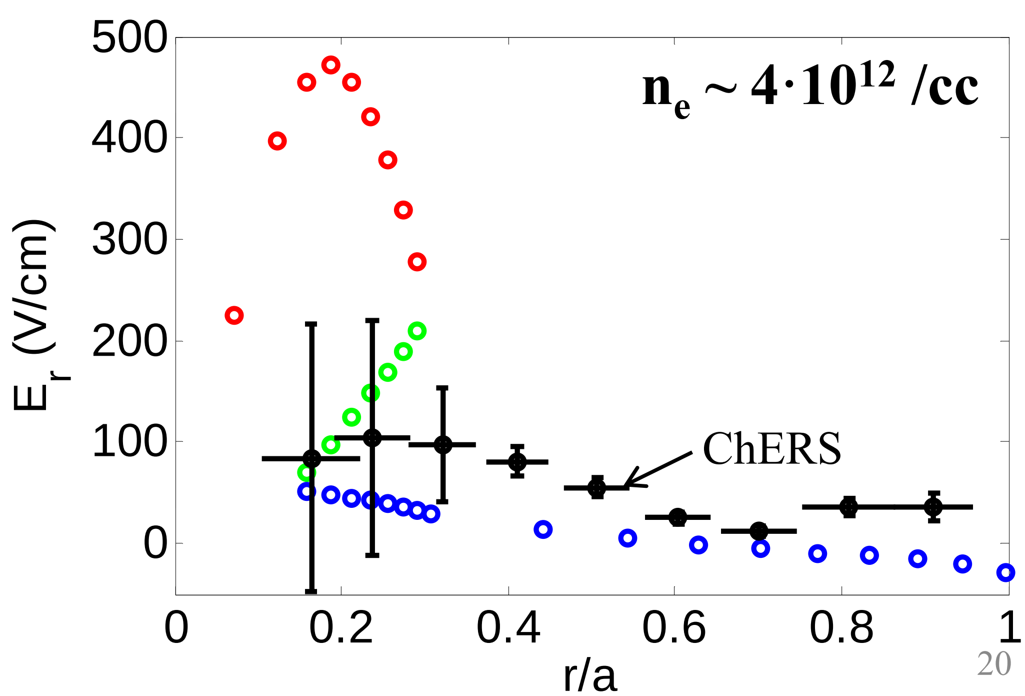




Ion Root is Predicted Across the Plasma Radius at High Density

- Measured E_r does not show large change with density
  - E_r measurements do not exclude core ion root solutions
- High density measurements closer to ion root solutions
- Planned experiment to operate at lower P/n to verify threshold behavior





Neoclassical Calculations Conserve Parallel Momentum

- Neoclassical calculations are performed using the PENTA[1] code
  - Based on the parallel momentum-conserving moments method of Sugama and Nishimura[2]
- Effects of parallel flow, interspecies collisions included
- Expressions used analytically reproduce intrinsic ambipolarity in symmetric limit
- In principle, this method can be applied to the full range of configurations:

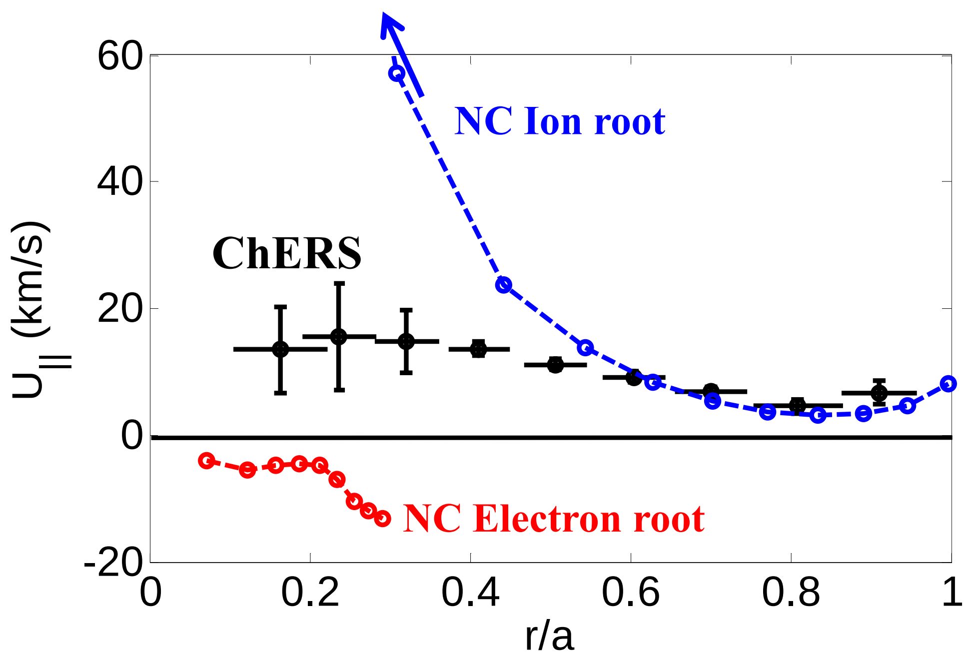
tokamaks → rippled tokamaks → quasi-symmetric → conventional stellarators

Increasing effective ripple →

1) D.A. Spong (2005), 2) H. Sugama and S. Nishimura (2002,2008)

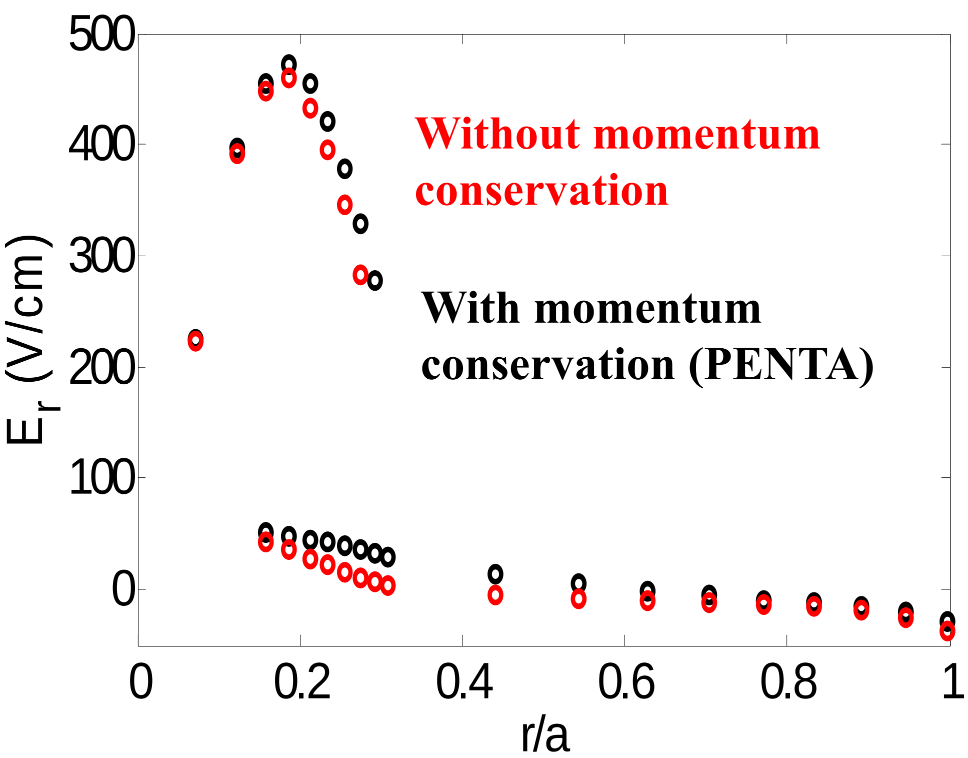
Momentum Conserving Calculations May be Important in Quasi-Symmetric Configurations

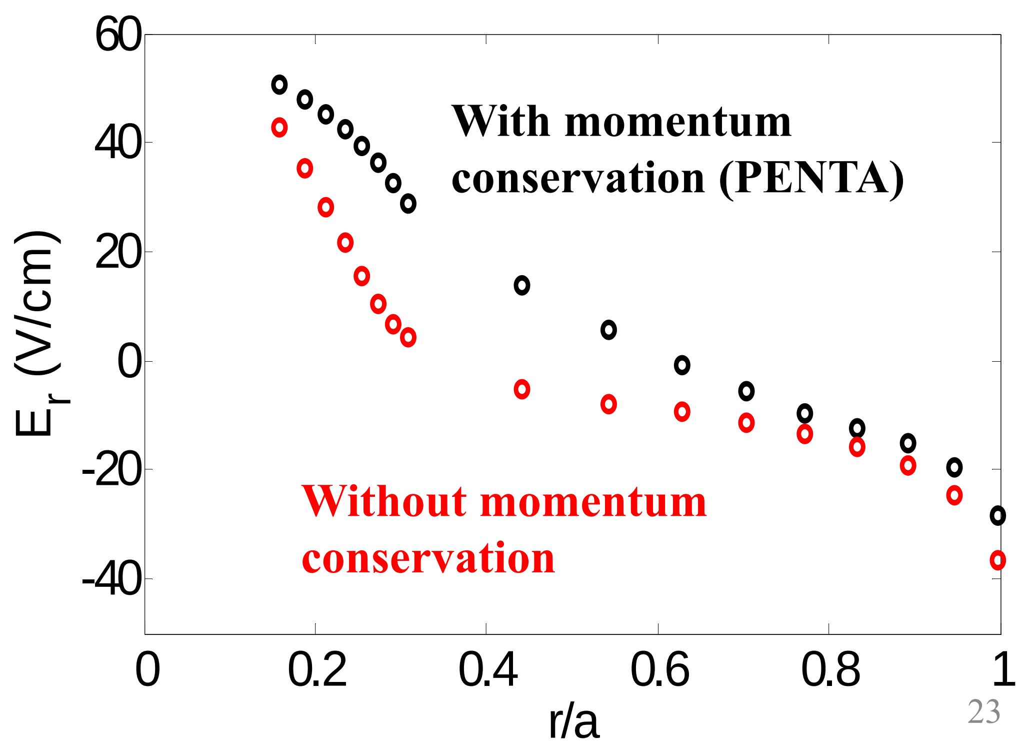
- Standard NC calculations assume $U_{||} = 0$
  - Justified in conventional stellarators, because no |B| symmetry leads to strong flow damping in all directions
  - Parallel flow may be large in quasi-symmetric configurations
- Large parallel flow (~10-25 km/s) measured in QHS
  - In agreement with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



Momentum Conservation Modifies Neoclassical E_r

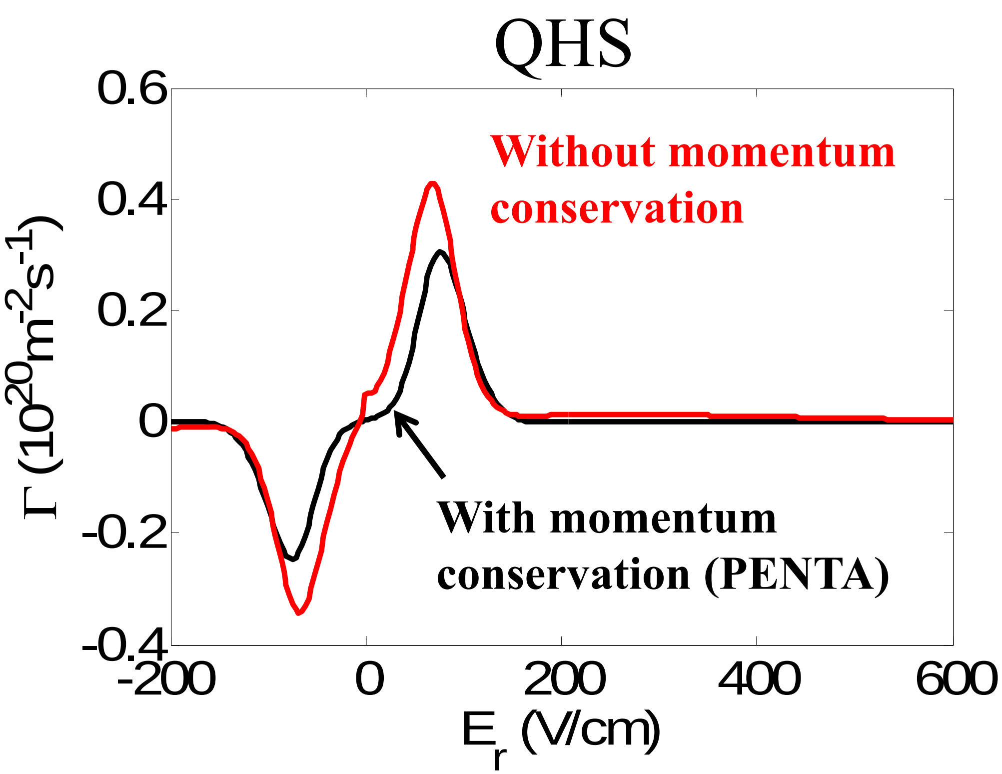
- Including momentum conservation changes ion root E_r by a factor of ~2x
- Effect is small in electron root, where ion flux is reduced due to poloidal resonance
- Modified E_r may be important for LMFP ion confinement
  - Change may be greater for larger T_i

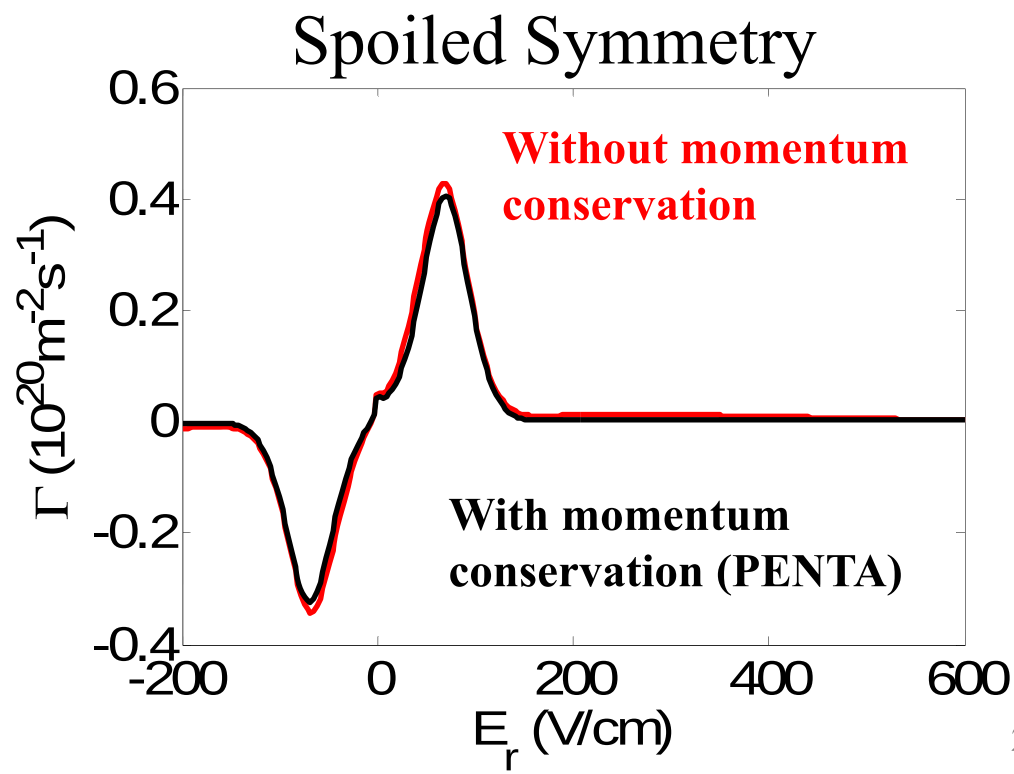




Effect of Momentum Correction Decreases When Quasi-symmetry Spoiled

- Ion particle flux modified in QHS due to momentum conservation
  - Effect is masked due to resonance
- Change in ion flux due to flows is smaller when symmetry spoiled
- Detailed investigation of scaling with symmetry breaking in progress
  - Currently no flow, E_r measurements in spoiled symmetry configuration





Conclusions

- Neoclassically driven transport barrier in QHS
  - Peaked T_e profiles measured, electron root 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 ion root neoclassical predictions
- Large parallel flow (10-25 km/s) measured in QHS
  - In agreement with predicted flow 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