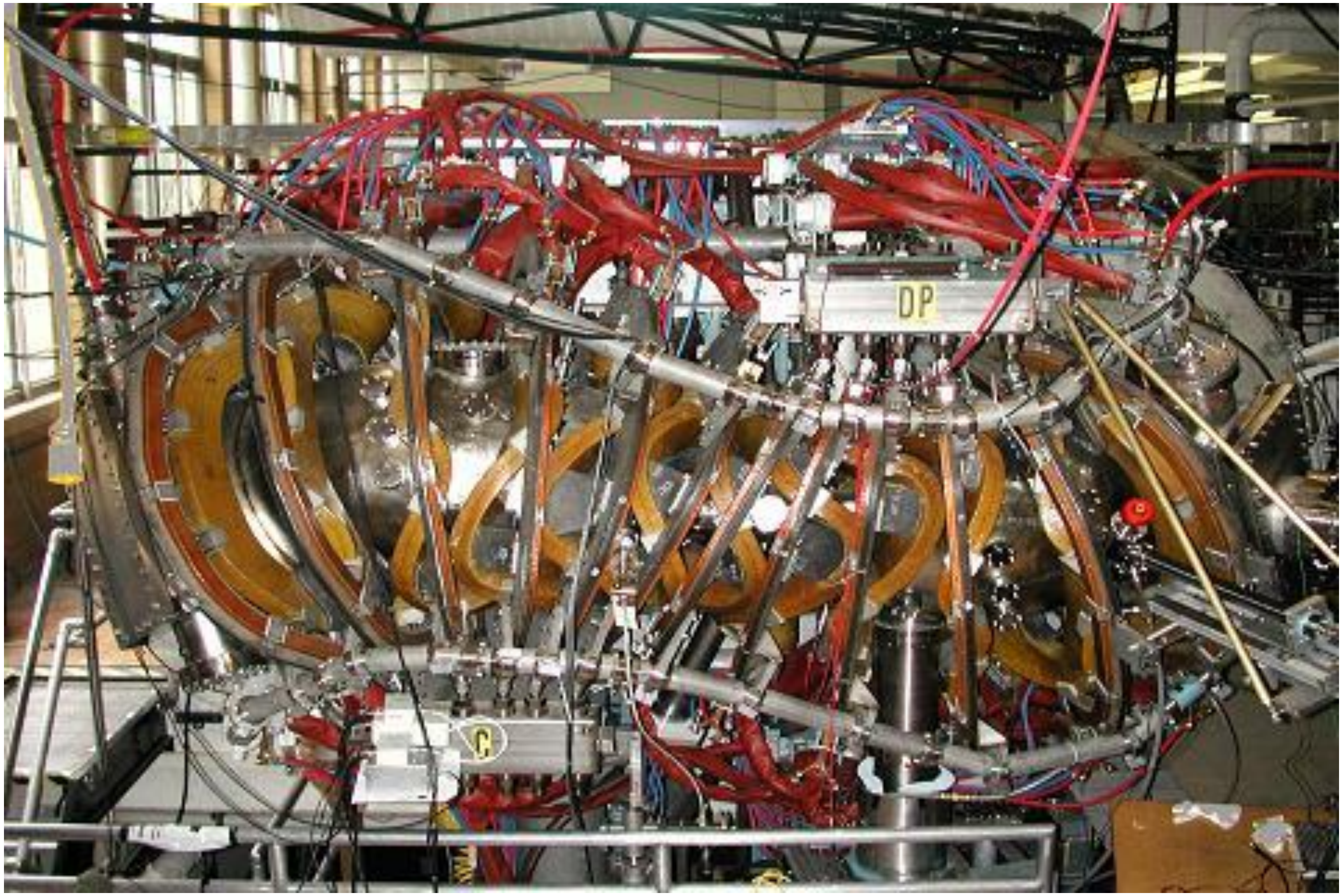
Transport in Quasisymmetric Plasma: Results from HSX



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2008 Innovative Confinement Concepts Workshop, Reno NV

Outline

- Quasihelically symmetric with no toroidal curvature ➔ high effective transform
  - ❑ Small deviation from flux surface; Parallel currents reduced in magnitude
  - ❑ Helical Pfirsch-Schlüter current
  - ❑ Bootstrap current reduces transform

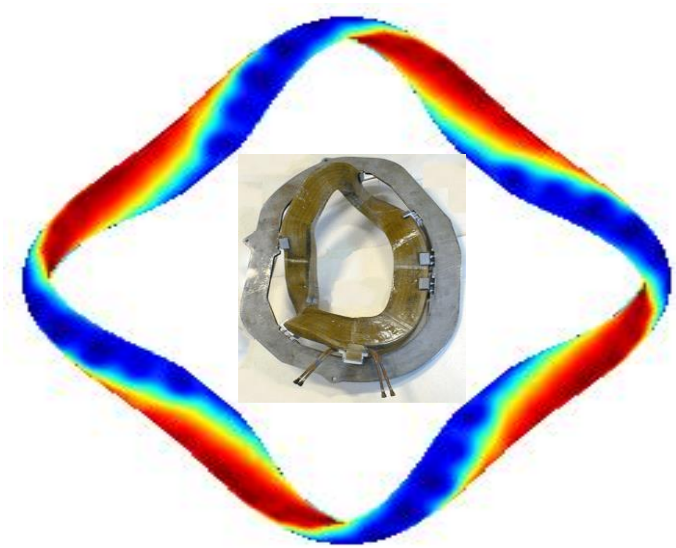
  ➔ Good initial agreement of V3FIT code to diagnostic coil data

- B = 0.5 T: Reduction of neoclassical momentum, particle and heat transport with anomalous component dominant in QHS
- B = 1.0 T: Thermal plasmas, T_e up to 2.5 keV
- GS2 3D simulation ➔ Large curvature drives TEM
  - ❑ 1D simulation for T_e profile and τ_E scaling gives good agreement with experiment outside core using Weiland anomalous model
  - ❑ Neoclassical E_r turbulence suppression gives good match to core

  ➔ First observation of internal electron transport barrier in HSX

- Future Plans and Conclusions

Quasihelical stellarators have high effective transform



Quasihelical: Fully 3-D, BUT

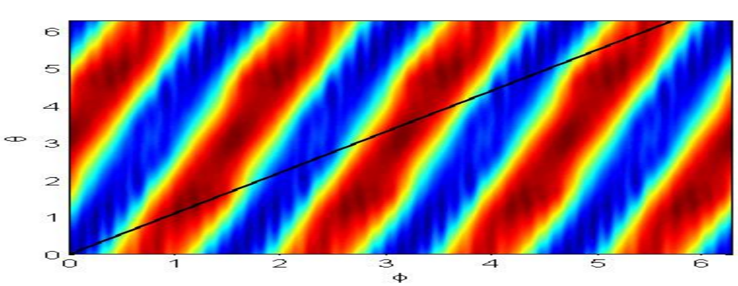
Symmetry in |B| : $B = B_0\left[1 - \varepsilon_h \cos\left(N\phi - m\theta\right)\right]$

In straight line coordinates $\theta = \iota\phi$, so that

$$B = B_0\left[1 - \varepsilon_h \cos\left(N - m\iota\right)\phi\right]$$

In HSX: N=4, m=1, and ι ~ 1

ι_{eff} = N-m ι ~ 3



With $\iota \geq 1$ and n = 4 periodicity of the quasisymmetric field, modulation of |B| on field line ➔ $\iota_{eff} \sim 3$

High effective transform reduces Pfirsch-Schlüter and bootstrap current

$$J_{PS} = \frac{1}{B_0}\frac{dp}{d\psi}\sum_{n,m}\frac{nI+mg}{n-m\iota}\delta_{nm}\cos\left(n\phi-n\theta\right)$$

Pfirsch-Schlüter current:

- reduced in magnitude
- helical in HSX due to lack of toroidal curvature
- dipole currents are opposite of tokamak where field in HSX is tokamak-like (grad B drift is opposite).

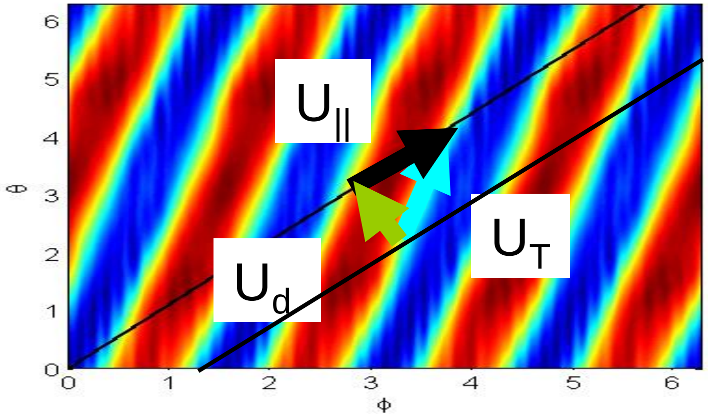
Bootstrap current:

$$J_B \sim 1.46\sqrt{b_{nm}}\,\frac{m}{n-m\iota}\,\frac{g}{B_0}\left[gradients\right]$$

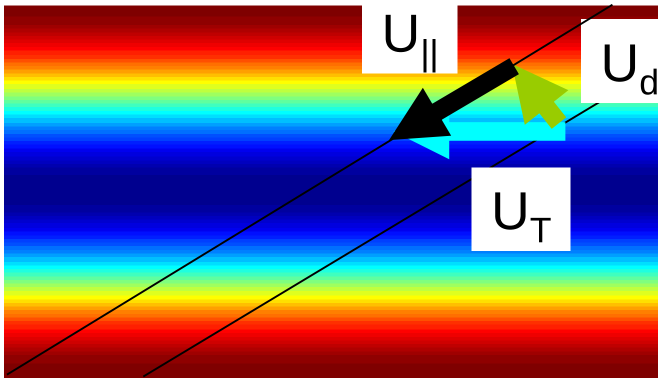
Boozer, '82 '92

- reduced in magnitude
- opposite direction to tokamak
- reduces transform but confinement improves due to factor $N-m\iota$

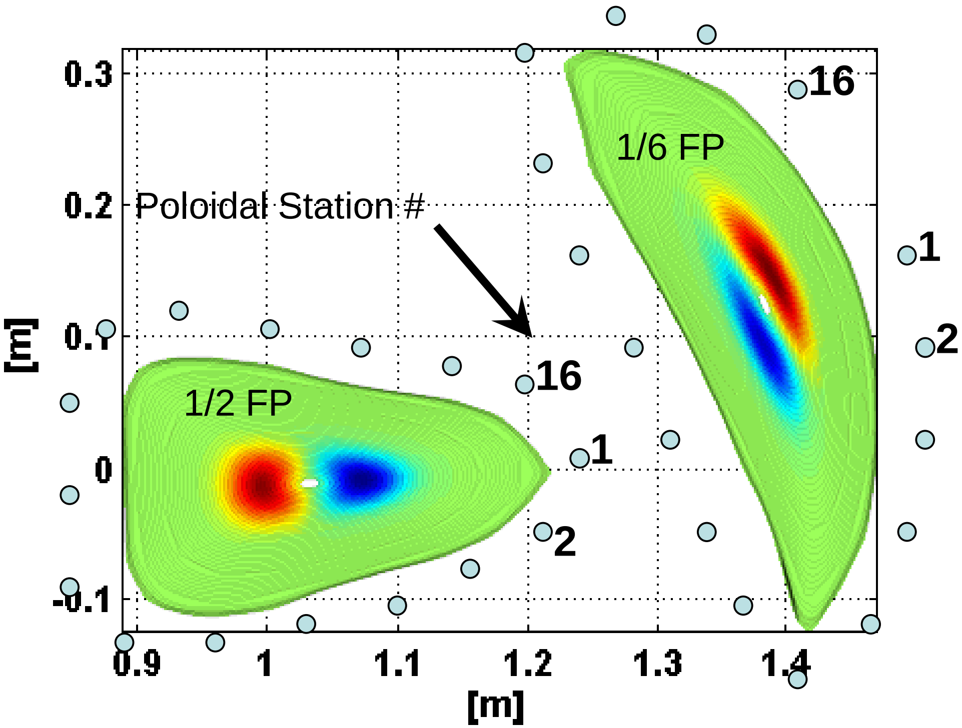
HSX

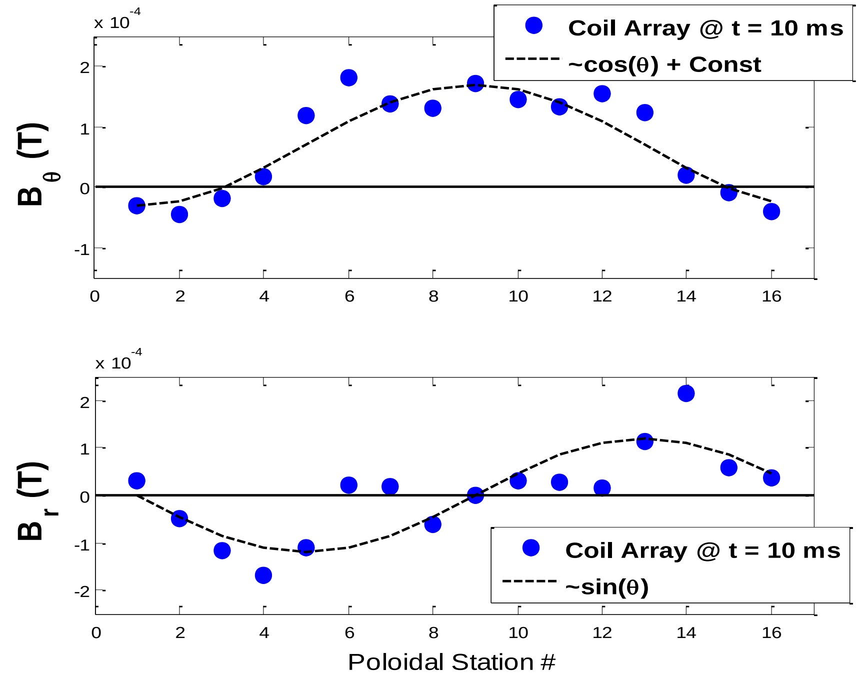


Tok



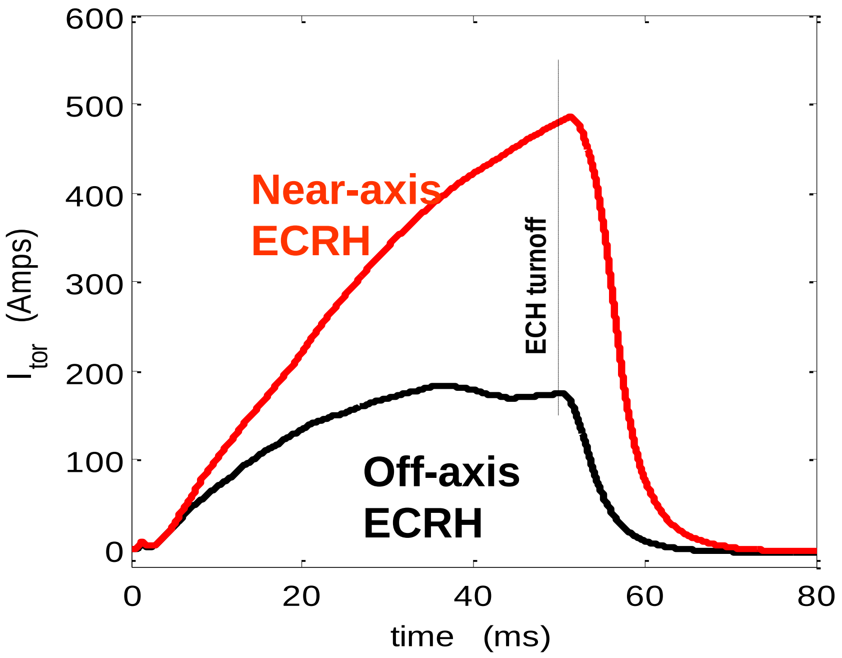
3 axis coils measure current evolution at two toroidal locations

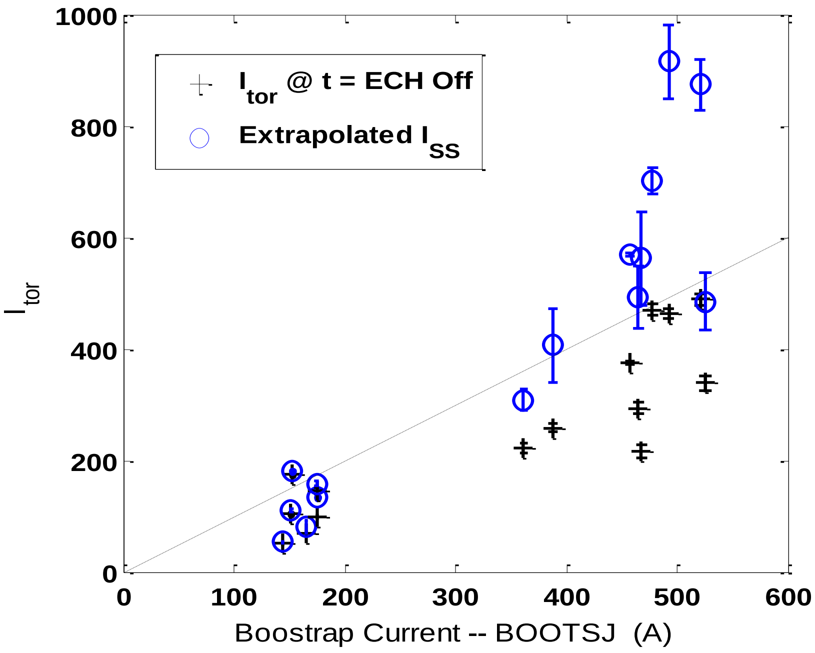




- 16 3-axis pick-up coils mounted in a poloidal array
- Two sets of measurements separated by <1/2 field period.
- From Pfirsch-Schlüter current: $B_\theta \sim \cos\theta$ and $B_r \sim \sin\theta$

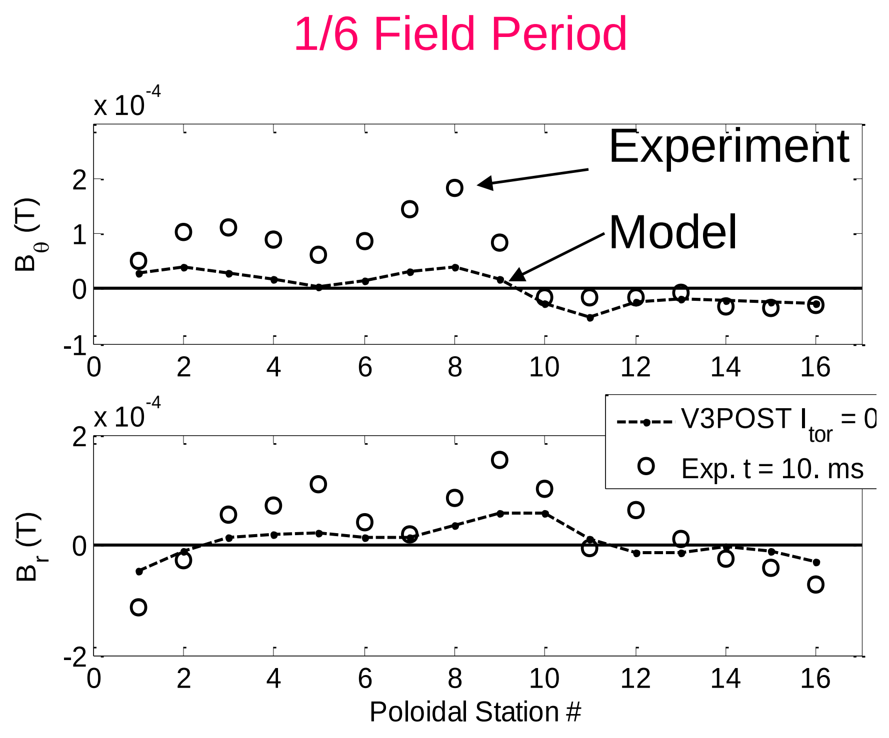
Rogowsky confirms bootstrap current unwinds transform

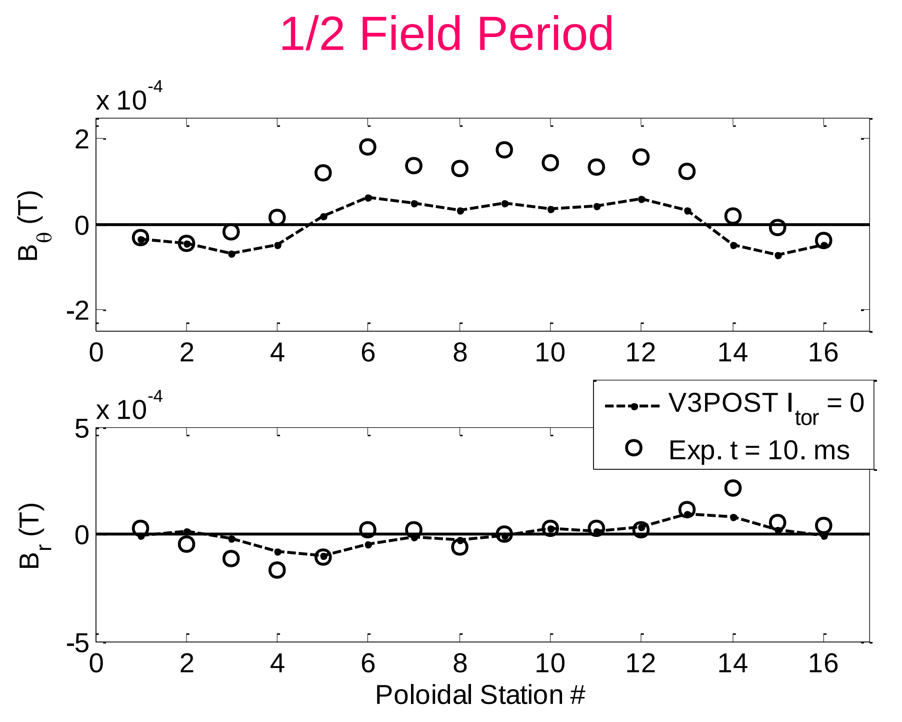




- For on-axis heating, bootstrap current rises during 50 ms ECH
- Colder plasmas with off-axis heating show saturation
- Good agreement with BOOTSJ (ORNL) for extrapolated currents
- Current direction consistent with lack of toroidal curvature

Coil array shows Pfirsch-Schlüter current dominant early in time

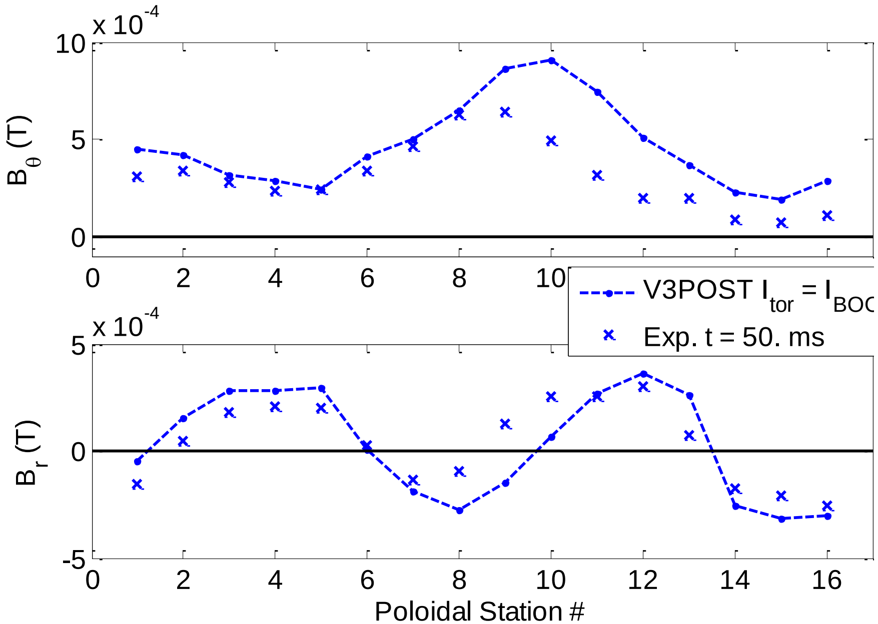




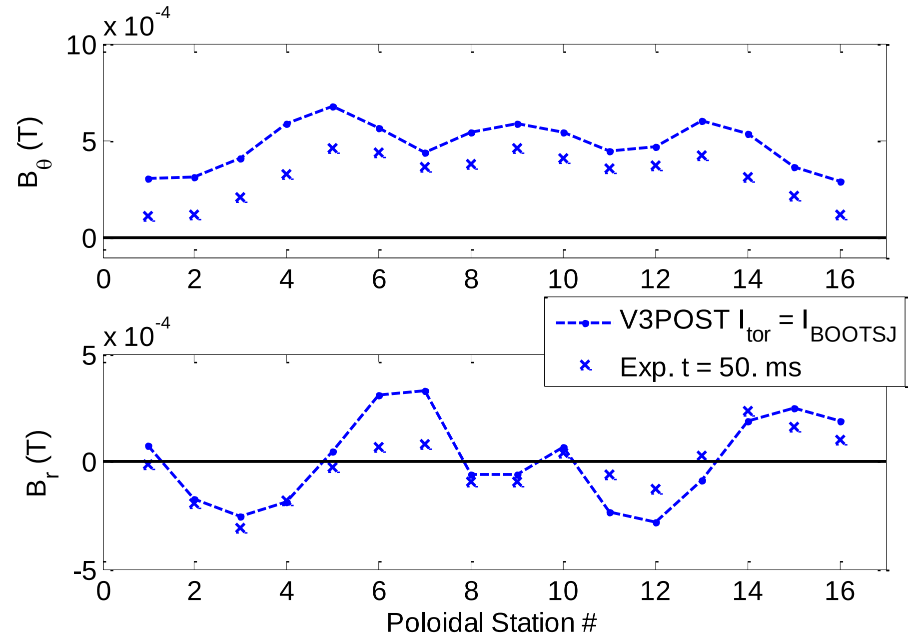
- Early time t= 10 ms ➔ I_B = 0 in model
- Bootstrap current probably underestimated

Bootstrap current shows up later in time

1/6 Field Period



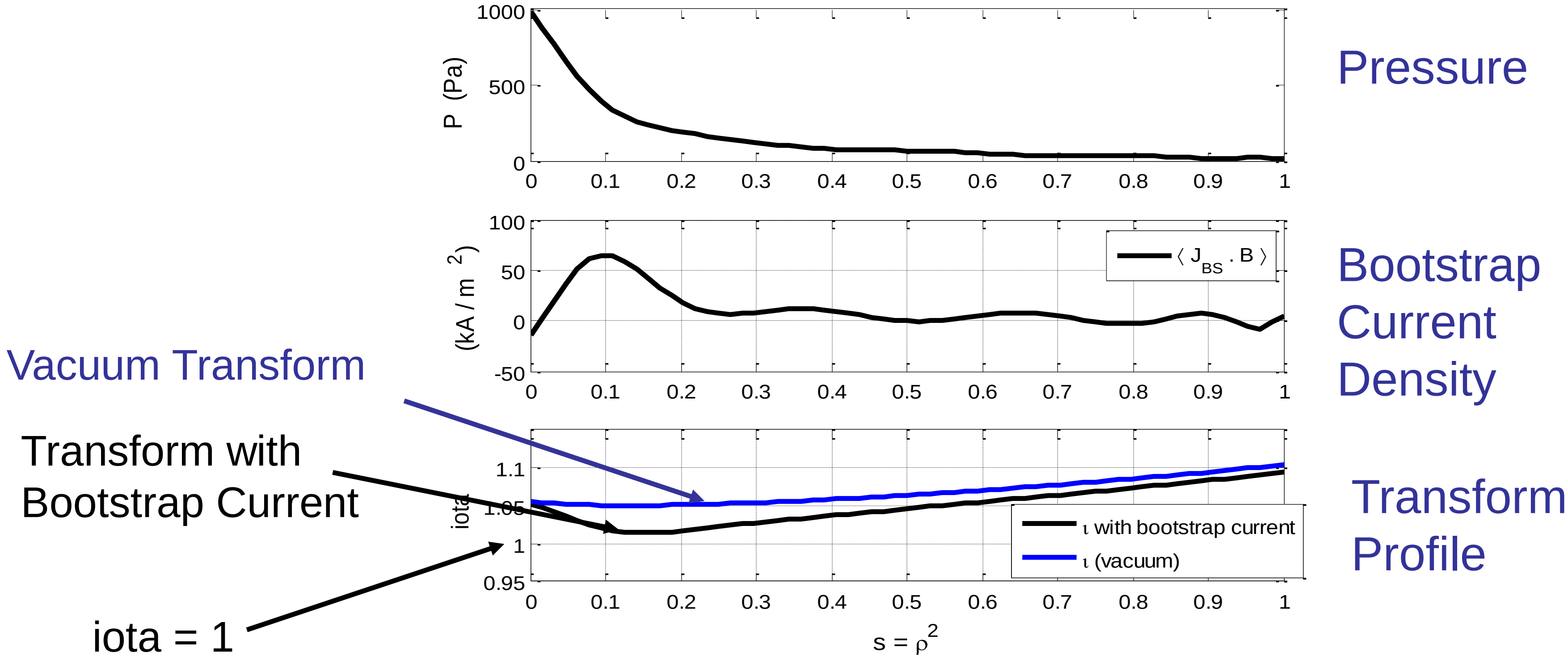
1/2 Field Period



- Bootstrap current shows up as DC offset in B_θ
- Later in time t= 50 ms ➔ I_B = BOOTSJ value (overestimated)
- Helical PS current evident in reversal of B_r

*** Special thanks to Steve Knowlton and V3FIT team! ***

Bootstrap current decreases transform in HSX

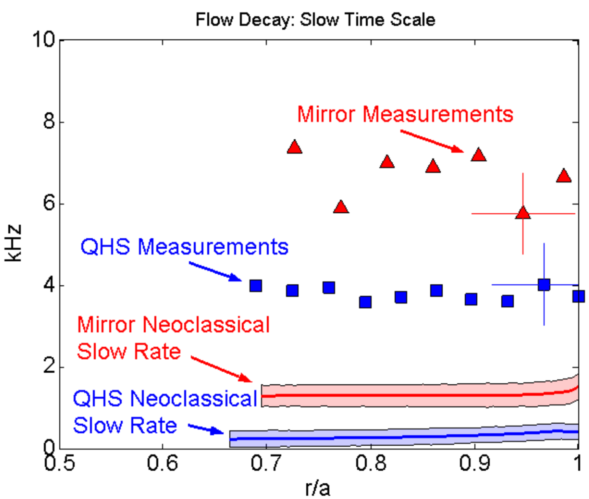


- Pressure profile from TS; current density profile from BOOTSJ
- Pressure and Current density profiles in VMEC ➔ transform profile
- With 500 A, iota is just above one ➔no instability signatures observed

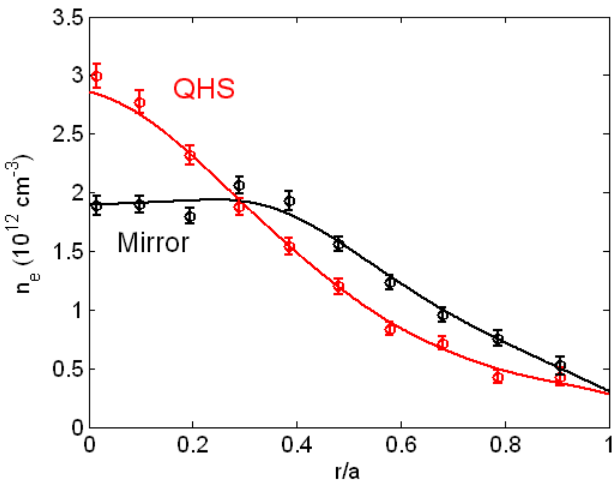
HSX has demonstrated transport benefits of quasisymmetry

- Reduction in momentum, particle and heat transport: B = 0.5 T
- Neoclassical is reduced; anomalous contribution now dominates

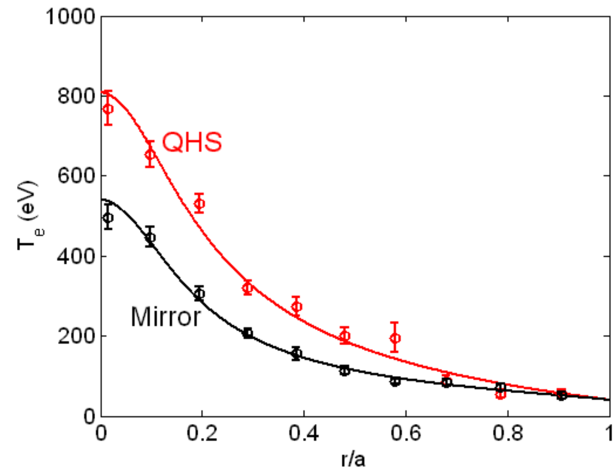
Momentum



Particle



Heat



Larger flows in QHS with equivalent torque

➔ Lower parallel viscous damping

Peaked density profiles in QHS

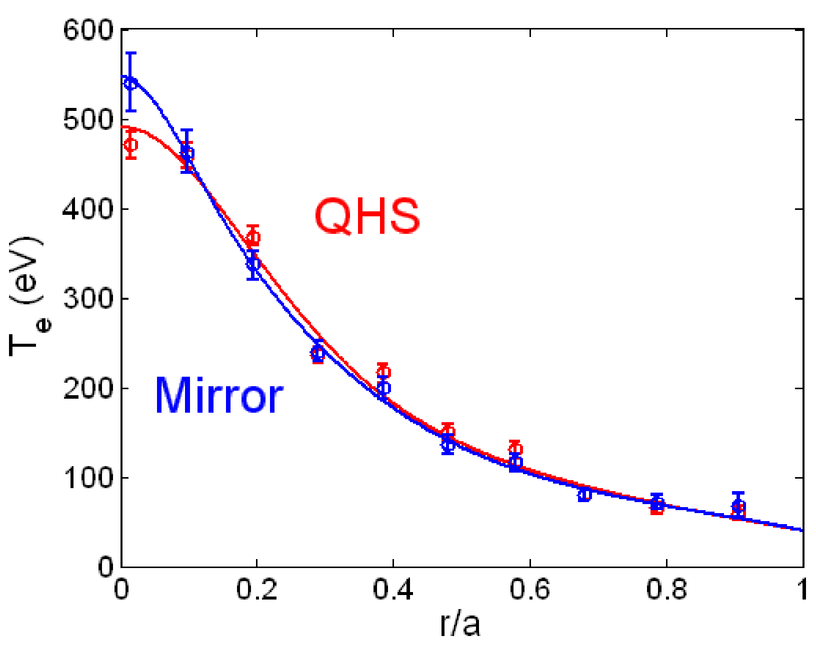
➔ Reduced thermodiffusion

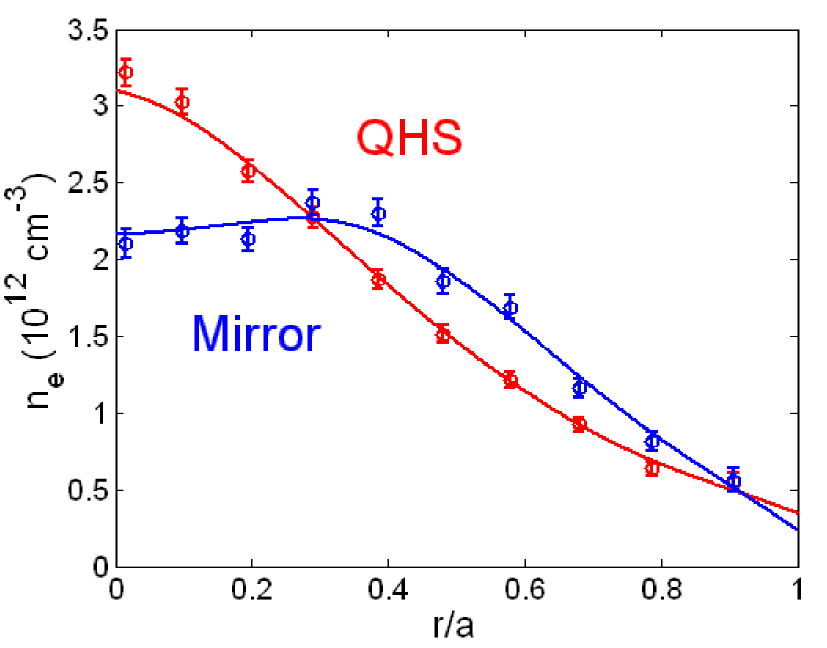
Higher T_e in QHS with same absorbed power

➔ Lower χ_e

Electron temperature profiles can be well matched between QHS and Mirror

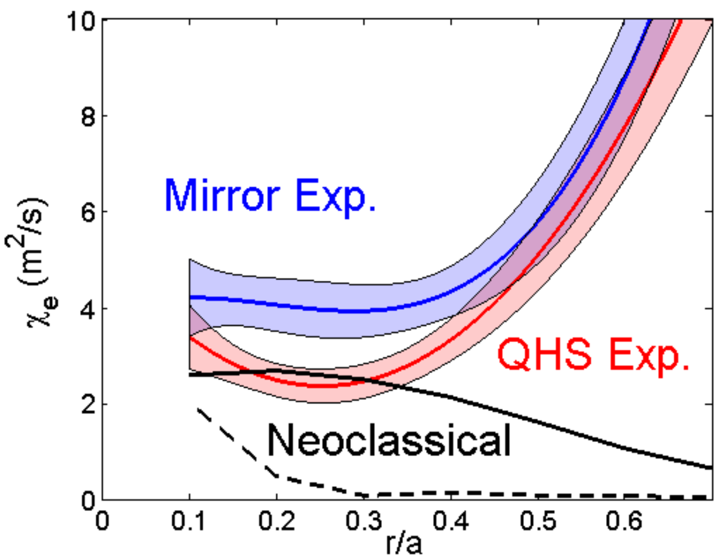
- To get the same electron temperature in Mirror as QHS requires 2.5 times the power
  - 26 kW in QHS, 67 kW in Mirror ➔ large nonthermal population at 0.5 T
  - Density profiles don't match because of thermodiffusion in Mirror



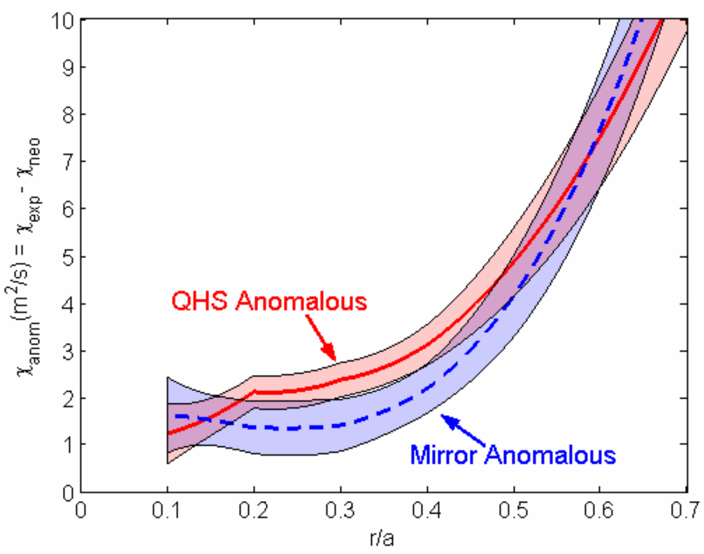


Thermal Diffusivity is Reduced in QHS

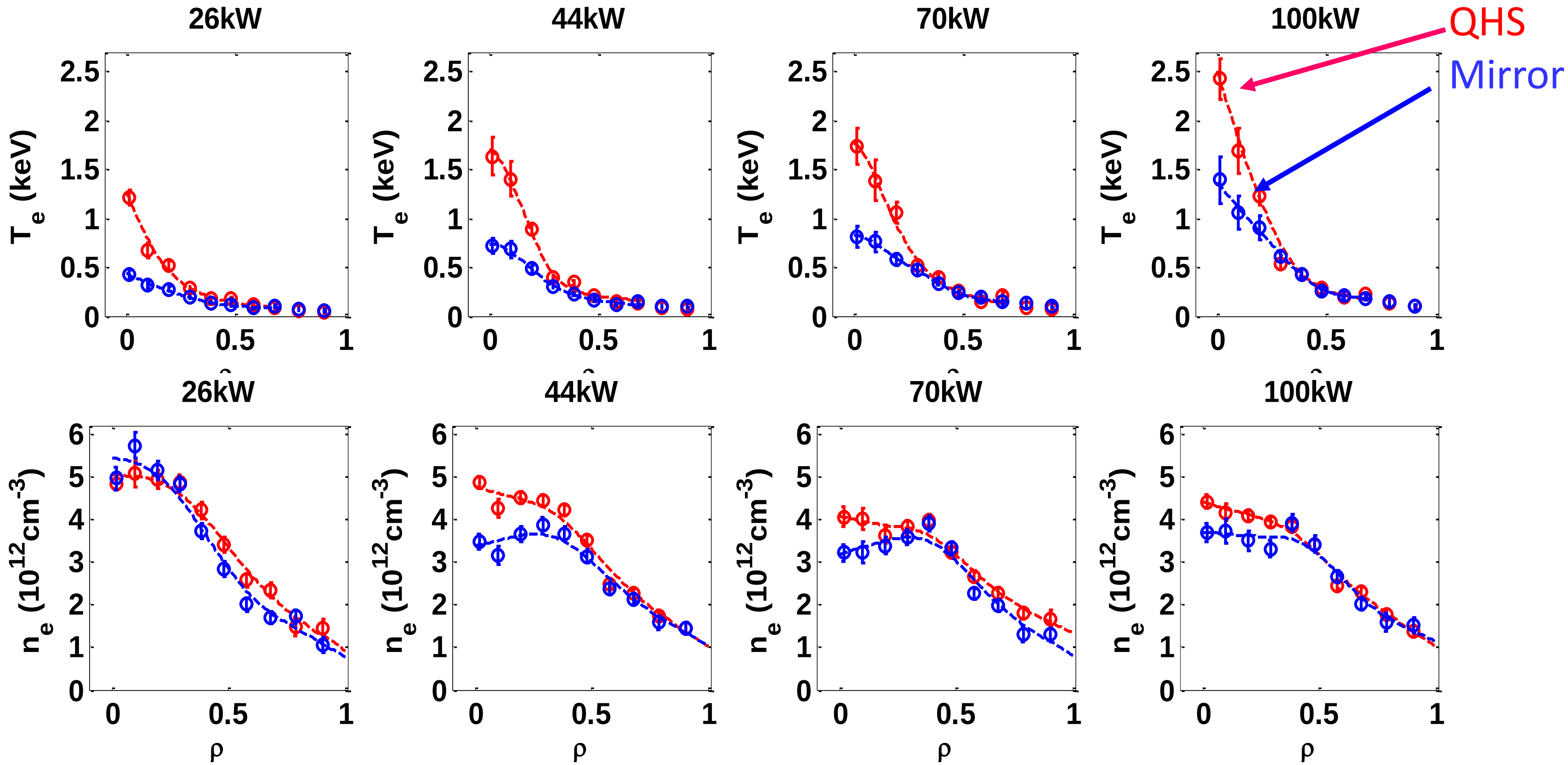
- QHS has lower core χ_e
  - At r/a ~ 0.25, χ_e is 2.5 m^2/s in QHS, 4 m^2/s in Mirror
  - Difference is comparable to neoclassical reduction (~2 m^2/s)
- Two configurations have similar transport outside of r/a~0.5



- Little difference in anomalous transport is observed between QHS and Mirror in B=0.5T operation



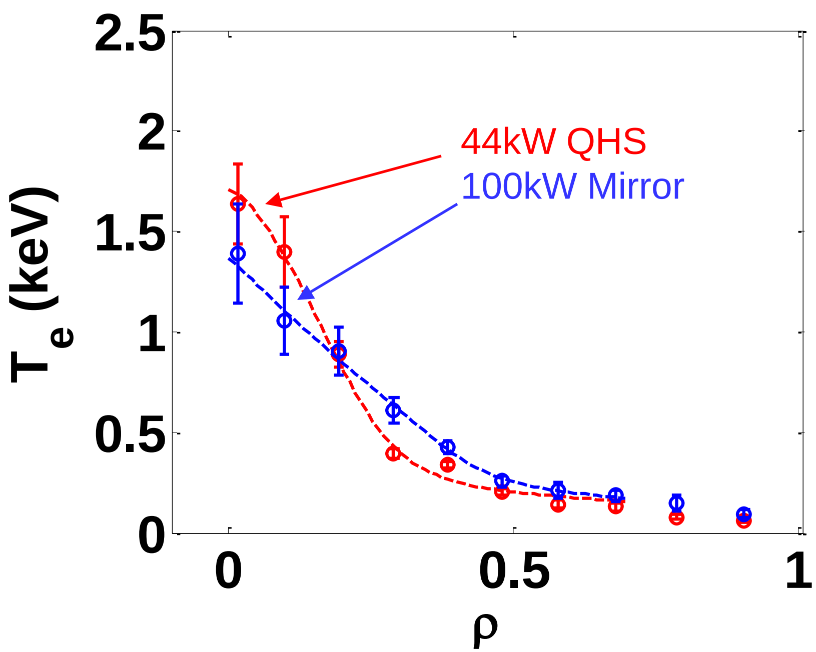
ECH at B = 1.0 T



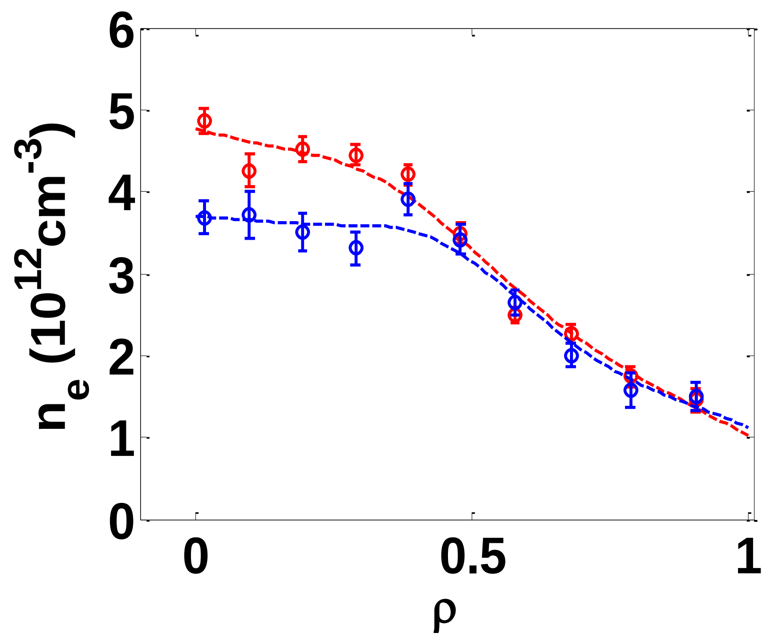
- Good agreement between kinetic and diamagnetic stored energy ➔ minimal nonthermal contribution
- Core T_e about twice as large in QHS as Mirror configuration
- Mirror density profile more hollow as T_e gradient increases

Minimum difference profiles to compare transport at B = 1.0 T

Temperature

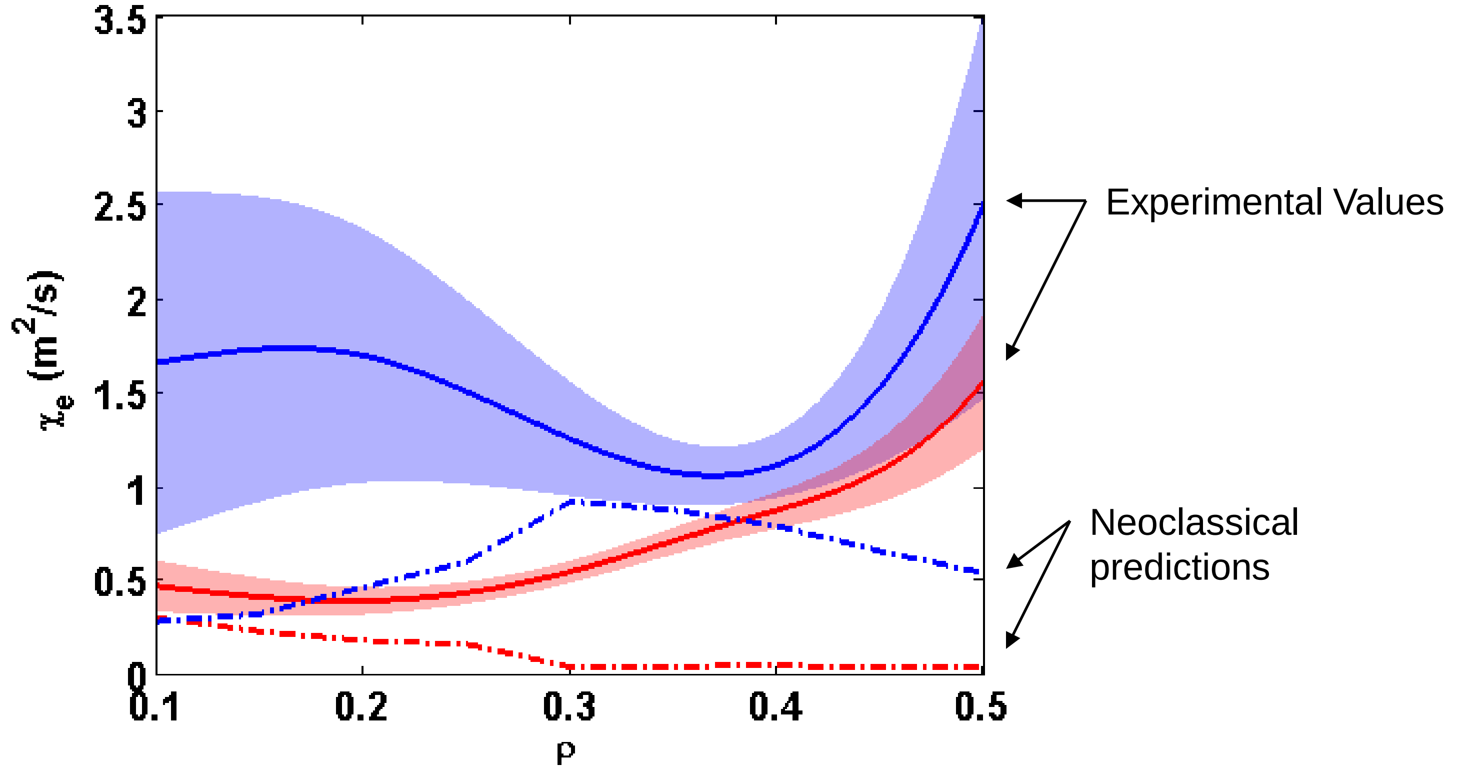


Density



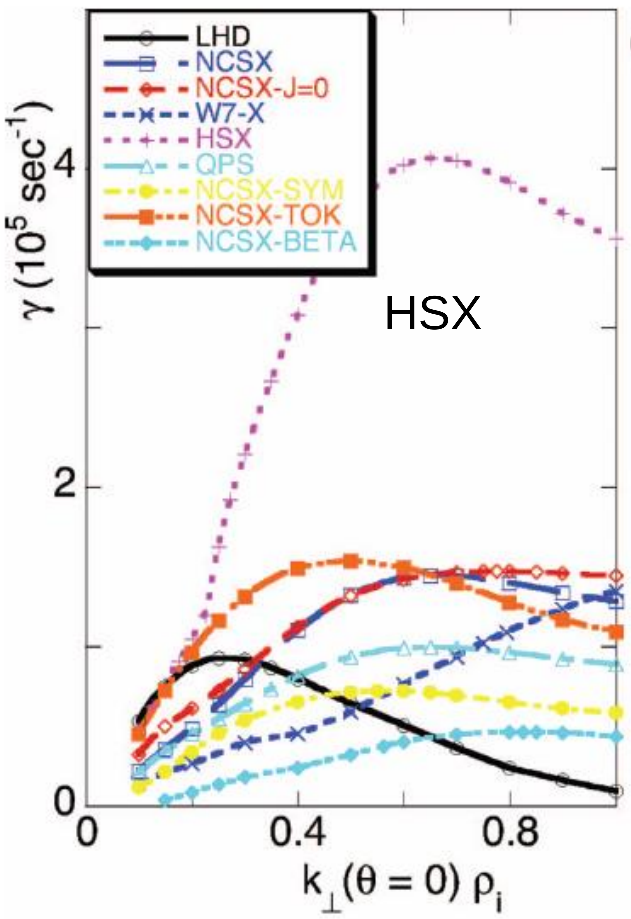
- More than twice the power in Mirror configuration to approximate the temperature profile in QHS
- Density profile still slightly more peaked in QHS than Mirror

Electron thermal conductivity lower in QHS than Mirror



- Ray-tracing code calculates power deposition profiles
- Total power scaled to diamagnetic loop measurement of stored energy
- QHS experimental thermal conductivity ~ 3 times lower than Mirror:
- Possibility that anomalous lower in QHS; new area of investigation!

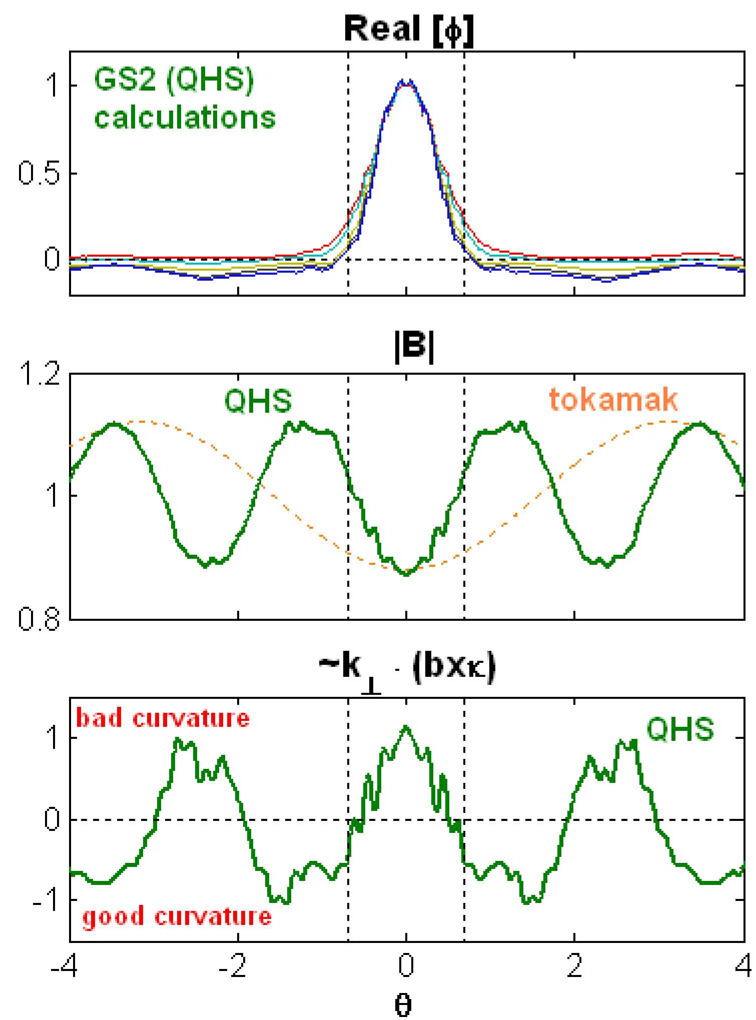
Can we model anomalous transport in HSX?



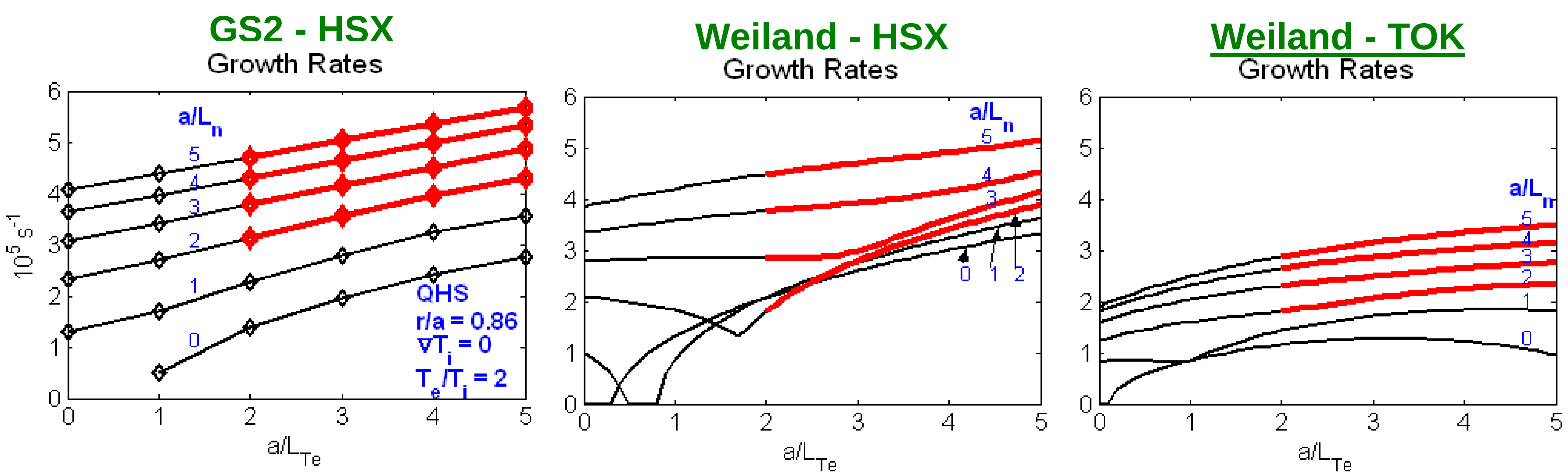
- Rewoldt '05 using FULL code showed HSX had largest linear growth rate to ITG/TEM modes compared to W7-X, NCSX, QPS
- Goal is to apply predictive transport modeling to HSX using multi-mode approach
- Neoclassical transport based on DKES, anomalous transport based on Weiland analytic model

Microstability estimates using axisymmetric models with "quasisymmetric" approximation

- 3D stability calculations find most unstable eigenmodes (ITG/TEM) ballooning in the low field, bad curvature region in HSX
- Dominant particle trapping comes from helical ripple, ε_H (0.14·r/a = 1.4·r/R)
- Reduced connection length, $L_c = q_{eff}R = R/|N-m\iota|$ $\approx R/3$, leads to very low collisionality electrons across the minor radius → TEM ($T_e >> T_i$)
- Normal curvature rotates helically, with bad curvature following the location of low field strength
- $\kappa_{N,max} \sim 1/45\ cm^{-1} \neq 1/R$ (R=120 cm)
- To account for toroidal drifts in drift wave models, R/L → (R/3)/L



Weiland model with simplified assumptions benchmarked against GS2 code

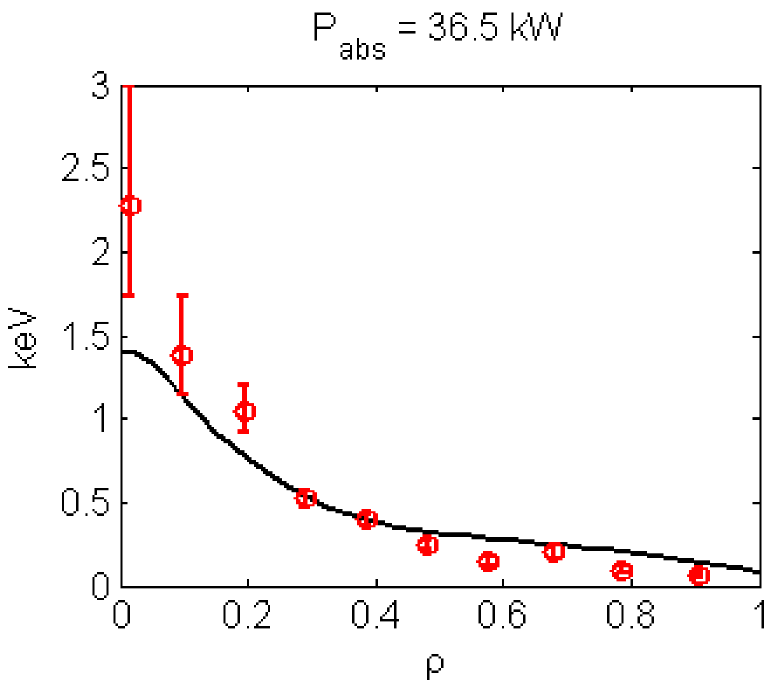


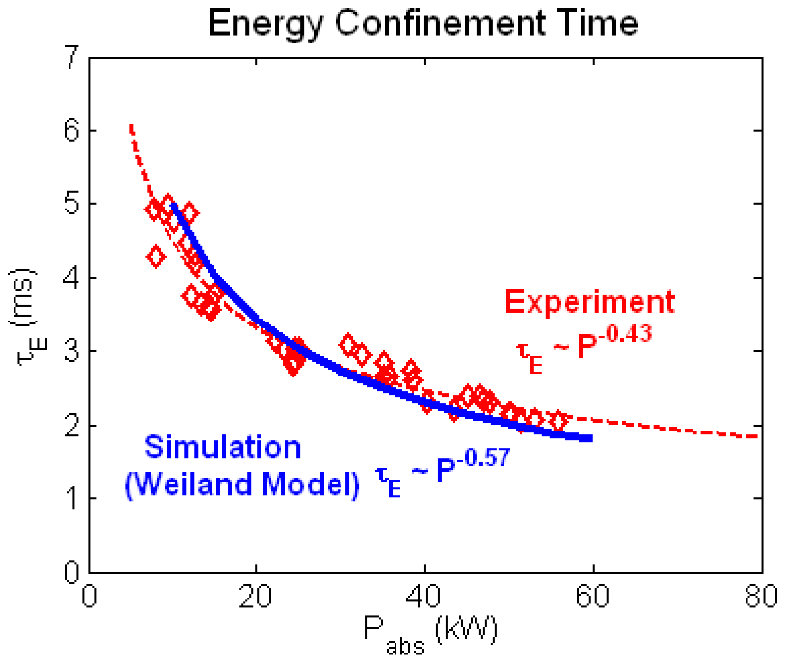
• Linear growth rates from Weiland and 3D GS2 are in agreement near experimental gradients (a/L_n, a/L_{Te} = 2 → 5, largest difference ~30%)

• Weiland growth rates 2× smaller without "quasisymmetric" approximation

•A 1-D predictive transport simulation incorporating turbulent (Weiland model) and neoclassical transport (DKES) has been performed.

Model predicts gross features of T_e profile and confinement scaling; low prediction in core

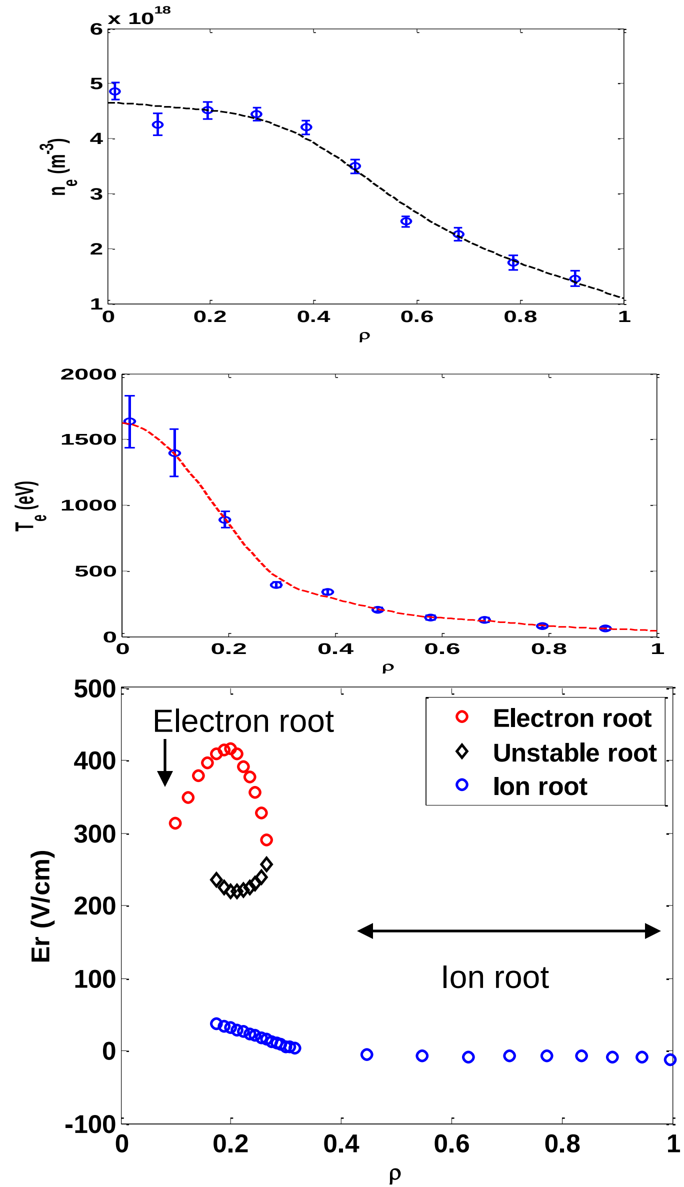




- Weiland model, with geometry approximations, gives reasonable fit to temperature profile for $\rho > 0.3$; <u>no</u> fitting factors (other than QH approx.)
- T_e significantly higher than model prediction in the core
- Captures the scaling and magnitude of confinement times at B = 1.0 T (L-mode/ISS95 has $\tau_E \sim P^{-0.6}$)

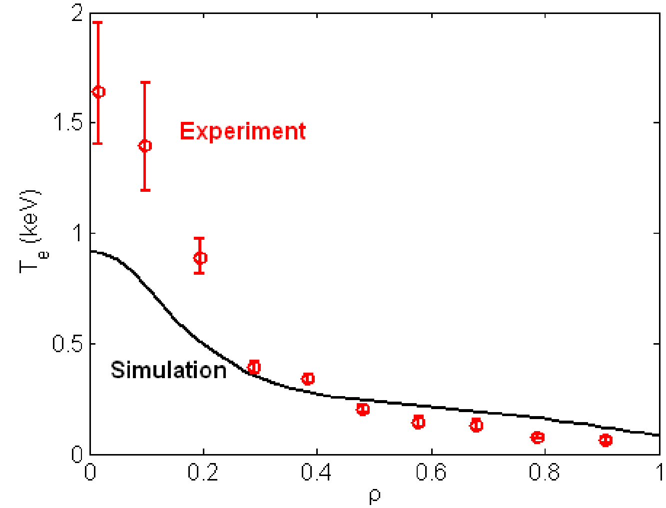
Large Electric Field Shear is Generated by a Radial Transition between Electron and Ion Root

- 44kW central ECRH heating (fundamental O-mode B=1T)
- Neoclassical fluxes are calculated using monoenergetic transport coefficients interpolated from a large database of DKES results.
- E_r values are found using the ambipolarity constraint: $Z_i\Gamma_i=\Gamma_e$
- Large E_r leads to very small levels of neoclassical transport.
- Large ExB shear may lead to reduction in anomalous transport, creating transport barrier.

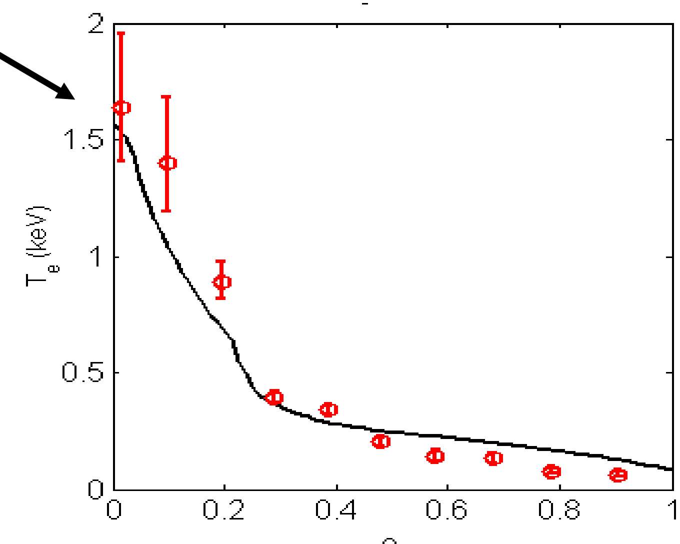


Turbulent transport suppressed by ExB shear

- Simulation results from neoclassical and anomalous transport without taking into account ExB shear suppression.
- Model predictions when turbulent transport suppressed when the ExB shearing rate is larger than the linear growth rate
- First observation of CERC type discharges in HSX
- This method of turbulent transport suppression is driven by neoclassical transport and is specific to helical devices.



Without ExB shear suppression

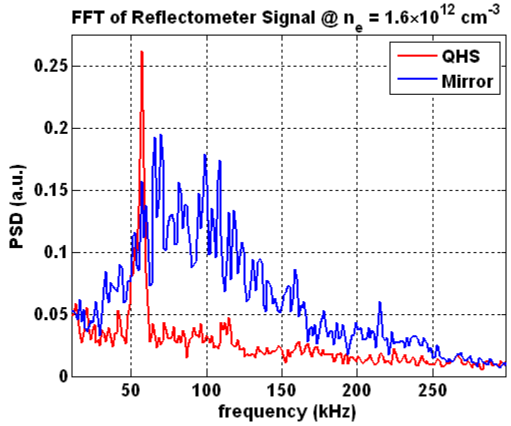


With ExB shear suppression

Future plans

• 16 channel ECE system now installed

•Reflectometer has begun operation



•PENTA calculations with Spong (ORNL)

to include effects of parallel flow

• Need to measure radial electric field

➔ diagnostic neutral beam mounted on HSX for CHERS

➔ Novel low-cost HIBP system being developed with RPI

• Second steerable 28 GHz gyrotron for additional heating, pulse propagation

• ICRF to heat ions into low collisionality regime ➔ Obtain ion root plasma

•Anomalous transport becoming key element of HSX program

Conclusions

- Lack of toroidal curvature verified by
  - grad-B drift of trapped particles
  - helical Pfirsch-Schlüter current
  - bootstrap current that decreases transform
- High effective transform verified by
  - small drift of passing particles from flux surface
  - reduced magnitude PS and bootstrap currents
- Good confinement of trapped particles with quasisymmetry ➔ MHD mode observed
  - first reflectometer results shows mode localized to core
  - broad density fluctuation spectrum in Mirror compared to QHS
- ECH at B=0.5T
  - Reduction of particle momentum and heat transport with QHS
  - Thermodiffusive term reduced with quasisymmetry
  - χ_e (r/a = 0.25) is 4.0 m^2/s in Mirror, 2.5 m^2/s in QHS

Conclusions

- ECH at B = 1.0 T
  - Nonthermal component is small
  - T_e up to 2.5 keV is observed
  - χ_e (r/a = 0.25) is 1.5 m^2/s in Mirror, 0.5 m^2/s in QHS
  - First evidence core anomalous transport may be reduced with QHS

- Weiland 2D anomalous transport model with geometric approximations gives reasonable fit to simulated temperature profiles (outside core)

- Turbulence suppression when the ExB shearing rate is greater than the linear growth rates for the TEM match simulated core T_e well

  ➔ First evidence of internal electron transport barrier in HSX

  ➔ High effective transform gives neoclassical reductions, but may provide increased drive for microinstabilities

  ➔ What are conditions needed for turbulence suppression?