ECRH Plasma Experiments at B=1.0T in HSX

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THE UNIVERSITY of WISCONSIN MADISON

18th International Toki Conference – Development of the Physics and Technology of Stellarators/Heliotrons en route to DEMO

Outline

- **U.S. Program Evolution** –Strategic planning process

- **First use of 3D equilibrium reconstruction Code V3FIT to model data in stellarator**
  - -First observation of helical Pfirsch-Schlüter current; good agreement with measured bootstrap current

- **Progress on neoclassical and turbulent transport modeling**
  - − Neoclassical: PENTA code includes momentum conservation and parallel flow → predicts lower E_r than standard ambipolarity constraint
  - − Turbulent: GS2, a 3D gyrokinetic code → good agreement with experimental T_e profile outside core as well as confinement scaling

- **First observation of internal transport barrier (CERC mode) in quasisymmetric stellarator**
  - − Close proximity of electron and ion roots in core → ExB shear suppression of turbulence results in very peaked T_e profile

- **Future Directions for HSX**

US Formulating a New Fusion Strategic Plan

- A Research Needs Workshop (ReNeW) will be held June 7-13, 2009 to provide the US DoE with a series of community-developed initiatives for guidance in MFE research

- DoE will utilize the results to formulate a vision and specific goals for MFE research activities over the next 15-20 year timeframe
  - International coordination specifically requested

- Efforts structured around recent "Greenwald Report": "Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy", with five themes:
  - Achieving and Understanding the Burning Plasma State
  - Creating Predictable High Performance Steady State Plasmas
  - Taming the Plasma Material Interface
  - Harnessing Fusion Power
  - Optimizing the Magnetic Configuration

Website for information: http://burningplasma.org/renew.html

US Stellarator Program Depends Critically on ReNeW Process

HSX

•The US FESAC "Toroidal Alternates Panel" has recently issued a report to DoE on the goals, scientific/technical questions, and gaps and opportunities non-tokamak toroidal systems 'in the ITER-era'

http://fusion.gat.com/tap/final_report.php/

•The report states: "The US stellarator program remains committed to the development of the quasi-symmetric stellarator approach"

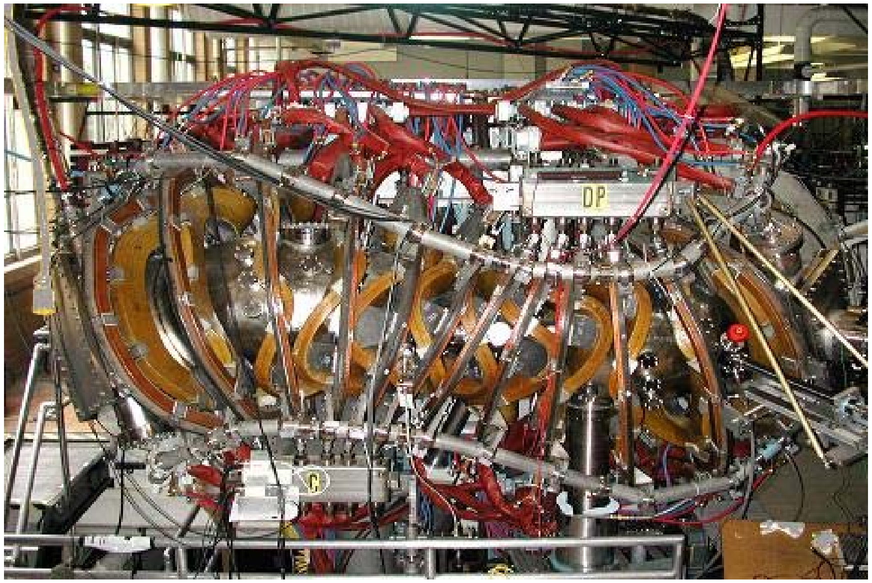
- Strong connection to 2-D tokamak physics
- Reduced transport and good energetic particle confinement
- Low flow damping and importance of plasma flows

•There is an understanding that a 'significant scale' device will be needed in the ITER-era

•Initiatives to address this need should be a result of the ReNeW process with strong community consent

Stellarator panel being formed: D. Anderson, J. Harris, C. Hegna, S. Knowlton, P. Politzer, A. Rieman, A. Ware, H. Weitzner

Quasihelical Stellarators have large effective transform



HSX is a Quasihelically Symmetric (QHS) Stellarator:

toroidal stellarator with ***almost no*** toroidal curvature

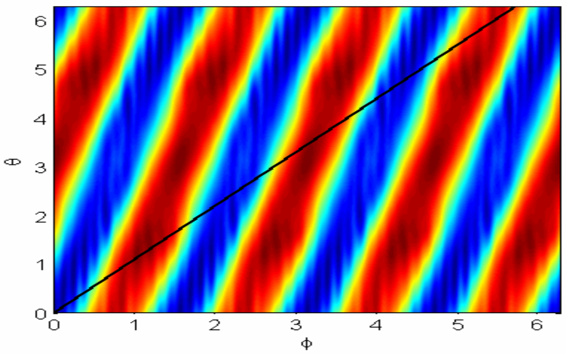
→ ε_t = 0.0025 in aspect ratio 8 device

Near symmetry in |B| :

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

In straight field line coordinates $\theta = ι\phi$ so,

$$B = B_0[1 - \varepsilon_h \cos(N - mι)\phi]$$



In HSX N = 4, m =1 and $ι \geq 1$

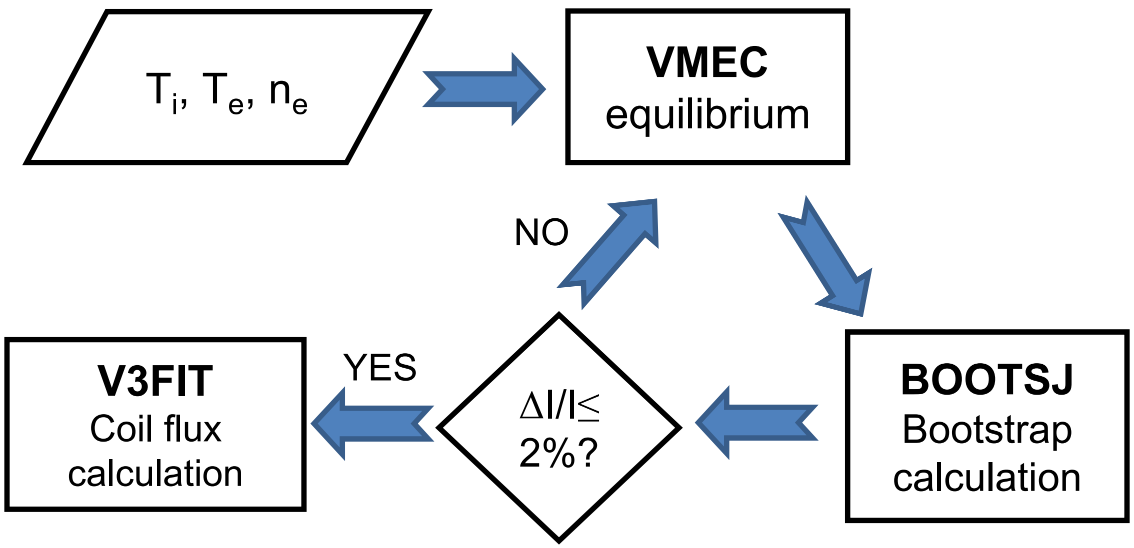
$$ι_{eff} = N - m\,ι \sim 3$$

Neoclassical currents reduced by this factor

V3FIT+ code calculates magnetic flux at pick-up coils due to neoclassical currents

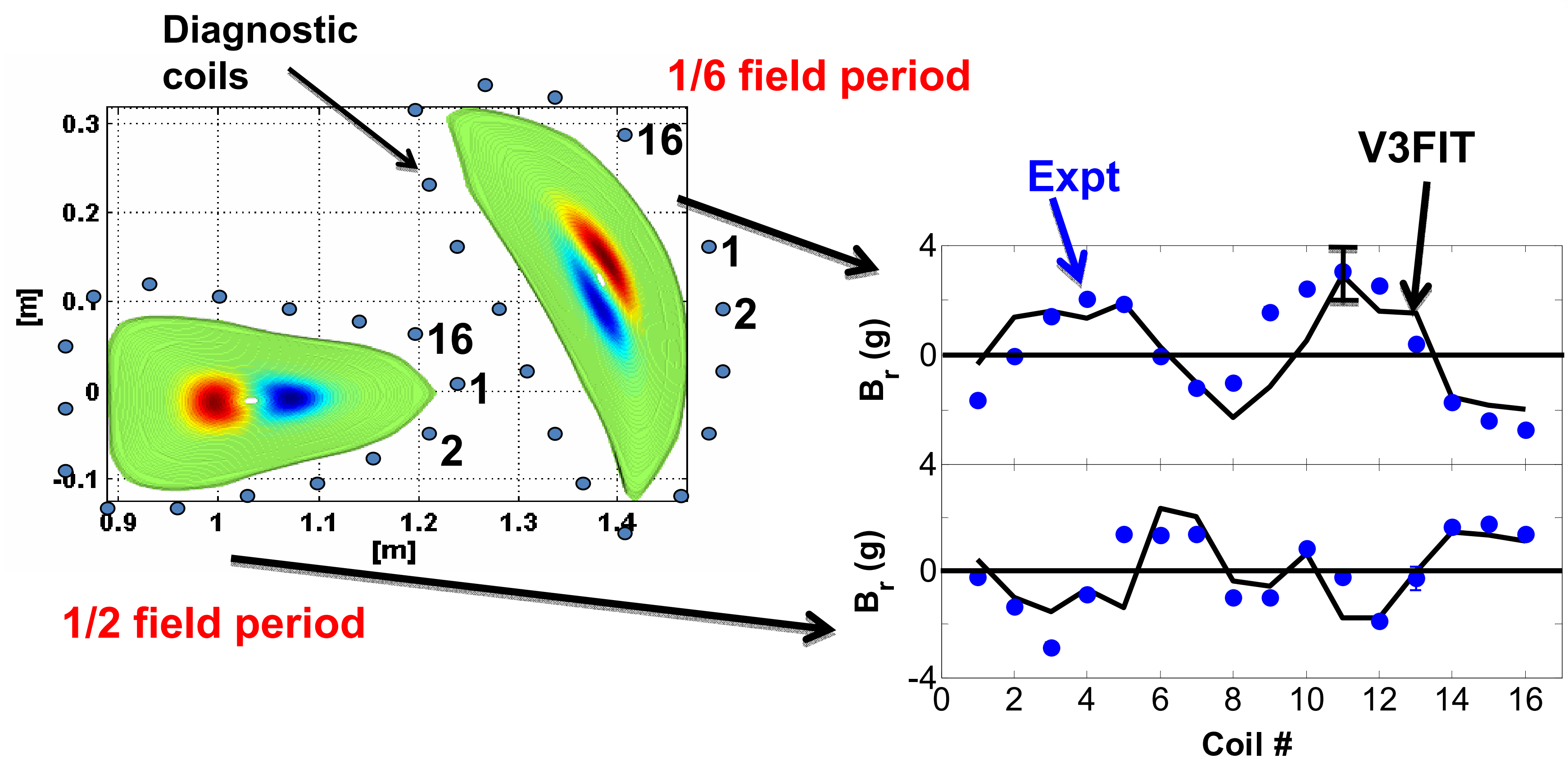
- **V3FIT: Equilibrium reconstruction for 3D toroidal devices, similar to EFIT**
  - Reconstruction is goal for CTH stellarator at Auburn University
  - Applicable to tokamak with nonaxisymmetric magnetic fields: edge ripple and field errors, RMP's for ELM suppression, inhibit onset of NTM, generate plasma rotation, 3D shaping for external transform

- **HSX: compare V3FIT calculation to pick-up coil data →** bootstrap current as function of E_r and symmetry-breaking, as well as Pfirsch-Schlüter current



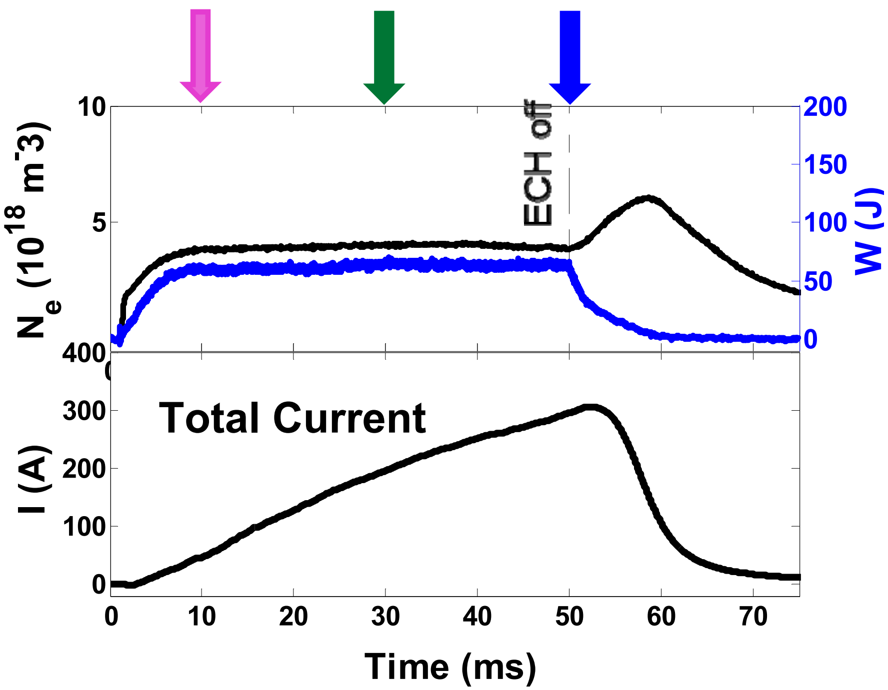
+Hirshman, Lazarus, Hanson, Knowlton, Lao, PoP 11, 595 (2004)

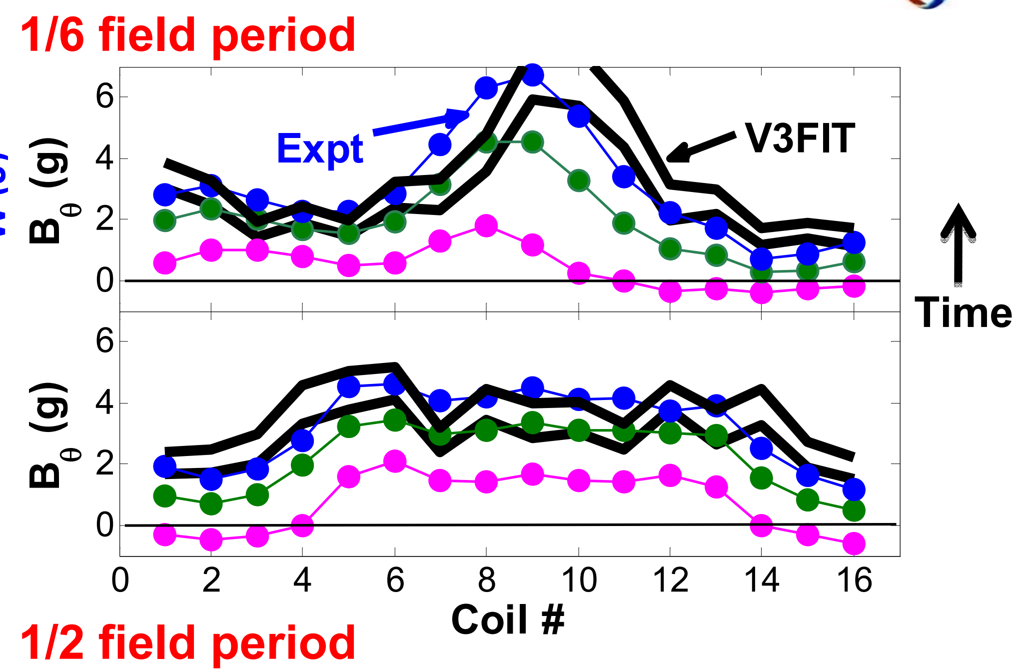
Helical Pfirsch-Schlüter current demonstrated by phase shift of B_r measurements separated by ~1/3 field period



• **16 3-axis pick up coils mounted in a poloidal array**

Bootstrap current characterized by increasing B_θ offset with time





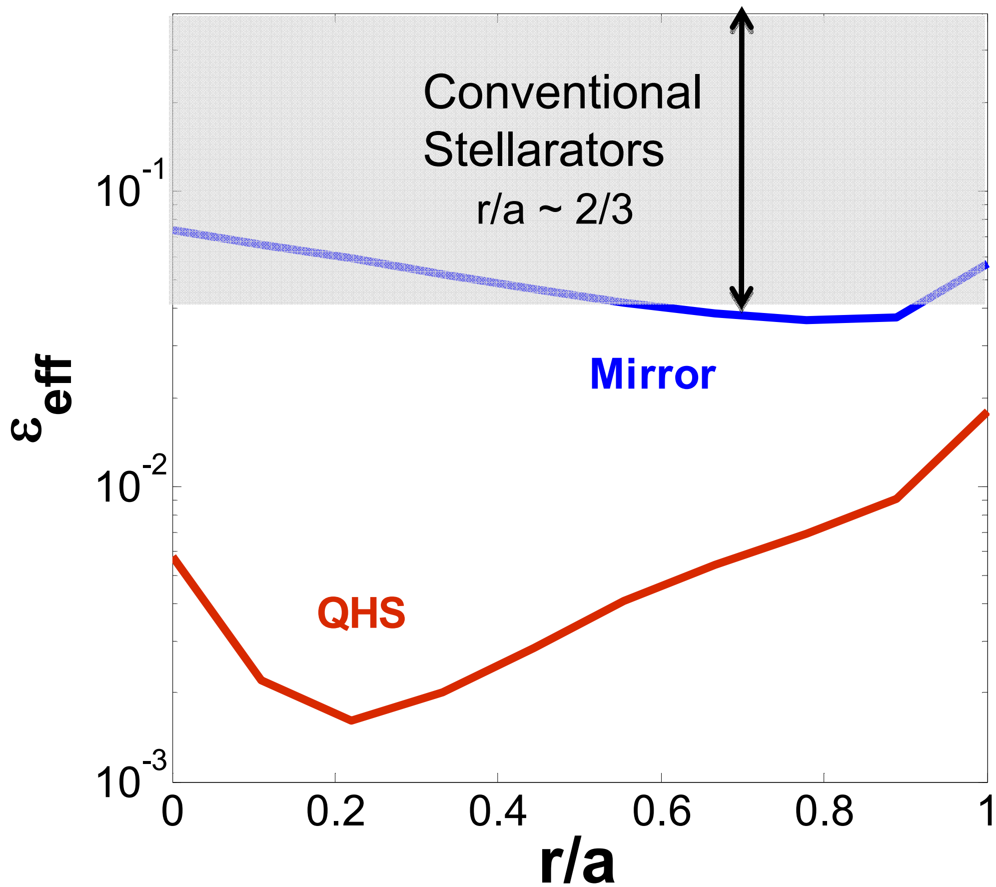
- Bootstrap current increases with time while density and stored energy remain constant

- V3FIT calculation for t = 50 ms and steady-state

- Bootstrap current is opposite direction and reduced by $n - m\iota \sim 3$ compared to tokamak, as predicted

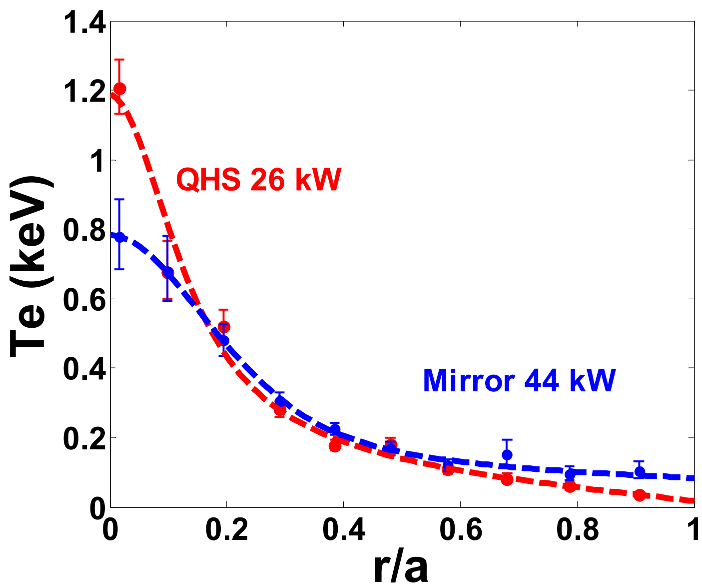
Quasisymmetry can be degraded with auxiliary coils

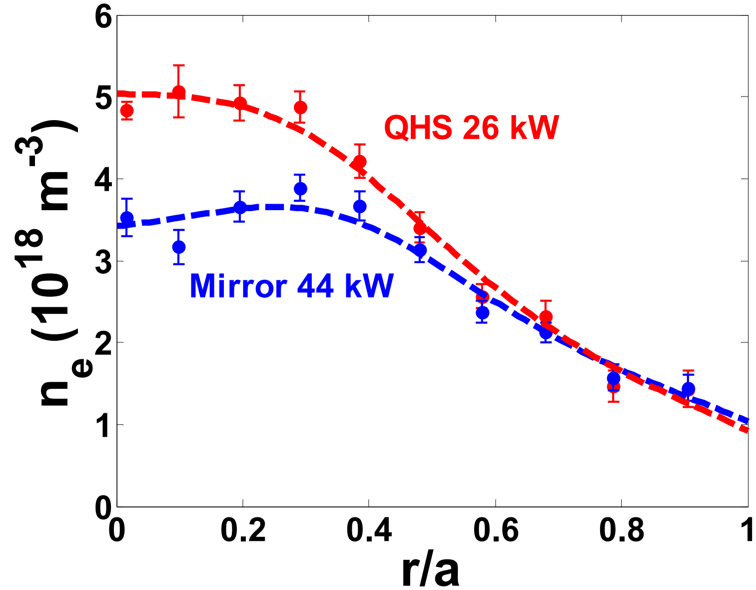
- **Auxiliary coils add n=4 and 8, m=0 terms to the magnetic field spectrum**
  - Called the **Mirror** configuration as compared to **QHS**
  - Increases neoclassical transport, flow damping similar to conventional stellarator



- **Effective ripple at r/a ~ 2/3 increases from 0.005 to 0.04**
- **Little change in volume, transform and well depth**
- **Towards axis, ε_{eff} for conventional stellarator can approach QHS**

Need ~ 70% more ECRH power in Mirror for similar T_e profile in QHS

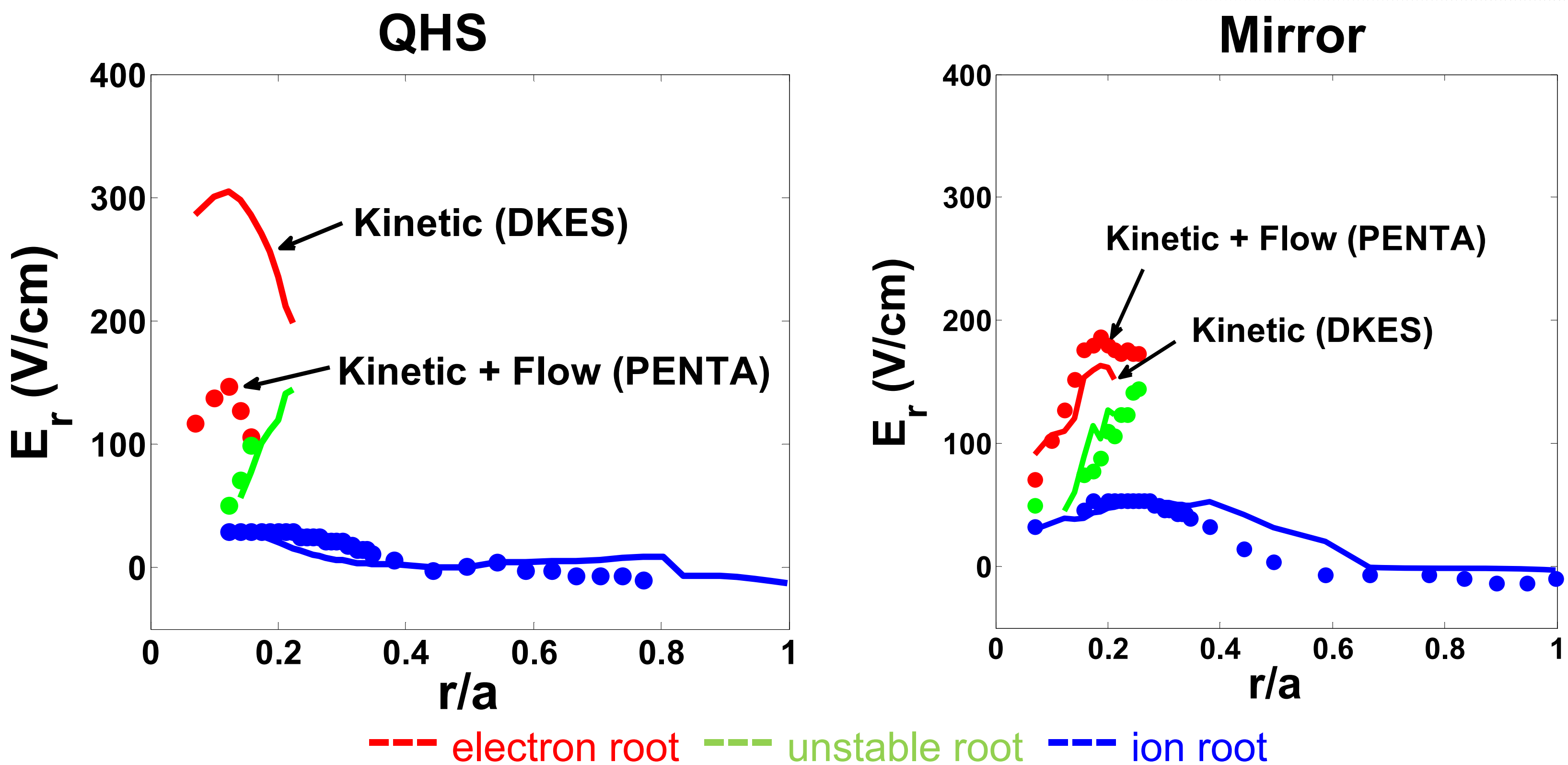




- **Adjust power to get similar profiles – 26 kW in QHS, 44 kW in Mirror**
  - **τ_E = 4 ms for QHS, 3 ms Mirror**
  - **Compare anomalous transport without assumptions as to scaling of temperature, density and gradients**

- **Theory** (Shaing, Sugama & Watanabe, Mynick & Boozer) **and expts in LHD suggest reducing neoclassical transport may also reduce anomalous transport**
  - **Is there any evidence for this in HSX?**

PENTA code shows importance of parallel flows in calculating E_r for QHS configuration



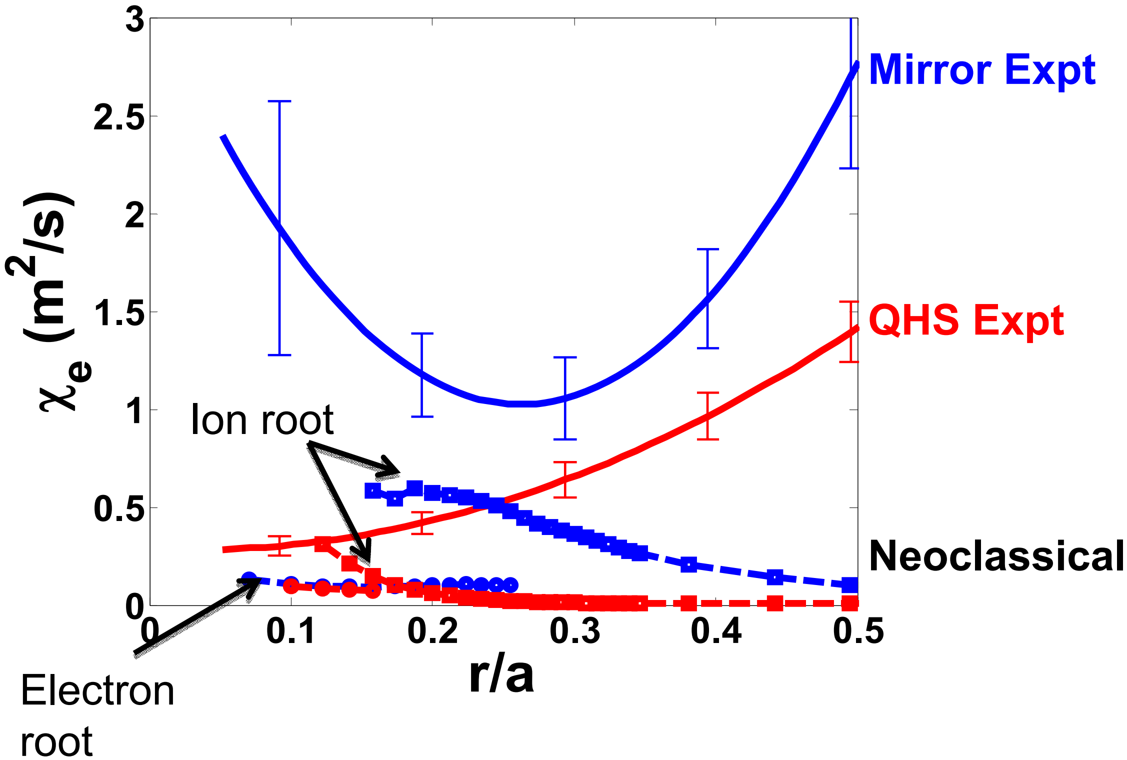
• **PENTA code** (Spong 2005) **includes momentum conservation and parallel flows** (based on Sugama & Nishimura 2002) **compared to DKES calculation**

• **E_r for QHS electron root from PENTA ~ 1/2 DKES using standard ambipolarity**

• **Agreement much better for Mirror, characteristic of conventional stellarator**

• **E_r measurements based on CHERS are forthcoming**

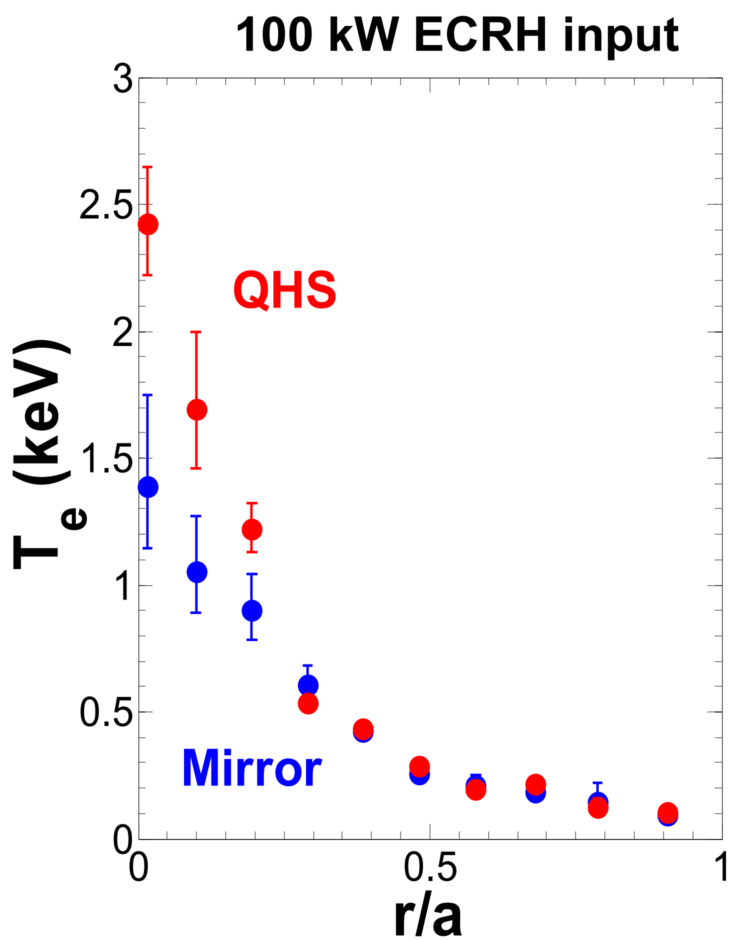
Electron thermal diffusivity higher in Mirror than QHS



- Both experimental and neoclassical diffusivities reduced due to quasisymmetry

- **Possibility that anomalous transport lower for QHS in core where T_e is very peaked *but need***
  − experimental measurement of E_r to verify neoclassical calculation
  − nonlinear gyrokinetic modeling of turbulent transport

First evidence of internal transport barrier in HSX



- Steep T_e gradient at core is first evidence of CERC – core electron root confinement – in a quasisymmetric stellarator at low ε_{eff}

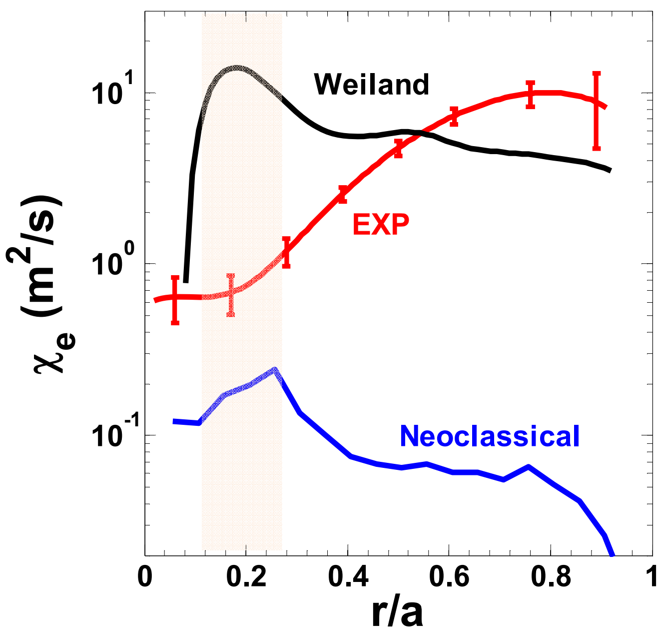
- Linear growth rates due to TEM calculated by 3D gyrokinetic code GS2

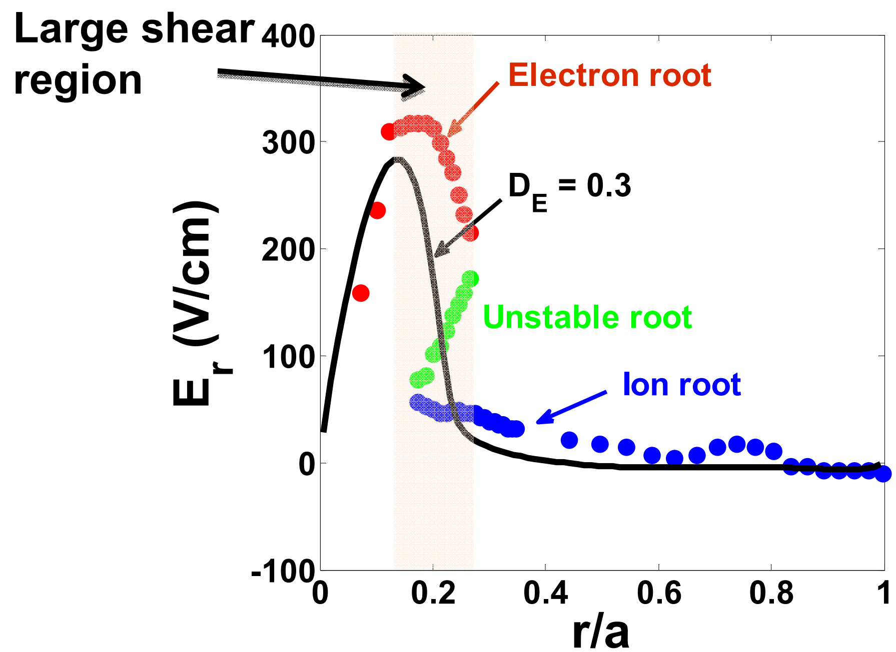
- Single class of trapped particles in QHS allows simpler quasilinear Weiland model to compute anomalous thermal diffusivity

- Curvature in HSX ~ 3 times that in tokamak with same major radius → need to account for local geometry

- Close proximity of electron root to ion root in ECRH plasma leads to E x B shear stabilization of turbulence

Transport due to TEM overestimated at plasma core where electron/ion root transition occurs





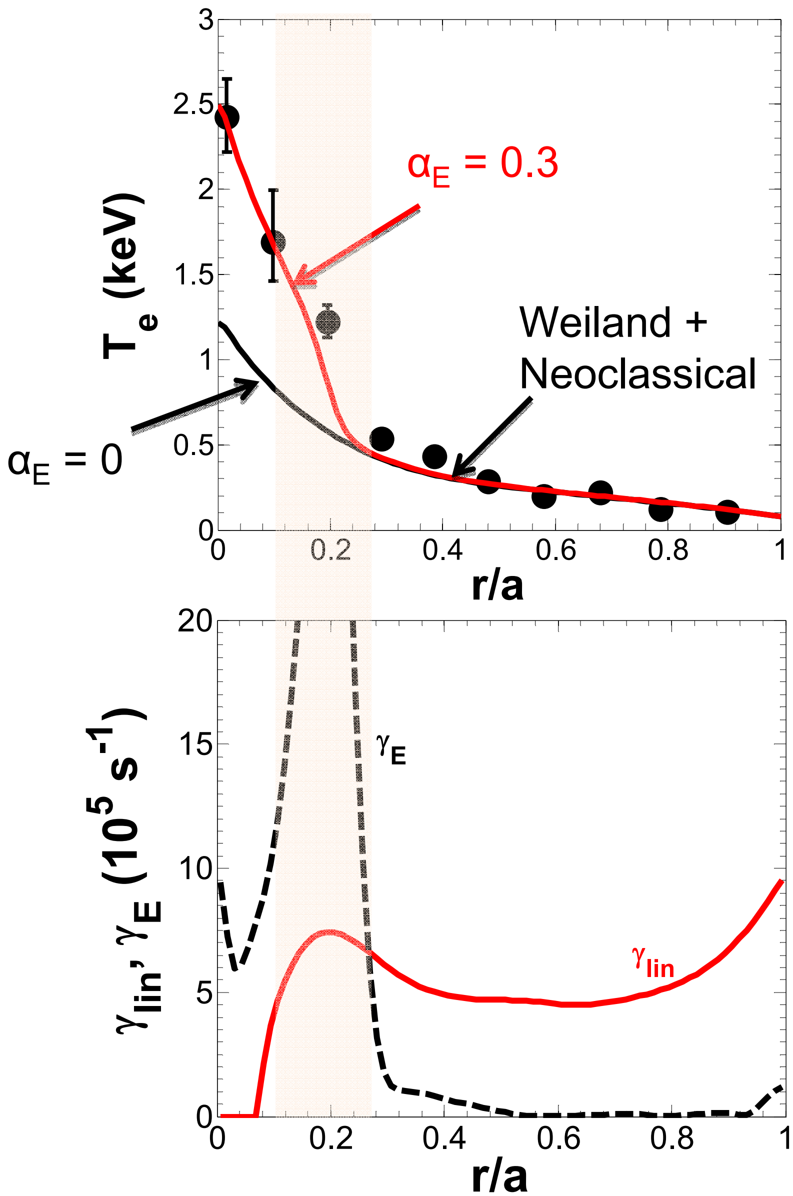
- **Inside plasma core, anomalous χ_e is factor 10-20 higher than experiment**

- **E_r and T_e can be modeled with transport equations:**
  D_E is electric field diffusion coefficient
  Q_e is heat flux due to sum of anomalous and neoclassical

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

$$\frac{3}{2} n_e \frac{\partial T_e}{\partial t} - \frac{\partial}{\partial V}\left[\langle \nabla V \rangle Q_e\right] = P_{ECRH}(\rho)$$

Sharp gradient in T_e profile corresponds to shearing rate >> linear growth rate



- Shearing rate greater than maximum linear growth rate inside r/a ~ 0.3

- **ExB shear suppresses turbulence: multiplying diffusivity by factor determined by quench rule:**

  max $(1-\alpha_E\gamma_E/\gamma_{max}, 0)$

  γ_E = shearing rate

  γ_{max} = maximum growth rate

- **Without shear suppression (α_E = 0), T_e at core is underestimated**

- **α_E = 0.3 gives good agreement with temperature at core**

Guttenfelder, et.al., PRL **101**, 215002 (2008)

Future Directions in HSX

Quasisymmetry provides strong scientific connection between tokamaks and stellarators

- Identified by TAP panel as high priority item
- HSX provides a good opportunity in near-term

Focus items:

- Conduct experiments on differences between QS and non-QS HSX plasmas
  - Explore whether lower neoclassical transport ➔ lower anomalous
  - Measure E_r and plasma flow (CXRS) and compare to PENTA code
  - Determine time evolution and E_r dependence of bootstrap current
  - Heat ions and measure T_i distribution and confinement (new initiative)
  - Determine effect of nonresonant fields on plasma flow (new initiative w/DIIID)
- Advance understanding of possible connection of QS to improved turbulent transport
  - Determine relation of configuration to zonal flows and turbulent transport (GENE, GS2 codes) ➔ compare to experiment when appropriate
  - Begin search for turbulent transport optimized configuration

Summary

• **Comparison of V3FIT to experiment confirms helical Pfirsch-Schlüter current, also magnitude and direction of bootstrap current**

  − Consistent with lack of toroidal curvature and high effective transform for a quasihelically symmetric stellarator

• **PENTA calculation yields lower E_r for electron root solution when momentum conservation and parallel flows included**

• **Electron thermal diffusivity smaller in QHS than Mirror**

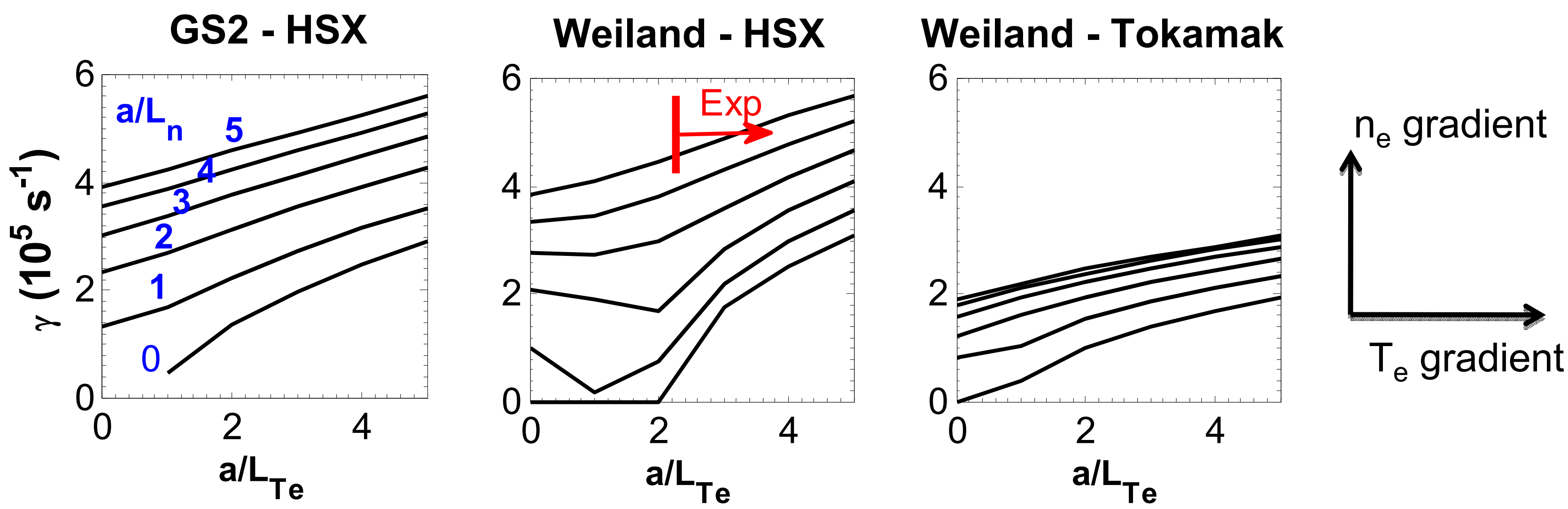
• **Anomalous transport model provides reasonable fit to temperature profile (outside core) and global energy confinement time**

• **First evidence of internal transport barrier (CERC mode) in a quasisymmetric stellarator**

  − ExB suppression of turbulence needed to explain very peaked core T_e

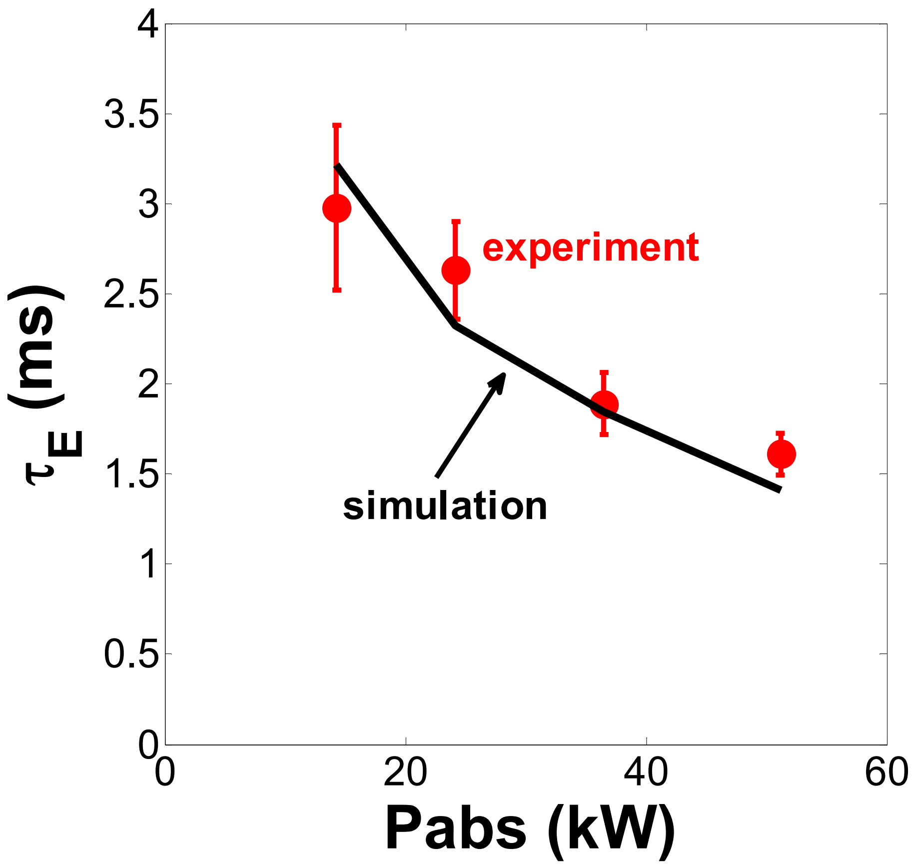
Single class of trapped particles in HSX allows 2D tokamak model for anomalous transport calculations

Growth Rates



- **Simpler quasilinear 2D Weiland model validated by 3D linear gyrokinetic calculations using GS2 and exact geometry**
- **Curvature in HSX ~ 3 times that in tokamak with same major radius**
- **Strictly tokamak model underestimates growth rates → needs correction for HSX local geometry**

Weiland model reproduces confinement scaling



- Captures scaling and magnitude of confinement times at B = 1.0 T
- Consistent with stellarator scaling ISS04:

  $\tau \sim P^{-0.6}$

- Without specific HSX geometry substitutions, predicted confinement time 2-3 times larger