

Neoclassical Currents and Transport Studies in HSX at 1 T

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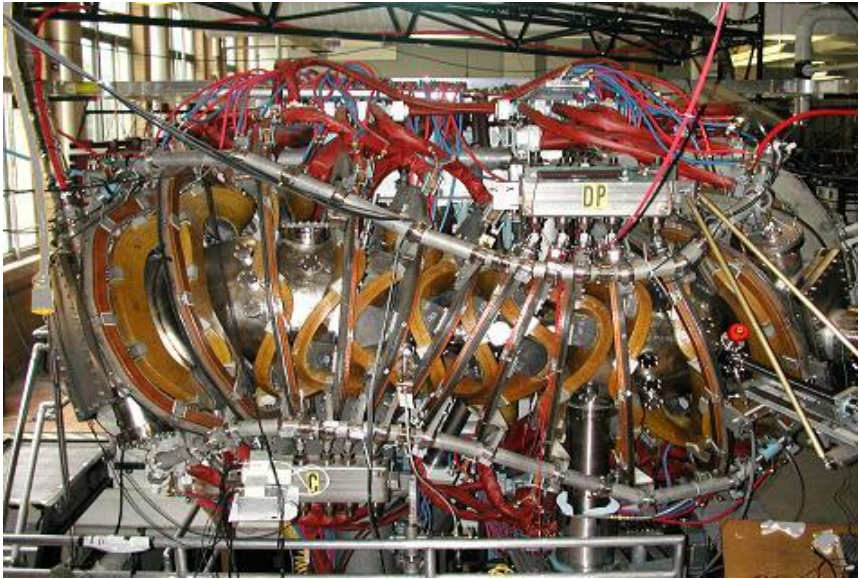
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- **First use of 3D Equilibrium reconstruction Code V3FIT to model data in stellarator**
 - Good agreement with measured bootstrap current, first observation of helical Pfirsch-Schlüter current
- **Progress on neoclassical and anomalous transport modeling**
 - Neoclassical: PENTA code includes momentum conservation and parallel flow → predicts lower E_r than standard ambipolarity constraint
 - Anomalous: GS2, a 3D linear gyrokinetic code → models experimental T_e profile (except towards core) and confinement scaling
- **First observation of internal transport barrier in quasisymmetric stellarator**
 - Proximity of electron and ion roots in core → large $E \times B$ shear to quench turbulence and generate very peaked T_e profile

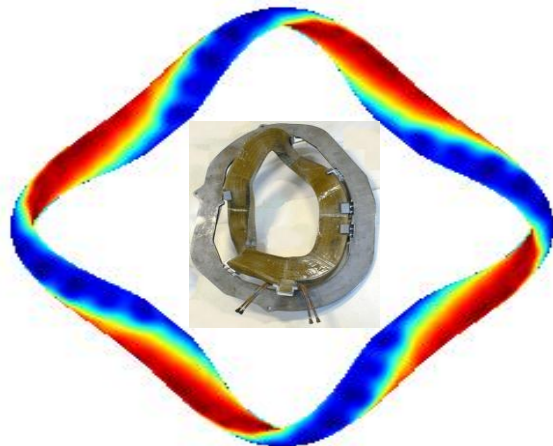
Quasihelical Stellarators have large effective transform



Quasihelically Symmetric (QHS)
Stellarator:

Toroidal stellarator with *almost no*
toroidal curvature

→ $\epsilon_t = 0.0025$ in aspect ratio 8 device



Quasihelical: Fully 3-D, BUT

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

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

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

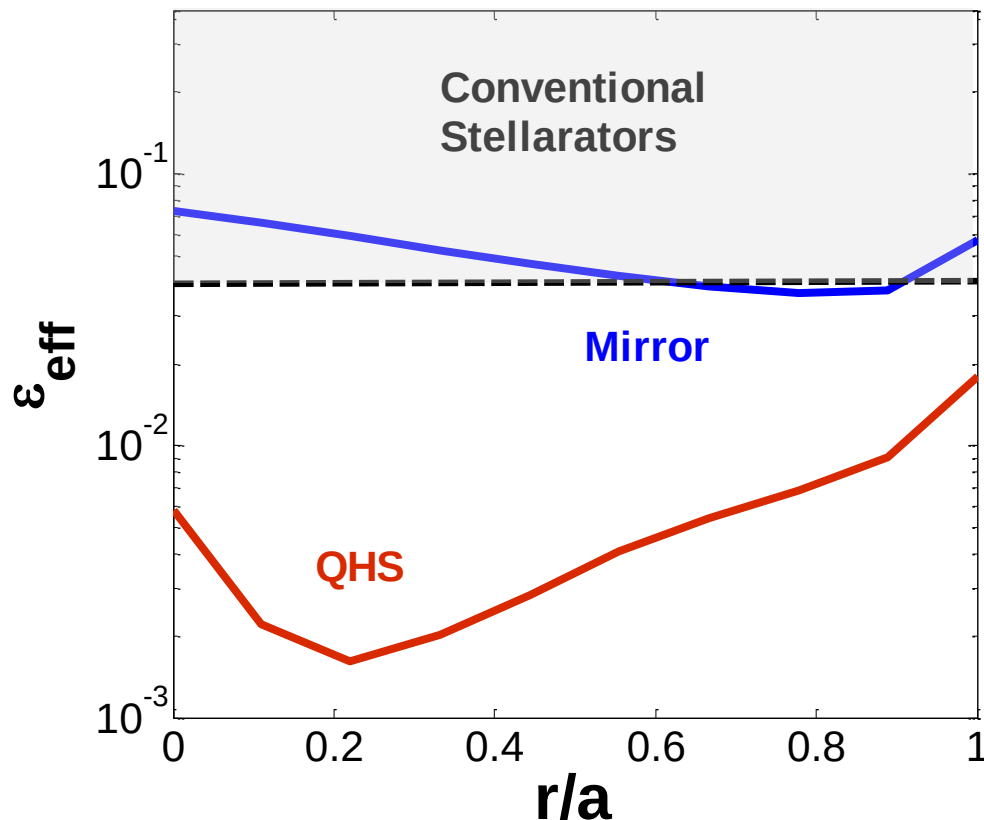
In HSX $N = 4$, $m = 1$ and $\iota \geq 1$

$$\iota_{\text{eff}} = N - m \iota \sim 3$$

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
 - Increases neoclassical transport, flow damping similar to conventional stellarator



- Effective ripple at $r/a \sim 2/3$ increases from 0.005 to 0.04

- Volume, transform and well depth change $< 10\%$

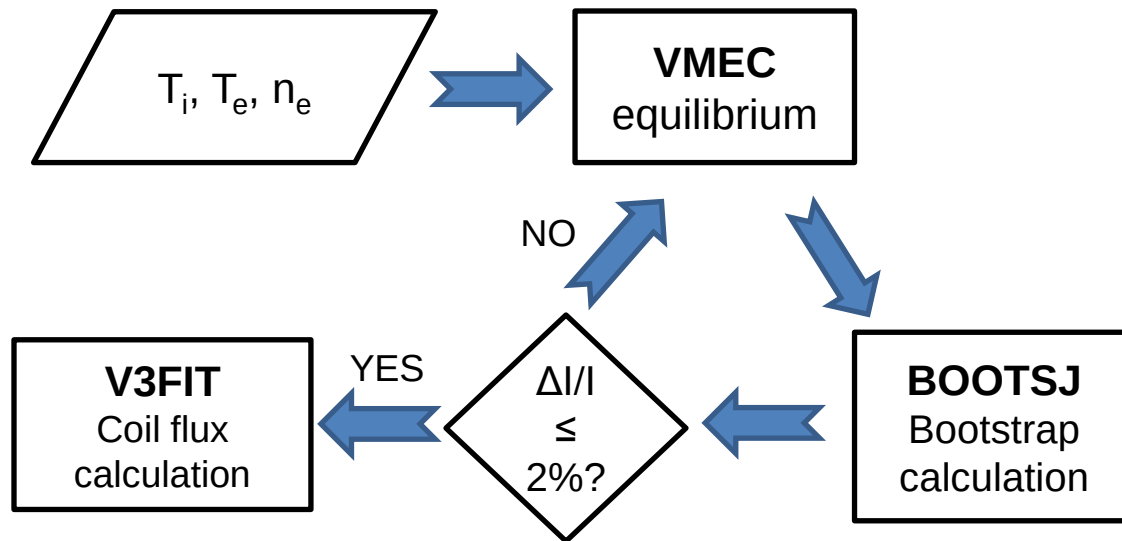
V3FIT code calculates magnetic coil flux due to neoclassical currents



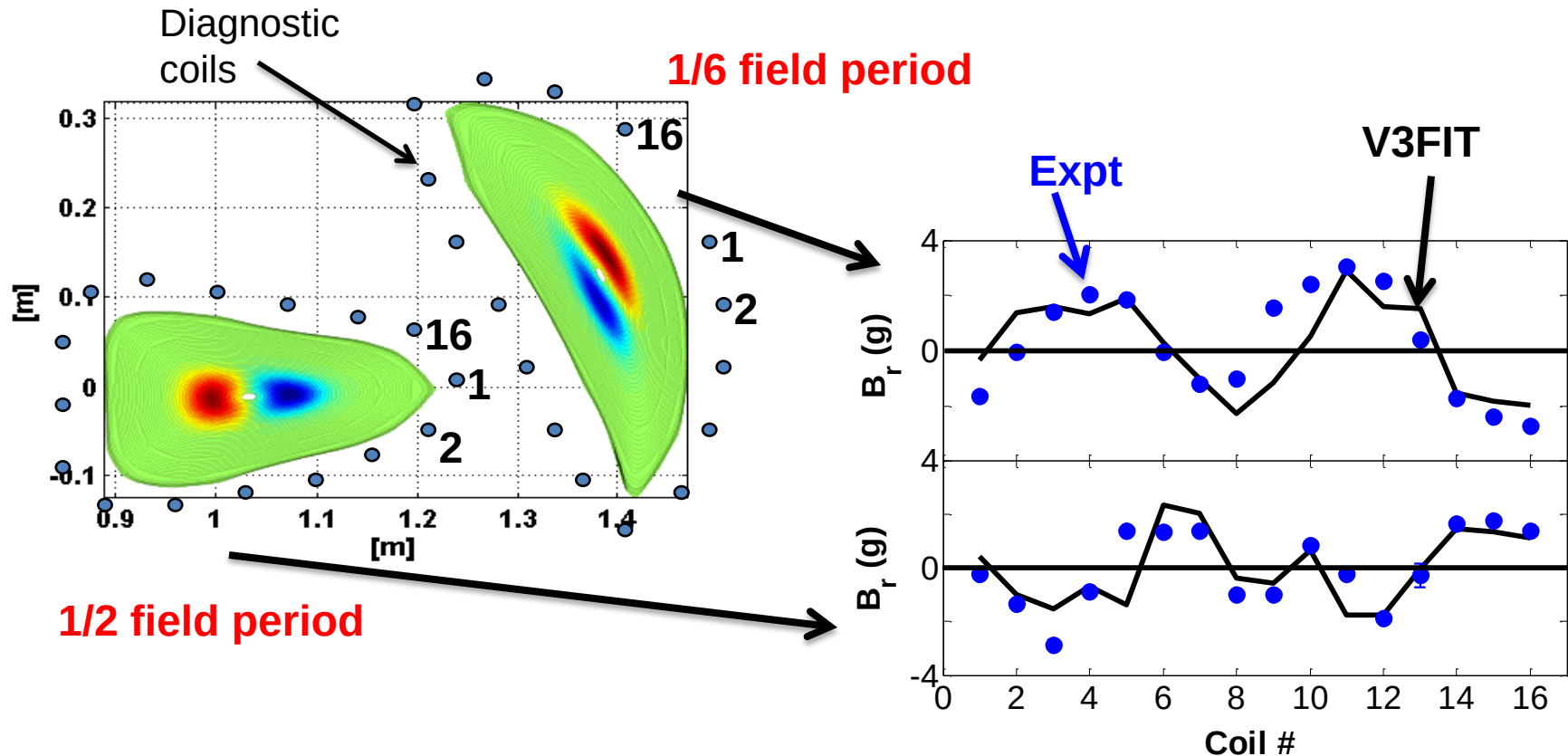
•V3FIT: Equilibrium reconstruction for 3D toroidal devices

- Reconstruction is goal for CTH stellarator at Auburn University, similar to EFIT
- Applicable to tokamak with small nonaxisymmetric magnetic fields: edge ripple and field errors, ELM suppression, inhibit onset of NTM, generate plasma rotation

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

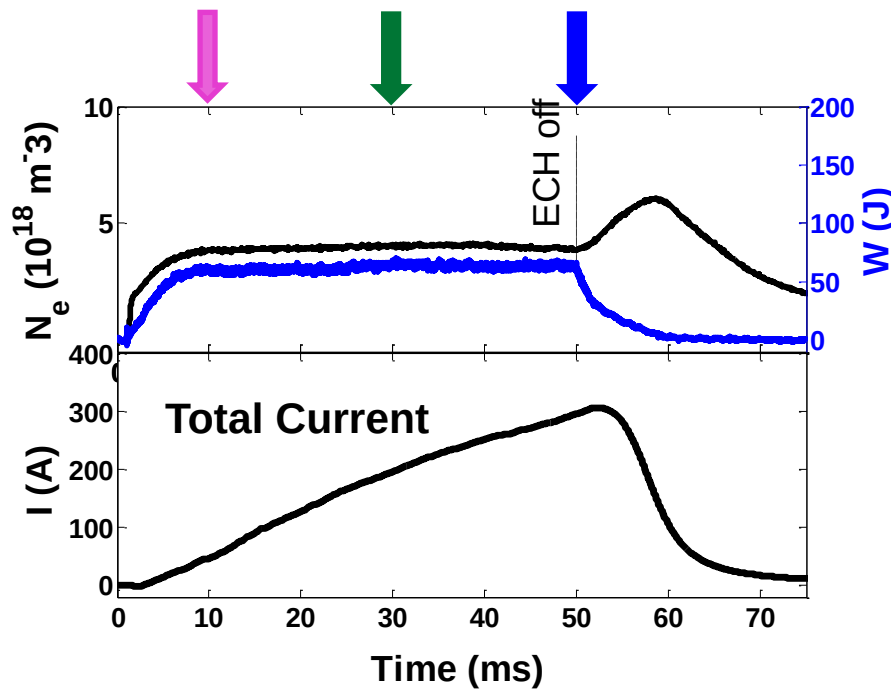


Helical Pfirsch-Schluter current demonstrated by opposite phase of B_r measurements separated by $\sim 1/3$ field period

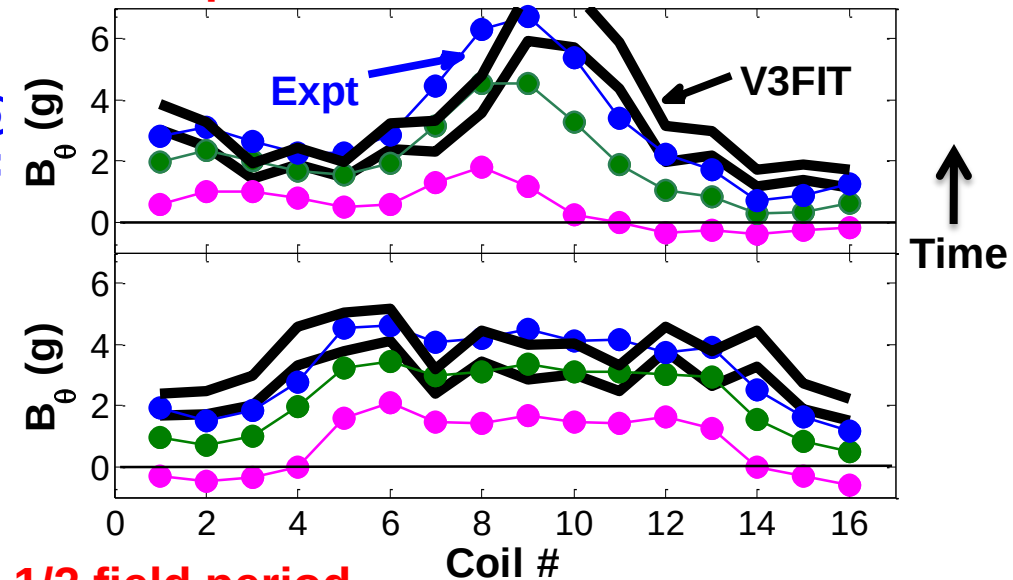


- 16 3-axis pick up coils mounted in a poloidal array
- Two sets of measurements separated by $\sim 1/3$ field period

Bootstrap current characterized by increasing B_θ offset with time



1/6 field period



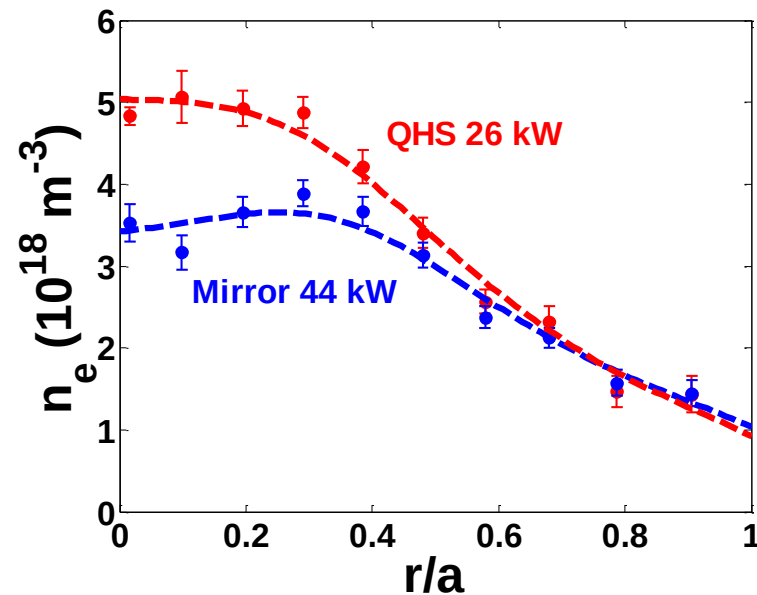
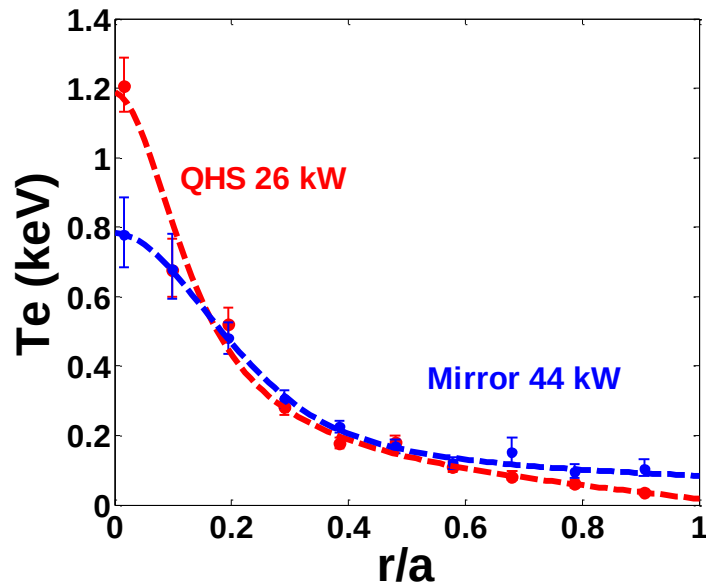
1/2 field period

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

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

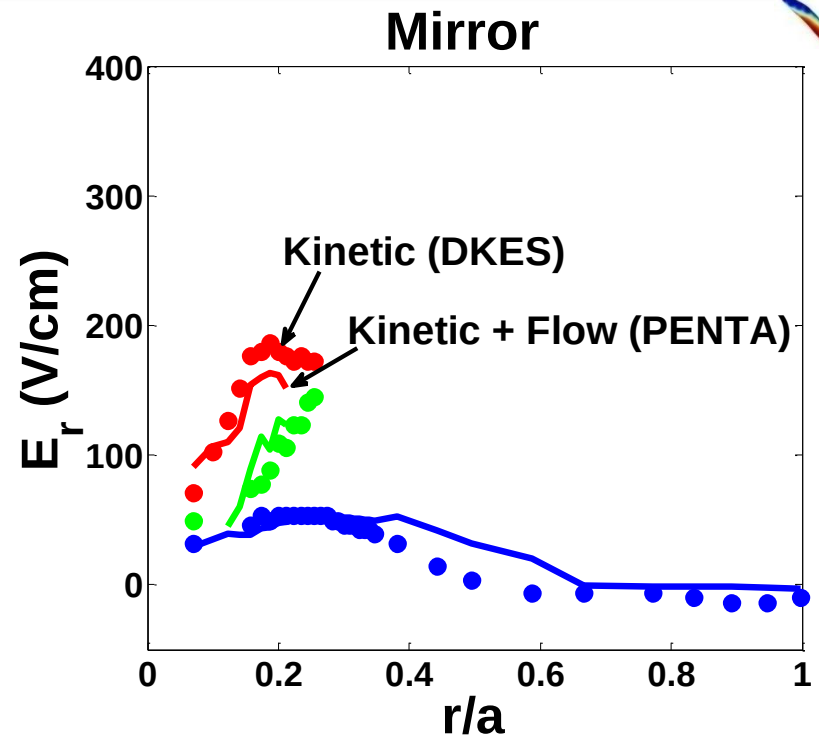
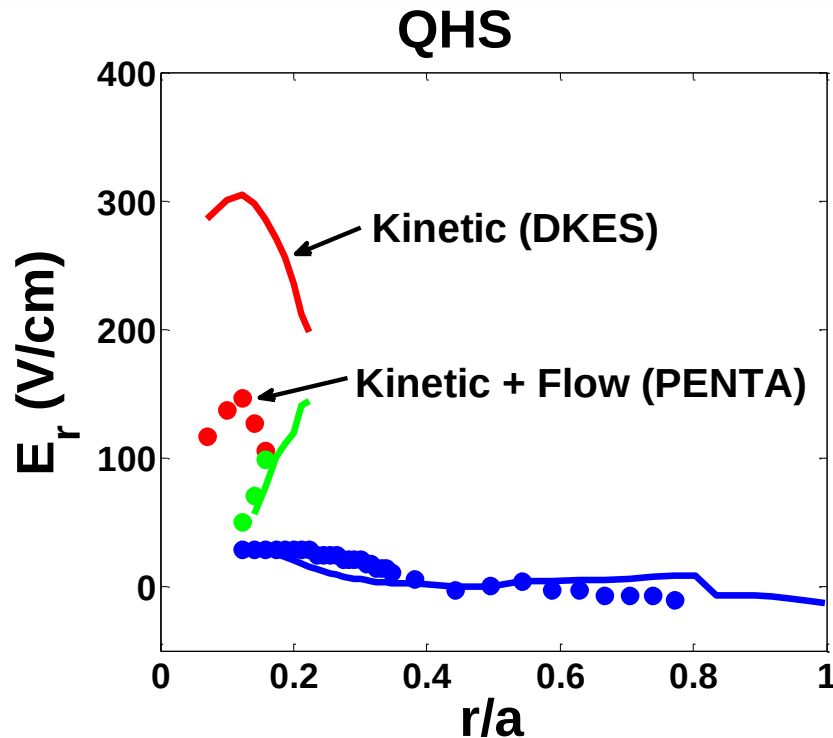
- Bootstrap current is opposite direction and reduced by $n - m_t \sim 3$ compared to tokamak, as predicted

About half ECH power needed for same T_e profile in QHS compared to Mirror



- Adjust power to get similar profiles – 26 kW in QHS, 44 kW in Mirror
 - Compare anomalous transport without assumptions as to scaling of temperature, density and gradients
- Theory (shaing, sugama & watanabe, mynick & boozier) and expts in LHD suggest reducing neoclassical transport may also reduce anomalous transport
 - Is there any evidence for this in HSX?

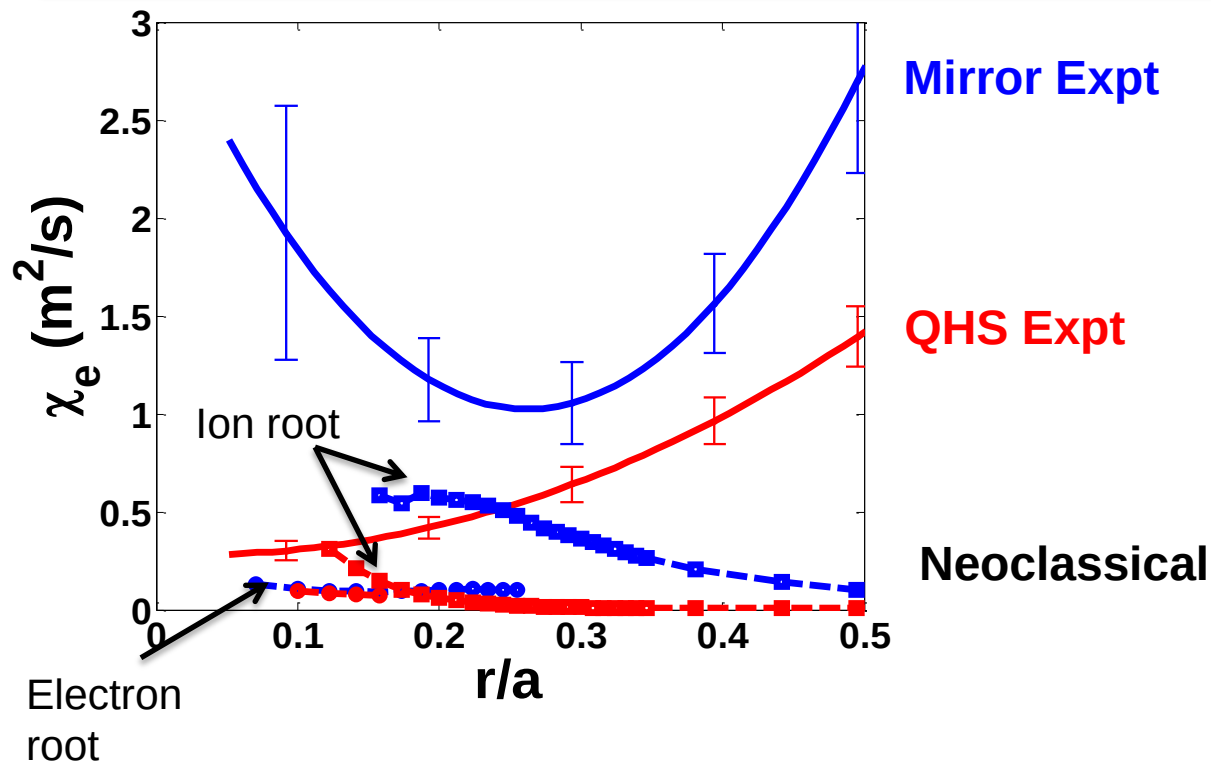
PENTA code shows importance of parallel flows in calculating E_r for QHS configuration



--- electron root --- unstable root --- ion root

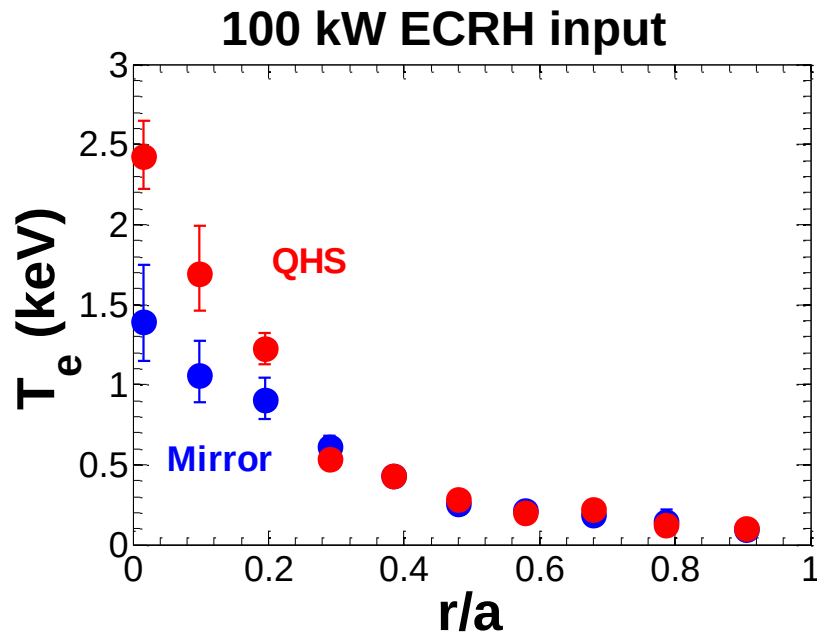
- PENTA code (Spong ORNL) includes momentum conservation and parallel flows (based on Sugama & Nishimura 2002) to DKES calculation
- E_r for QHS electron root from PENTA $\sim 1/2$ DKES from ambipolarity constraint
- Agreement much better for Mirror, characteristic of conventional stellarator.
- E_r measurements based on CHERS are forthcoming

Electron thermal diffusivity higher in Mirror than QHS



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

First evidence of internal transport barrier in HSX

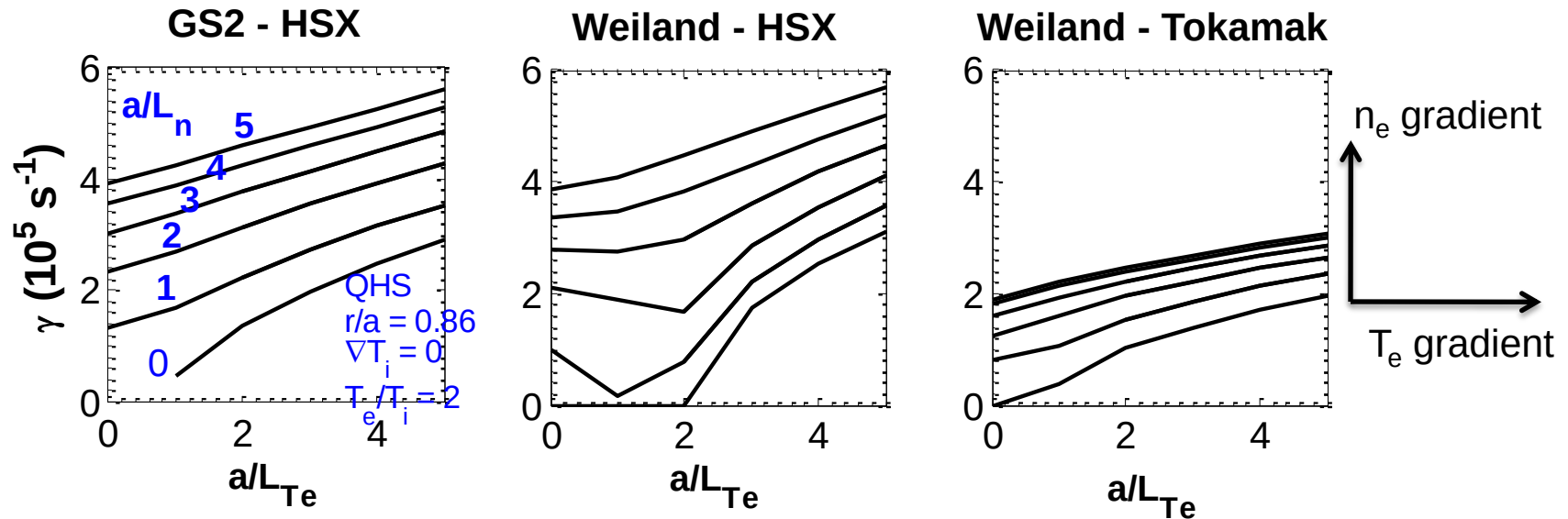


- Steep T_e gradient at core is first evidence of CERC – core electron root confinement – in a quasisymmetric stellarator
- Model of anomalous transport in HSX developed based on 3D linear gyrokinetic calculations
- Proximity of electron root to ion root in ECRH plasma leads to $E \times B$ shear stabilization of Trapped Electron Mode turbulence

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

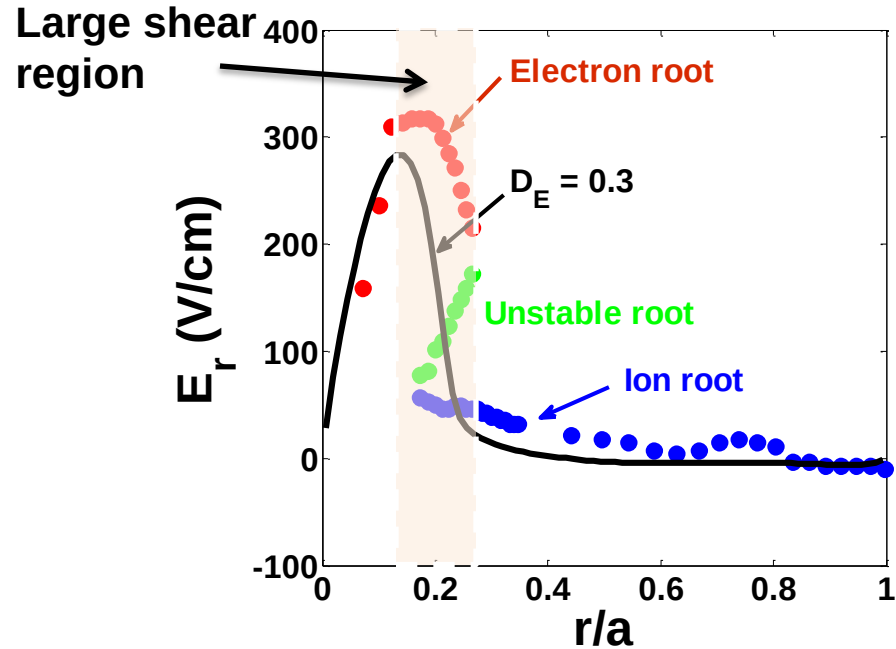
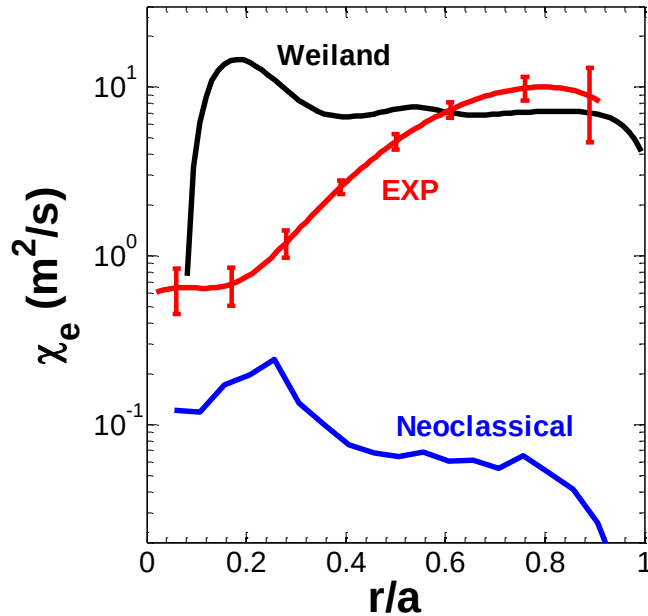


Growth Rates



- 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 $\rightarrow$ needs correction for HSX local geometry

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:

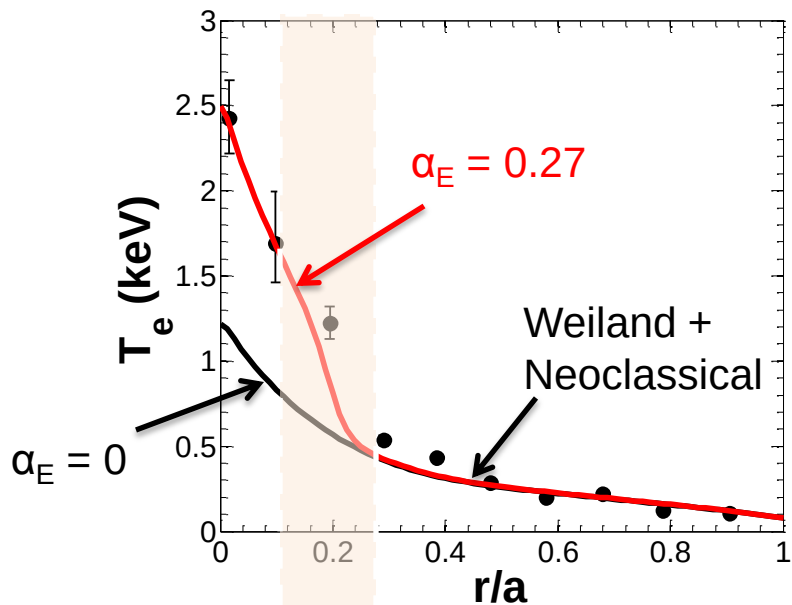
D_E is electric field diffusion coefficient

Q_e is heat flux due to sum of anomalous and neoclassical

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

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

Sharp gradient in T_e profile corresponds to shearing rate $\gg$ linear growth rate



- Shearing rate greater than maximum linear growth rate inside $r/a \sim 0.3$

- ExB shear suppresses turbulence: multiplying diffusivity by quench rule:

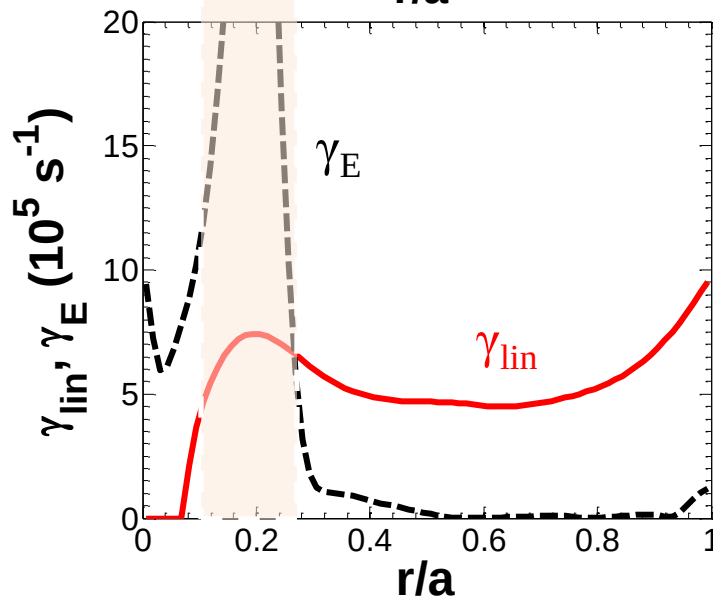
$$\max(1 - \alpha_E \gamma_E / \gamma_{\max}, 0)$$

γ_E = shearing rate

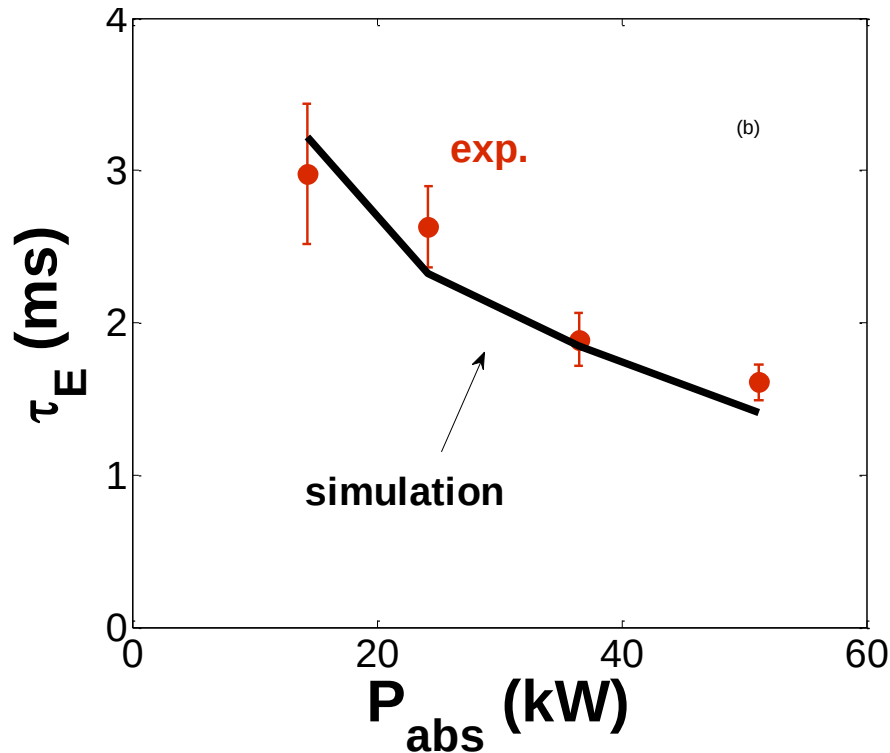
$\gamma_{\max}$ = maximum growth rate

- Without shear suppression ($\alpha_E = 0$), T_e at core is underestimated

- $\alpha_E = 0.27$ gives good agreement with temperature at core



Weiland model reproduces confinement scaling



- Captures scaling and magnitude of confinement times at $B = 1.0$ T
- Without specific HSX geometry substitutions predicted confinement time 2-3 times larger

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 in quasi-helically 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)**
 - ExB suppression of turbulence needed to explain very peaked core T_e .