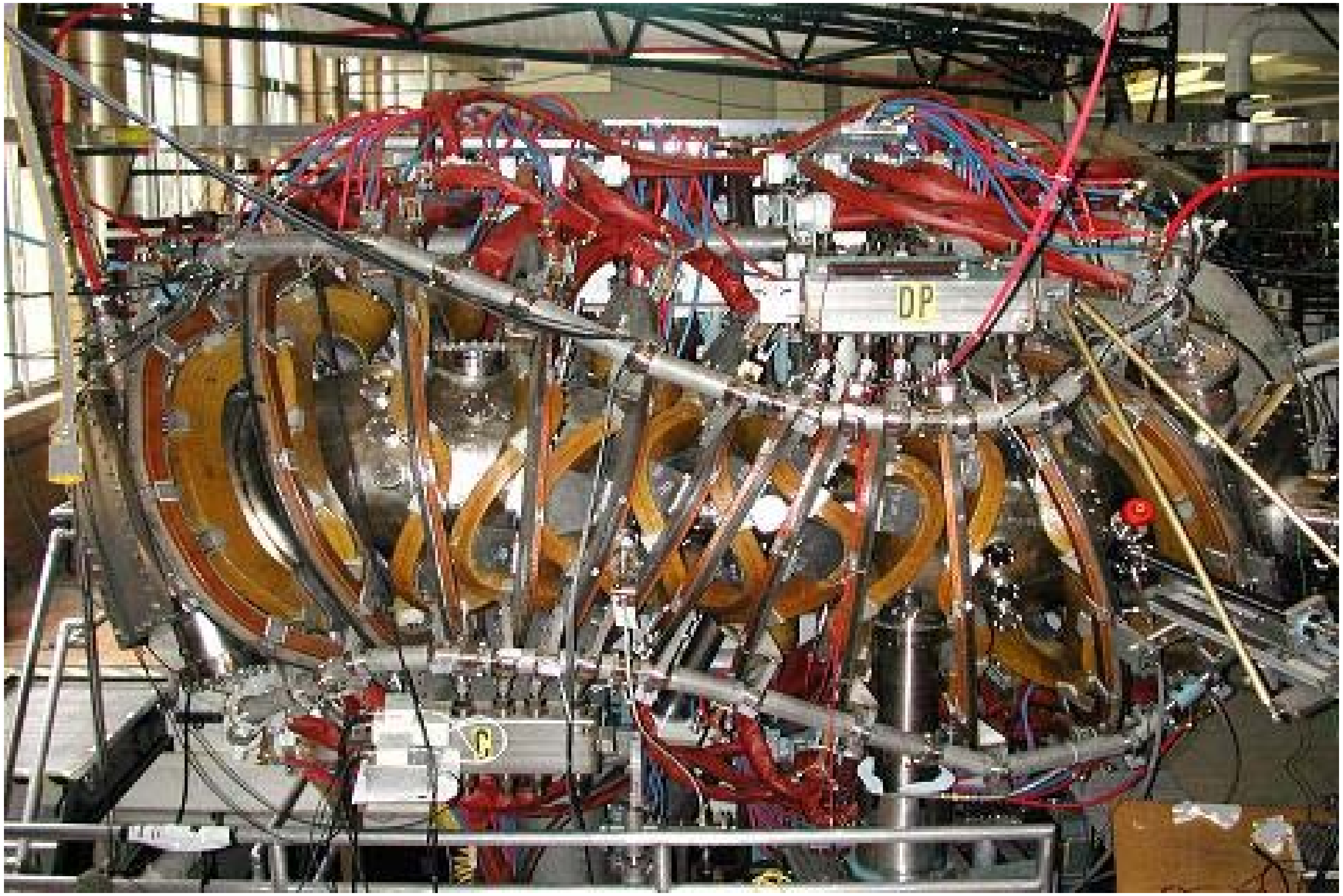
Experimental Tests of Quasisymmetry in HSX



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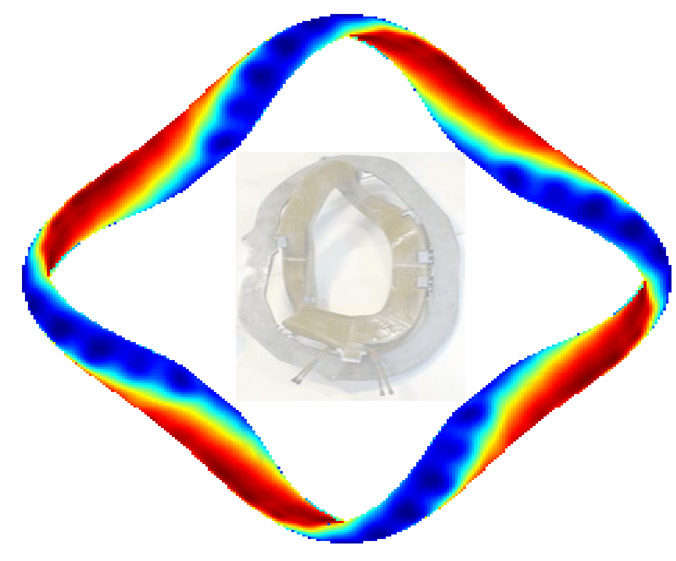
Outline

- 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 agreement of V3FIT code to diagnostic coil data
- Good confinement of trapped particles ➔ MHD instability
  - ➔ First reflectometer measurements shows core localization of mode
- 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
- 1D transport model ➔ Large curvature, short connection length drives TEM and anomalous transport
  - ❑ Good model for temperature profile and confinement scaling
- Future Plans and Conclusions

Quasihelical stellarators have high effective transform



Quasihelical: Fully 3-D, BUT

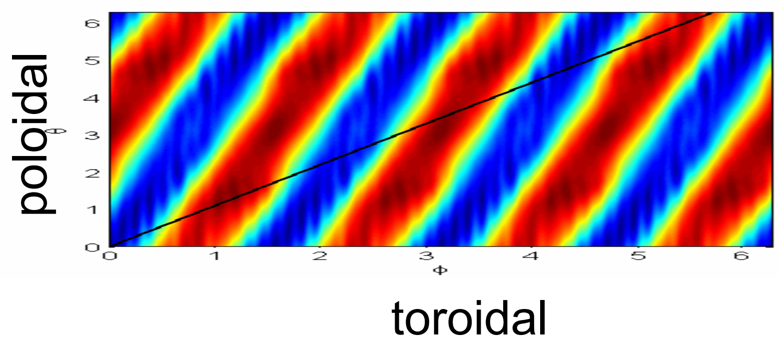
Symmetry in |B| : $B = B_0\left[1 - \varepsilon_h \cos\left(N\phi - m\theta\right)\right]$

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

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

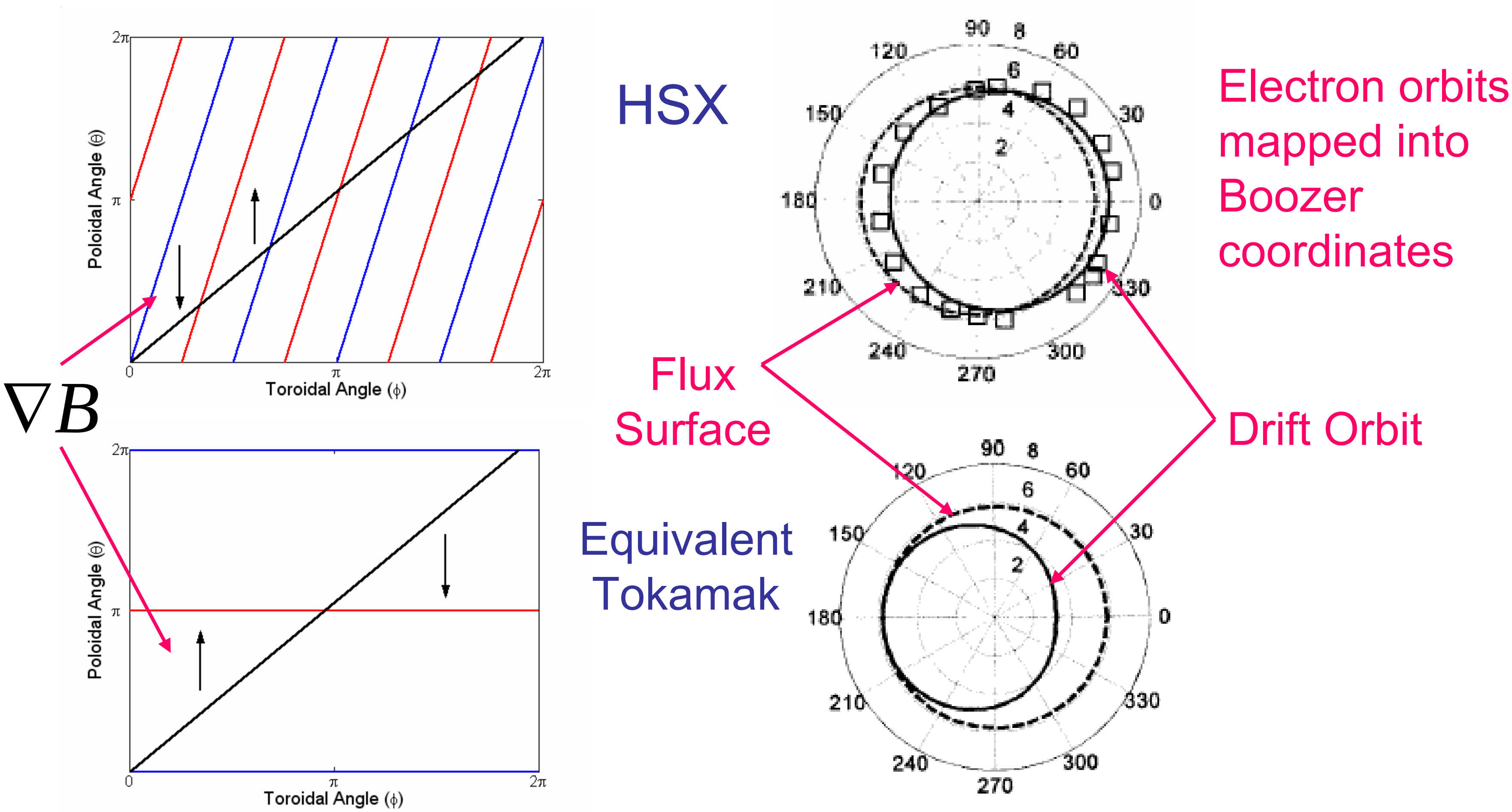
In HSX: N=4, m=1, and ι ~ 1

ι_{eff} = N-m ι ~ 3



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

Lack of toroidal curvature verified by passing orbit measurements



- Grad B drift in HSX confirms lack of toroidal curvature
- Small orbit shift confirms large effective transform of $N - m\iota$

High effective transform reduces Pfirsch-Schlüter and bootstrap current

Pfirsch-Schlüter current:

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

- 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).

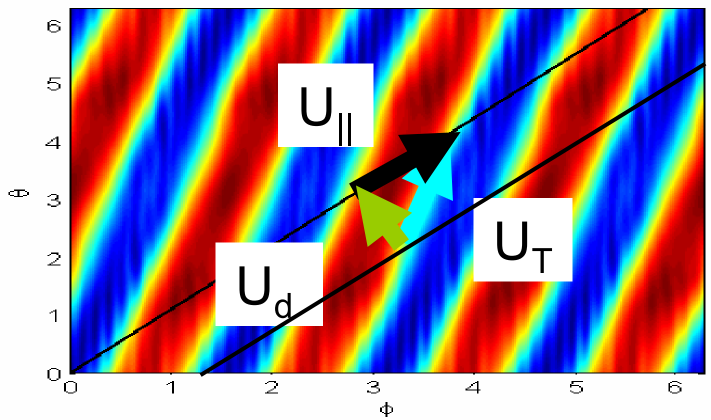
Bootstrap current:

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

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

Boozer, '82 '92

HSX



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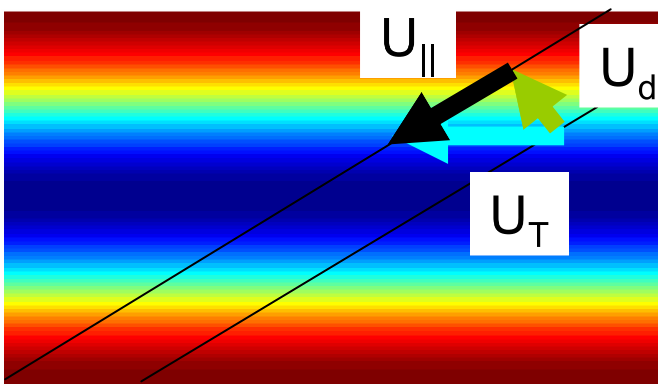
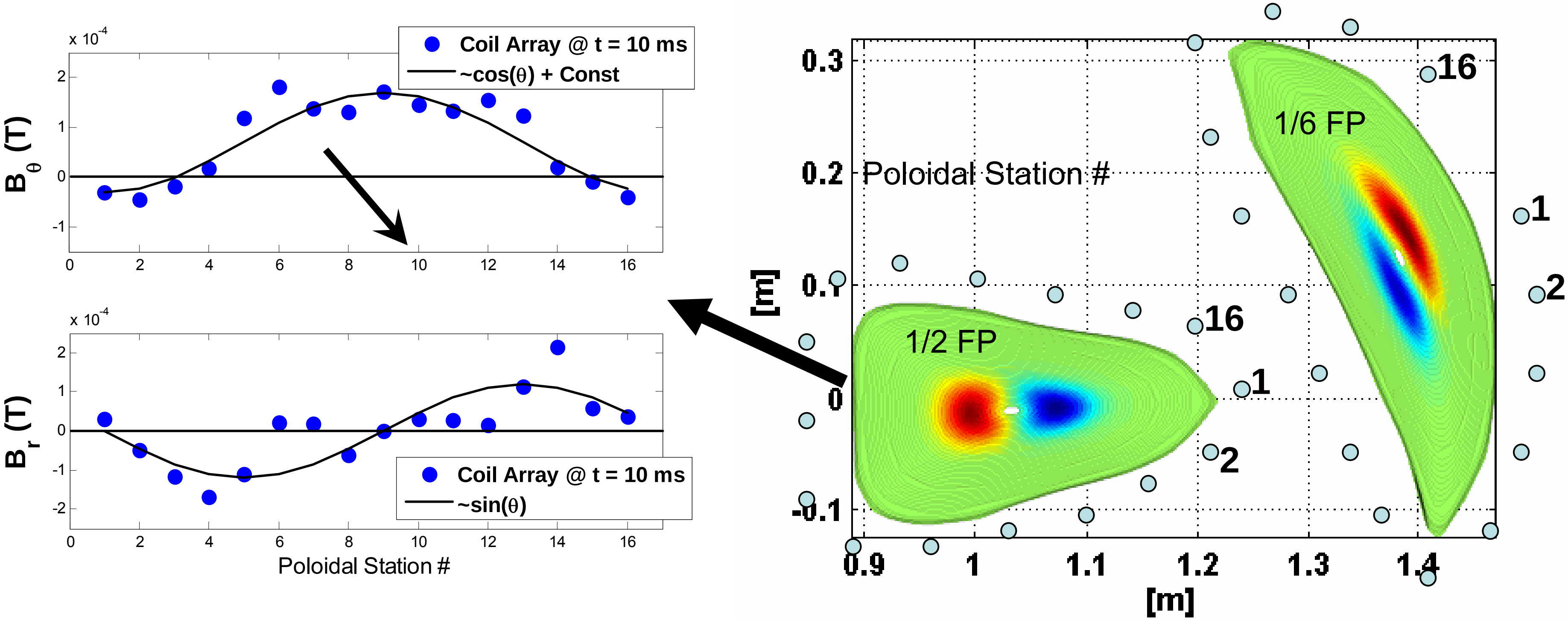


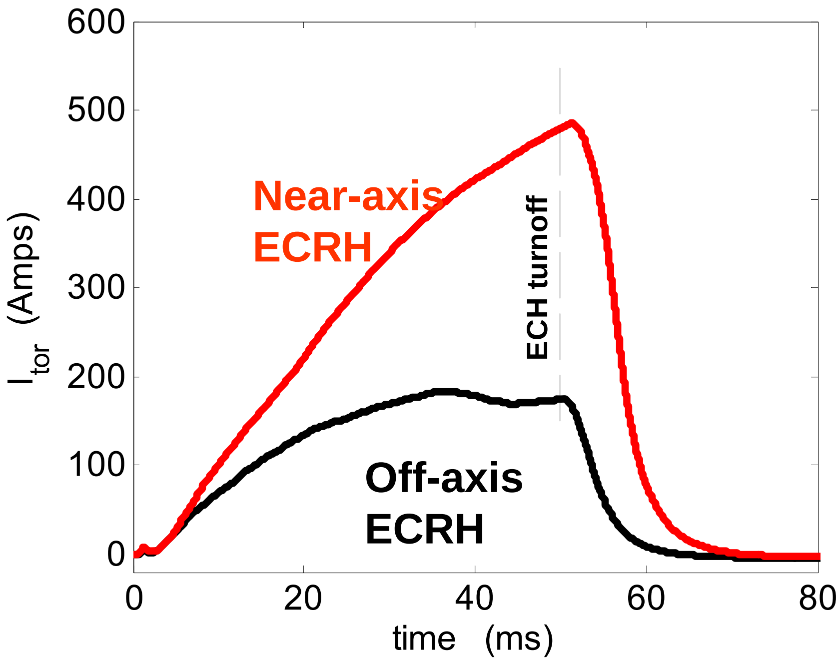
3 axis coils measure current evolution at two toroidal locations

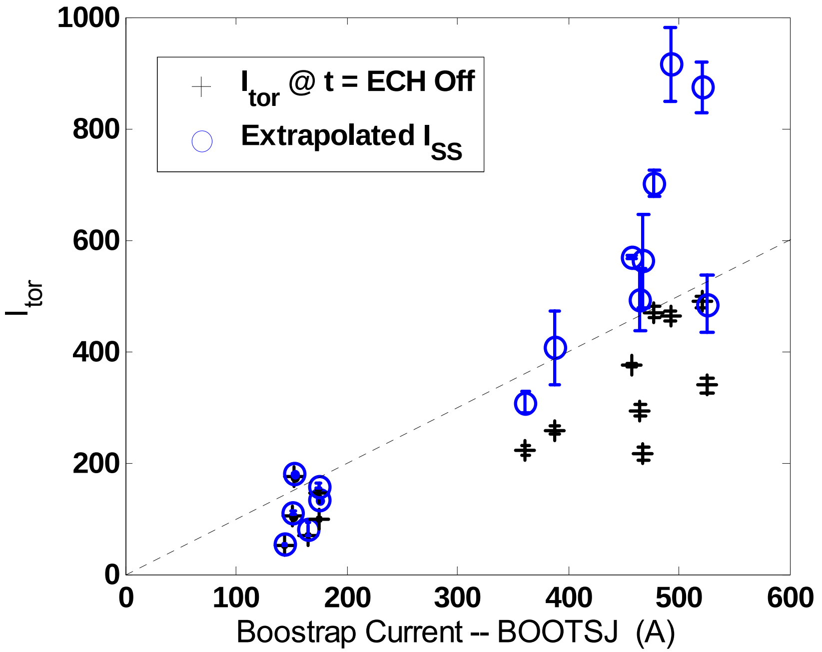
1/2 Field Period Location



- 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 $B_r \sim \sin\theta$

Rogowski confirms bootstrap current unwinds transform

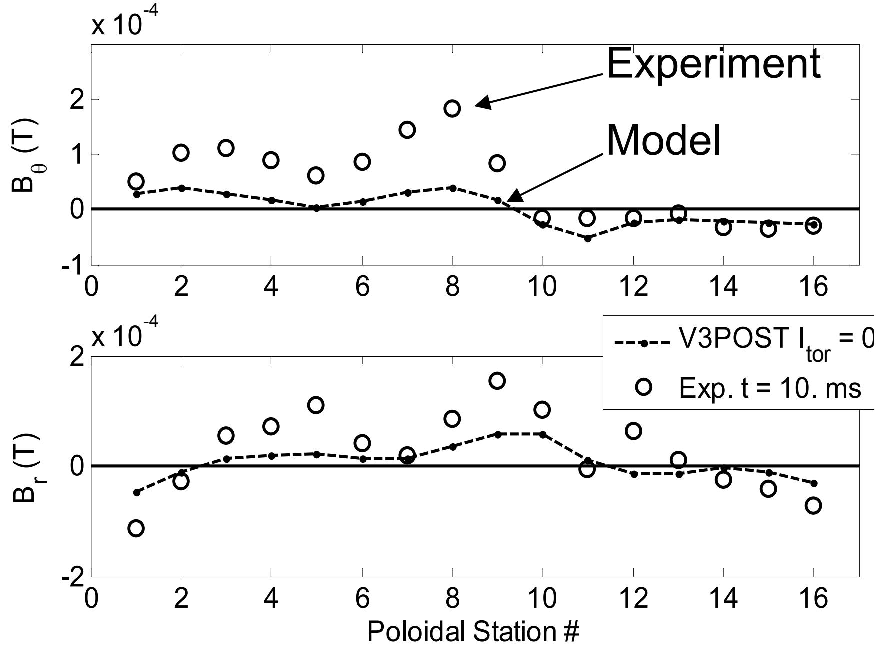




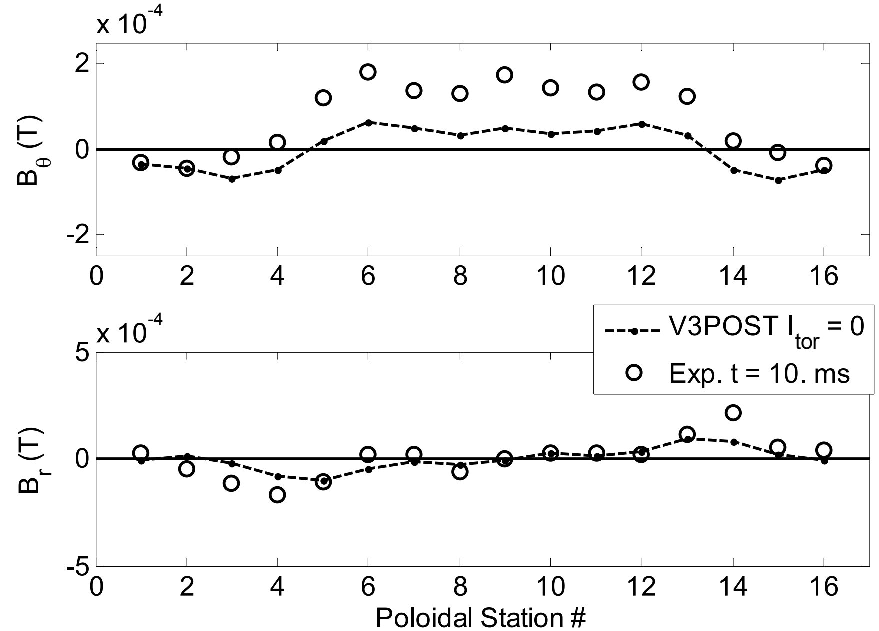
- For on-axis heating, bootstrap current rises during 50 ms ECH
- Colder plasmas with off-axis heating show saturation
- Good agreement with BOOTSJ (ORNL) for extrapolated currents
- Current direction consistent with lack of toroidal curvature

Coil array shows Pfirsch-Schlüter current dominant early in time

1/6 Field Period



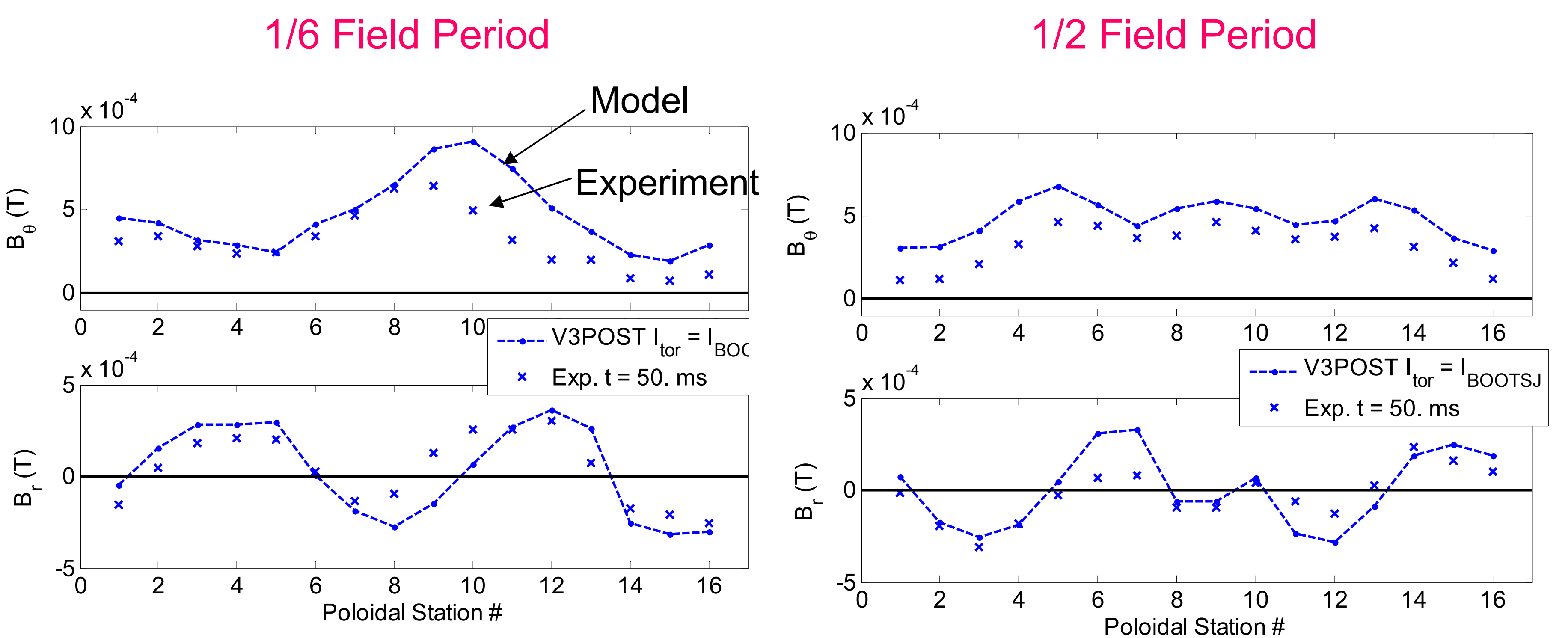
1/2 Field Period



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

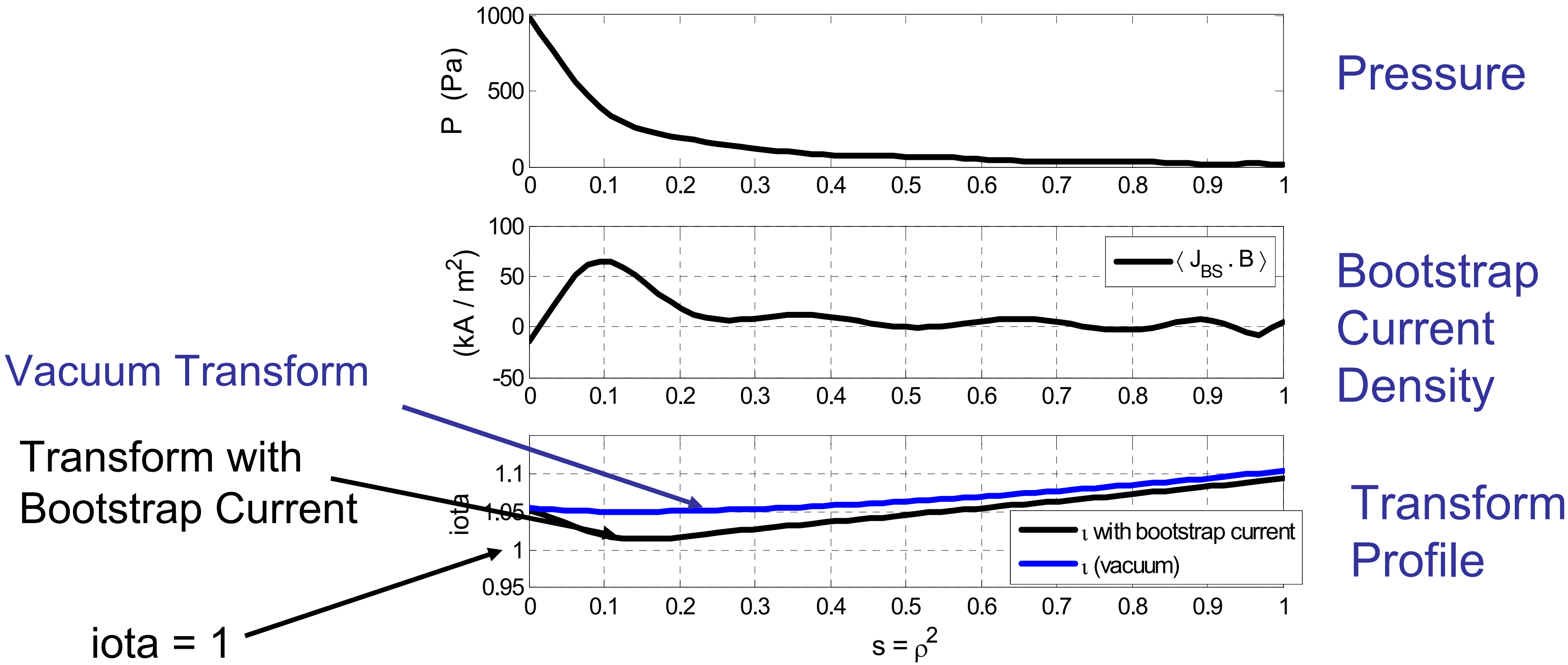
*** Special thanks to Steve Knowlton and V3FIT team! ***

Bootstrap current shows up later in time



- 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

Bootstrap current decreases transform in HSX



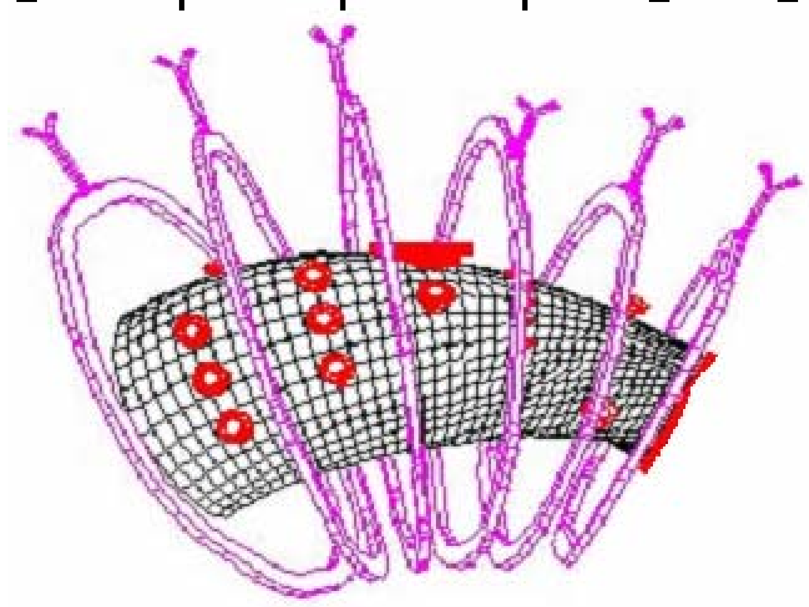
- Pressure profile from TS; current density profile from BOOTSJ
- Pressure and Current density profiles in VMEC ➔ transform profile
- With 500 A, iota is just above one ➔no instability signatures observed

Symmetry is broken with auxiliary coils

- Phasing currents in auxiliary coils breaks quasihelical symmetry (n=4, m = 1) with n = 4 & 8, m = 0 mirror terms
- Neoclassical transport and parallel viscous damping increased

\+ + + - - - 'Old' Mirror

\- + + + - - 'New' Mirror

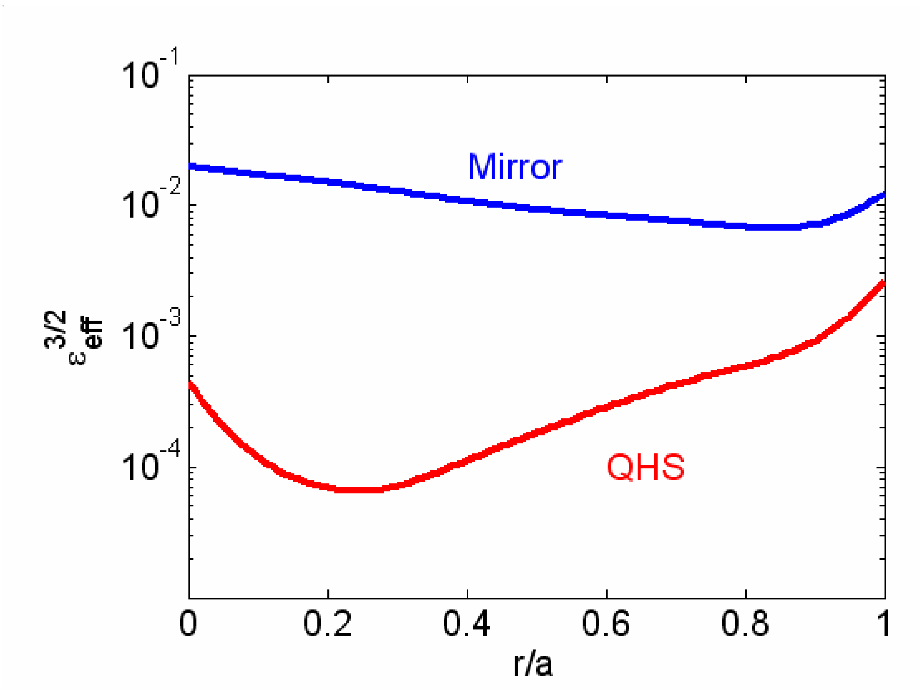


1 2 3 4 5 6

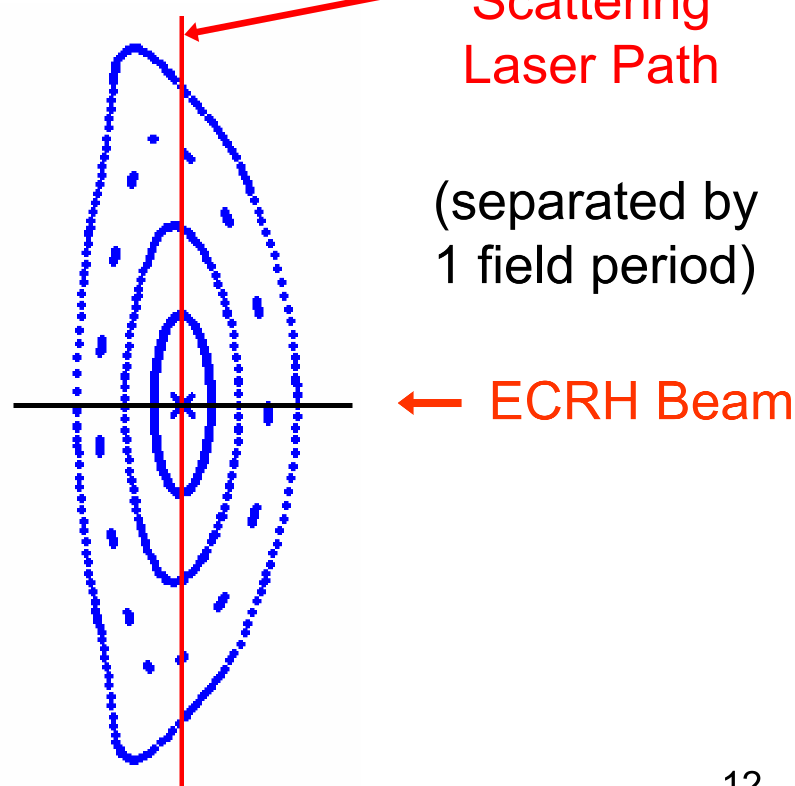
Minimal displacement of magnetic axis at ECH and TS ports

New mirror configuration increases effective ripple while keeping magnetic axis stationary

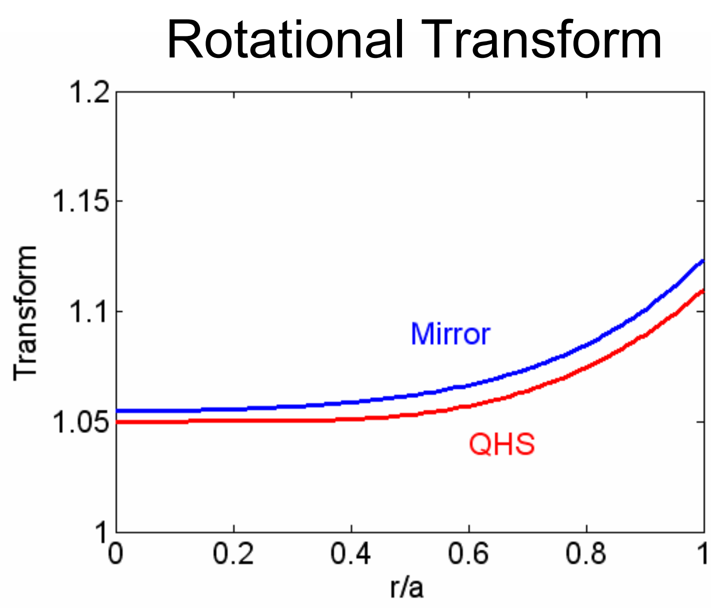
ε_{eff} increases by factor of 8 at r/a ~ 2/3

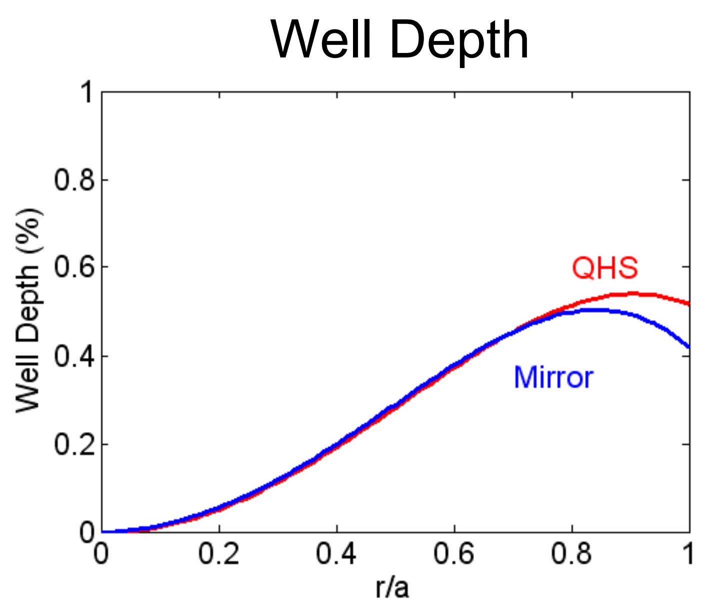


New Mirror Configuration allows for both on-axis heating and on-axis Thomson profiles



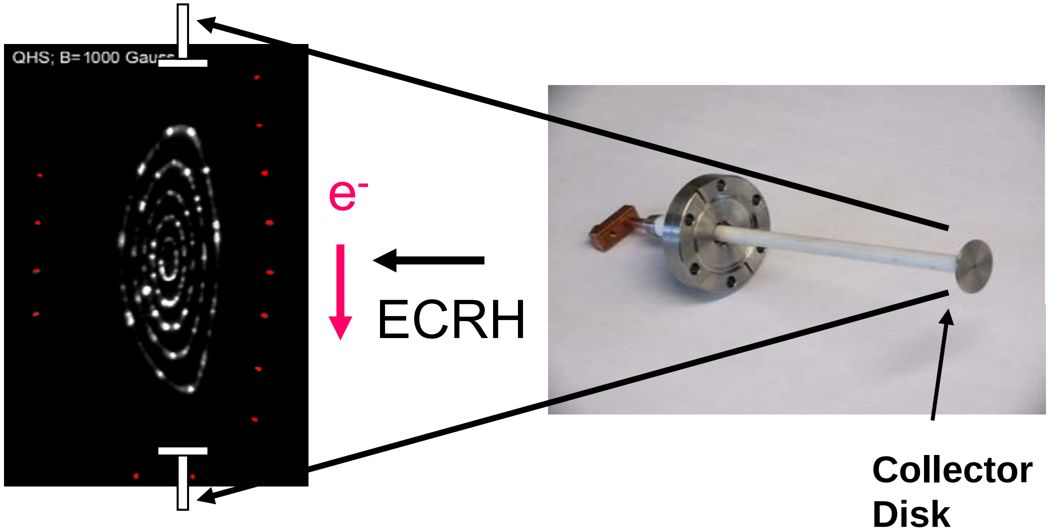
…. while transform, well depth and volume remain almost fixed



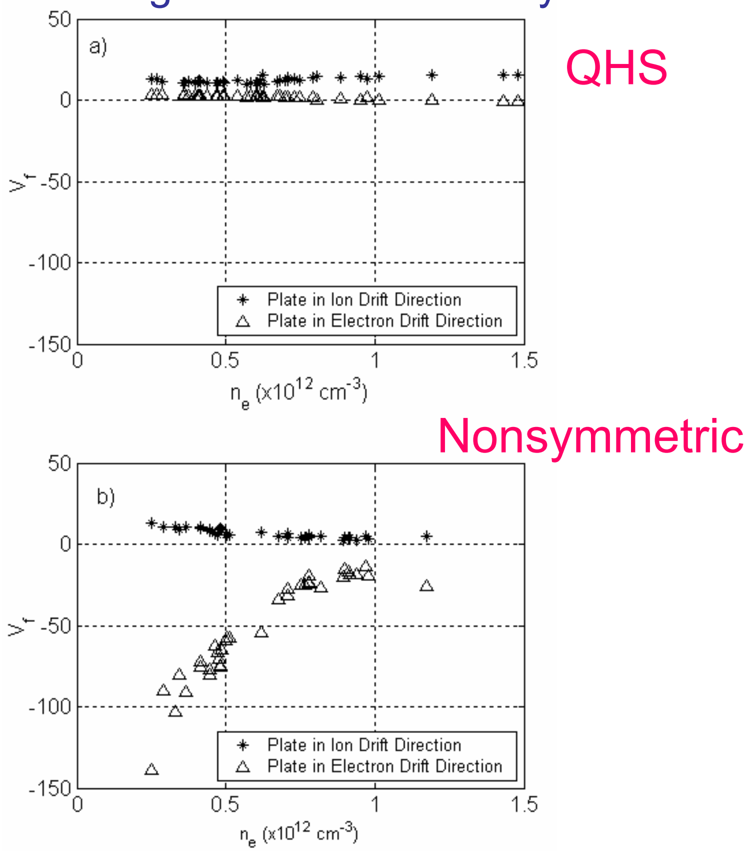


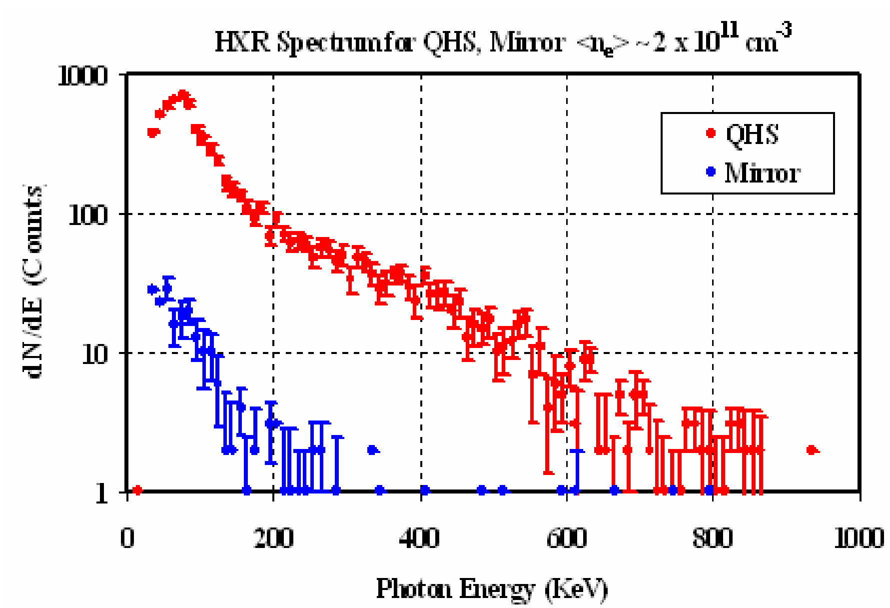
	QHS	'New' Mirror	
Transform (r/a = 2/3)	1.062	1.071	**< 1%**
Volume (m^3)	0.384	0.355	**< 10%**
Axis location (m)	1.4454	1.4447	**< 1 mm shift**
ε_{eff} (r/a = 2/3)	0.005	0.040	**factor of 8**

Good confinement of trapped particles



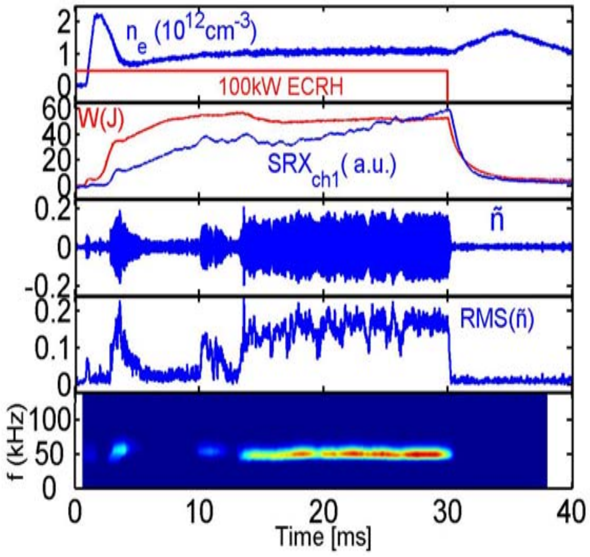
Floating Potential vs Density

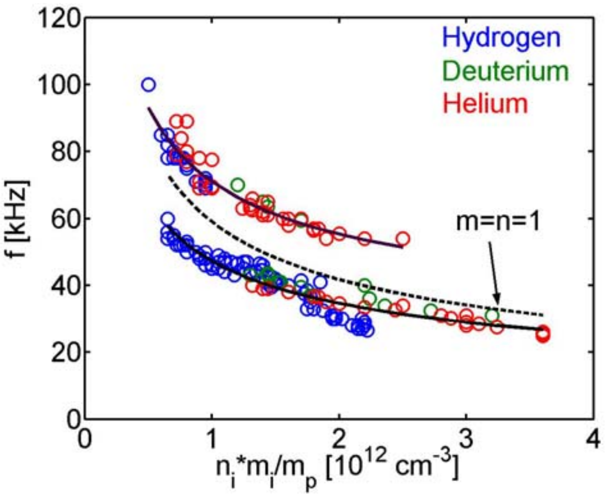




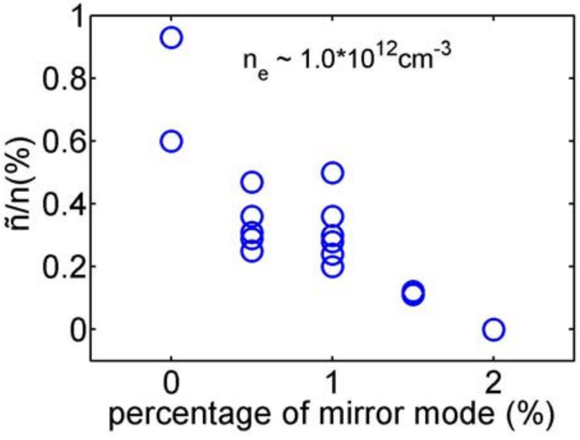
- Collector plate in direction of electron ∇B drift shows large negative potential when quasisymmetry broken.
- Larger HXR flux in QHS configuration.

BUT … global coherent mode observed at 0.5 T



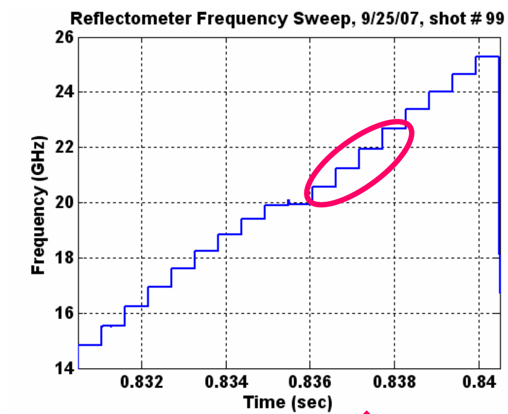


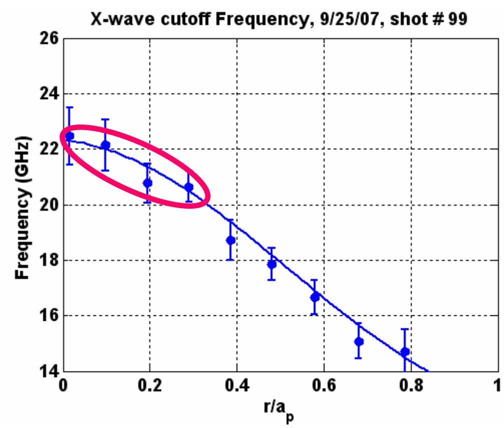
$$\omega_{GAE} \leq k_{//} v_A = \frac{(m\iota - n)}{R} \frac{B}{\sqrt{4\pi n_i m_i}}$$

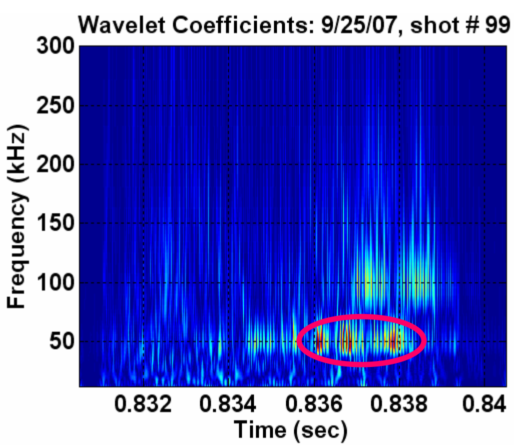


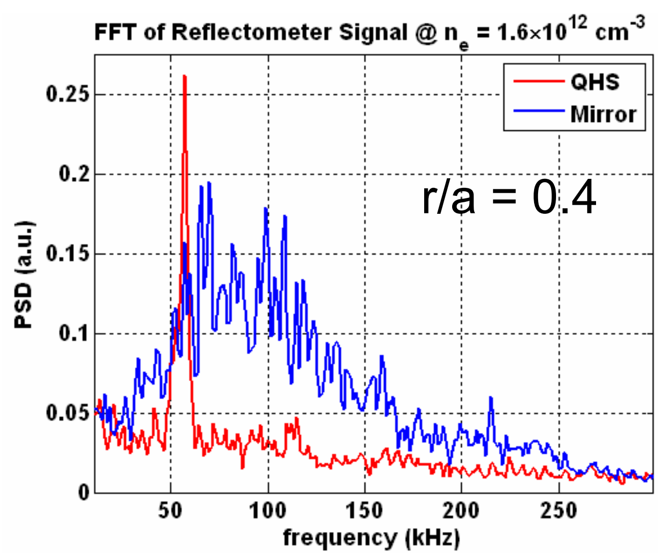
- Fluctuation observed on interferometer and magnetic coils. Absent at B = 1.0 T
- Frequency scaling with mass density consistent with Alfvenic mode
- Propagates in electron diamagnetic direction
- Amplitude decreases as quasisymmetry is degraded

First results from Reflectometer







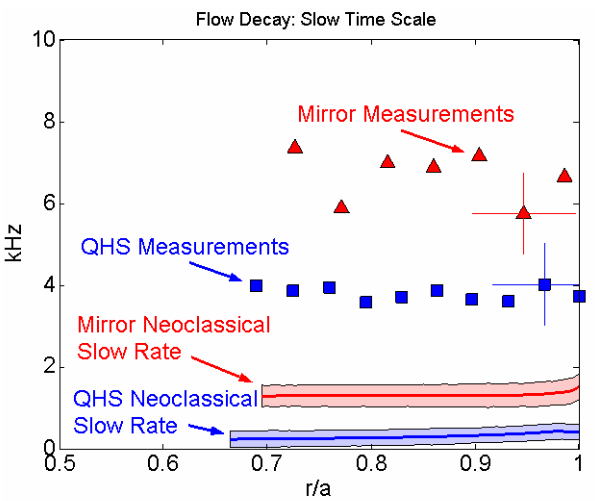


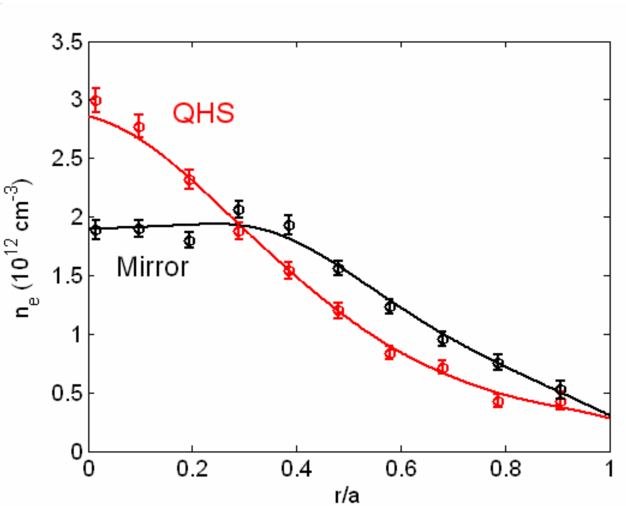
- Extraordinary mode at B = 0.5 T
- Coherent mode in QHS localized to core region
- Mode is absent at high symmetry-breaking
- Broad turbulent spectrum observed in Mirror mode

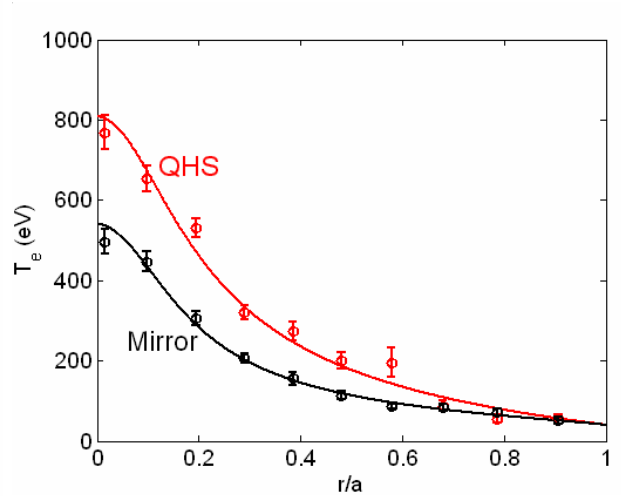
HSX has demonstrated benefits of quasisymmetry

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

Momentum	Particle	Heat







Larger flows in QHS with equivalent torque

➔ Lower parallel viscous damping

Peaked density profiles in QHS

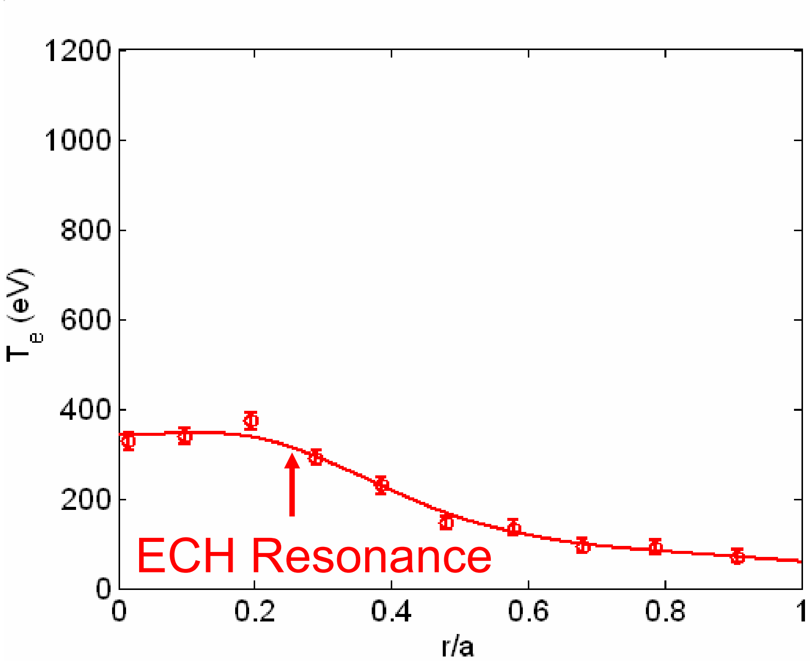
➔ Reduced thermodiffusion

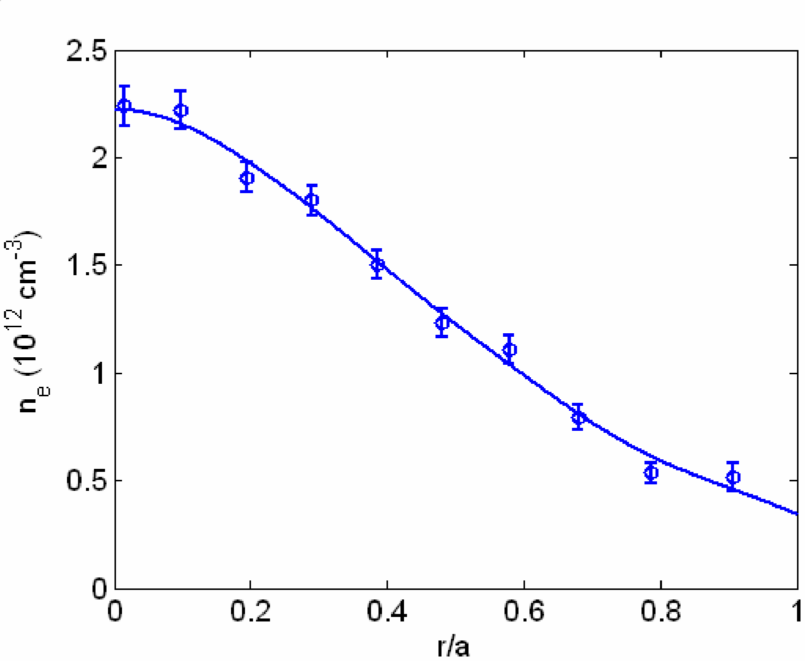
Higher T_e in QHS with same absorbed power

➔ Lower χ_e

Off-axis Heating Confirms Thermodiffusive Flux in Mirror

- With off-axis heating, core temperature is flattened
- Mirror density profile becomes centrally peaked





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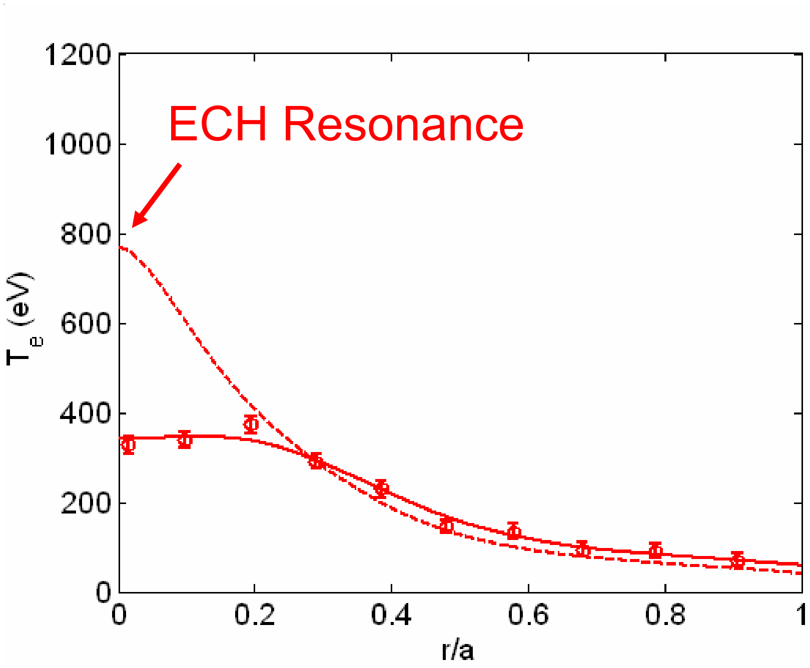
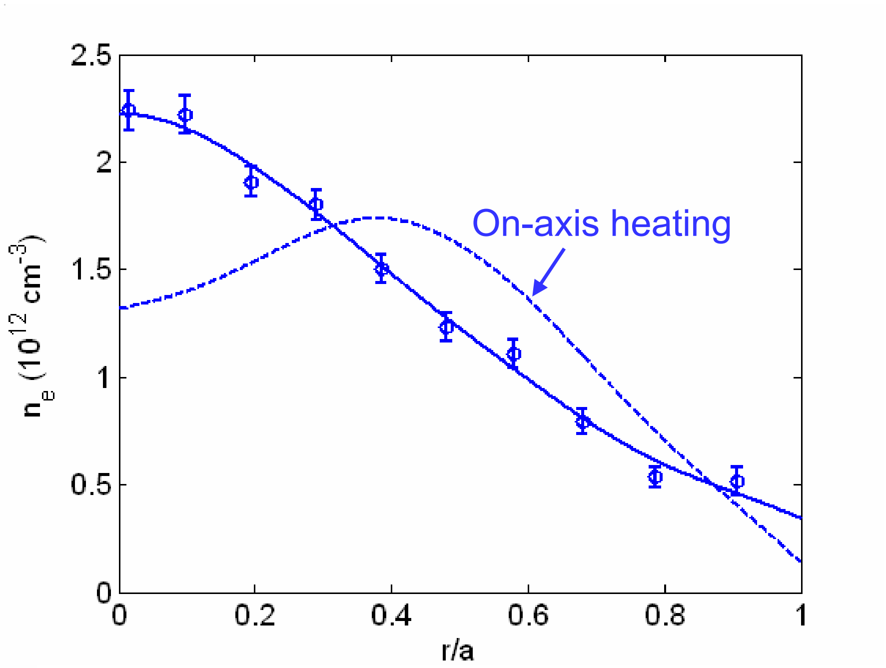
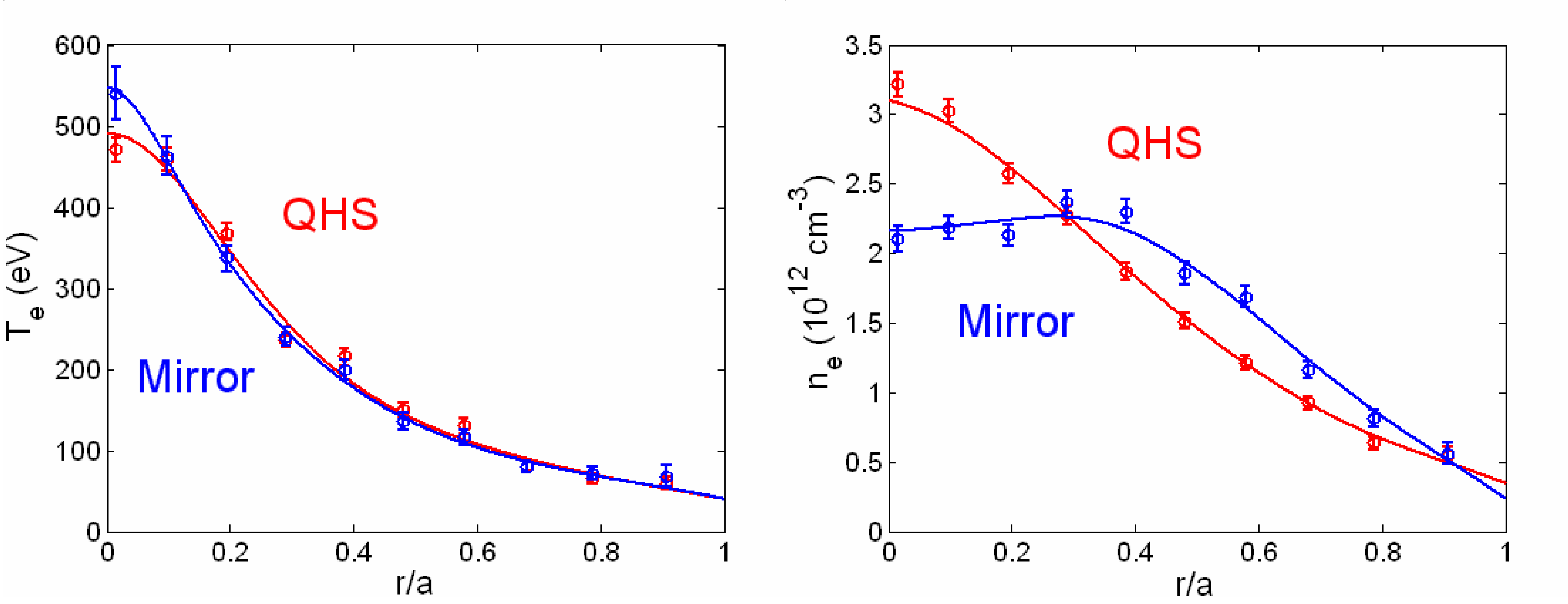




Electron temperature profiles can be well matched between QHS and Mirror

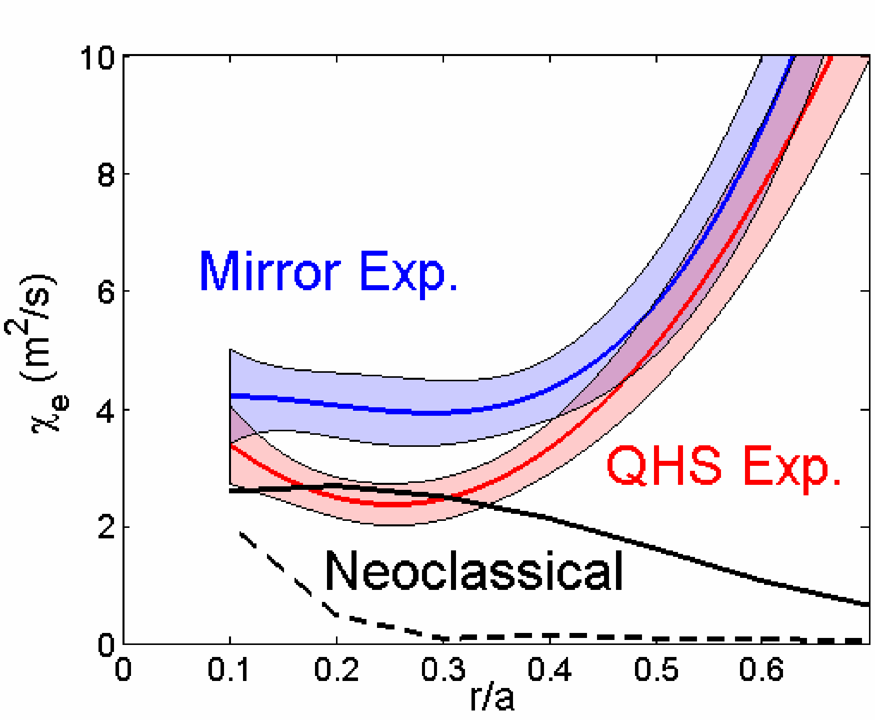
- To get the same electron temperature in Mirror as QHS requires 2.5 times the power
  - 26 kW in QHS, 67 kW in Mirror ➔ large nonthermal population at 0.5 T
  - Density profiles don't match because of thermodiffusion in Mirror



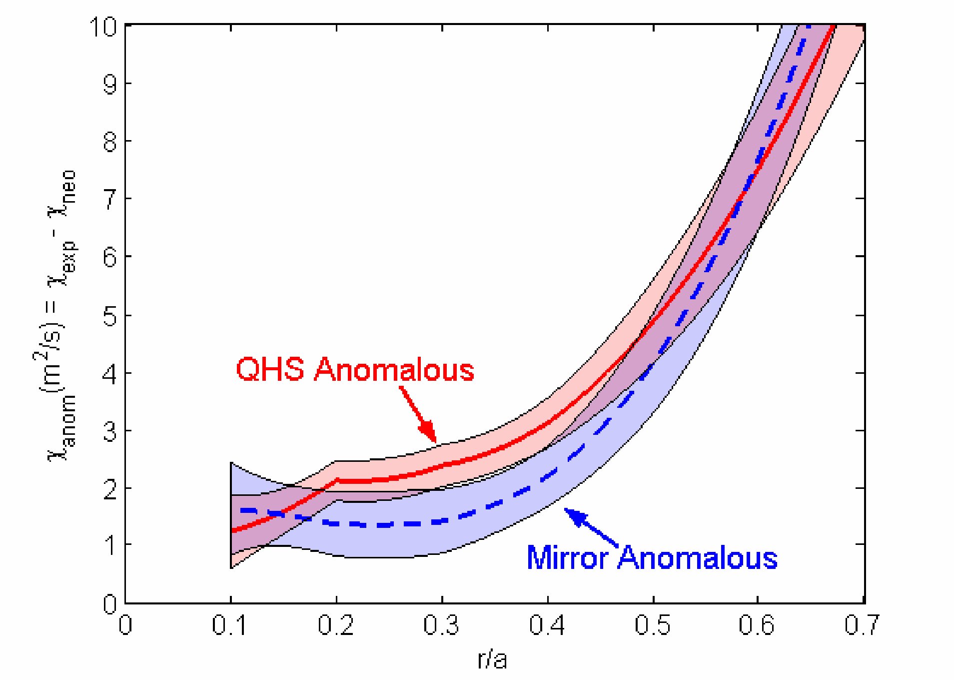
Thermal Diffusivity is Reduced in QHS

- 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

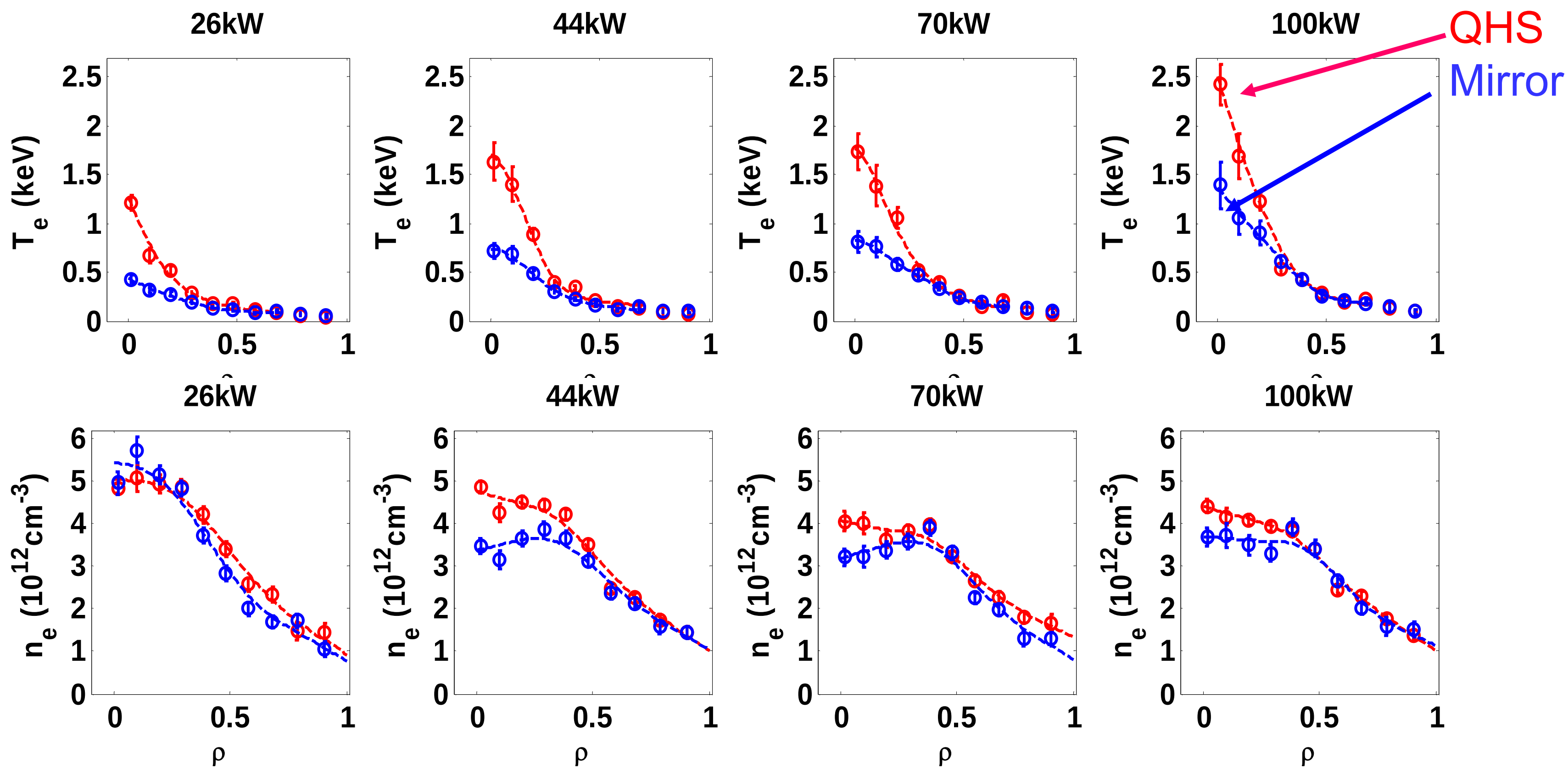


Anomalous conductivity is difference between experimental and neoclassical



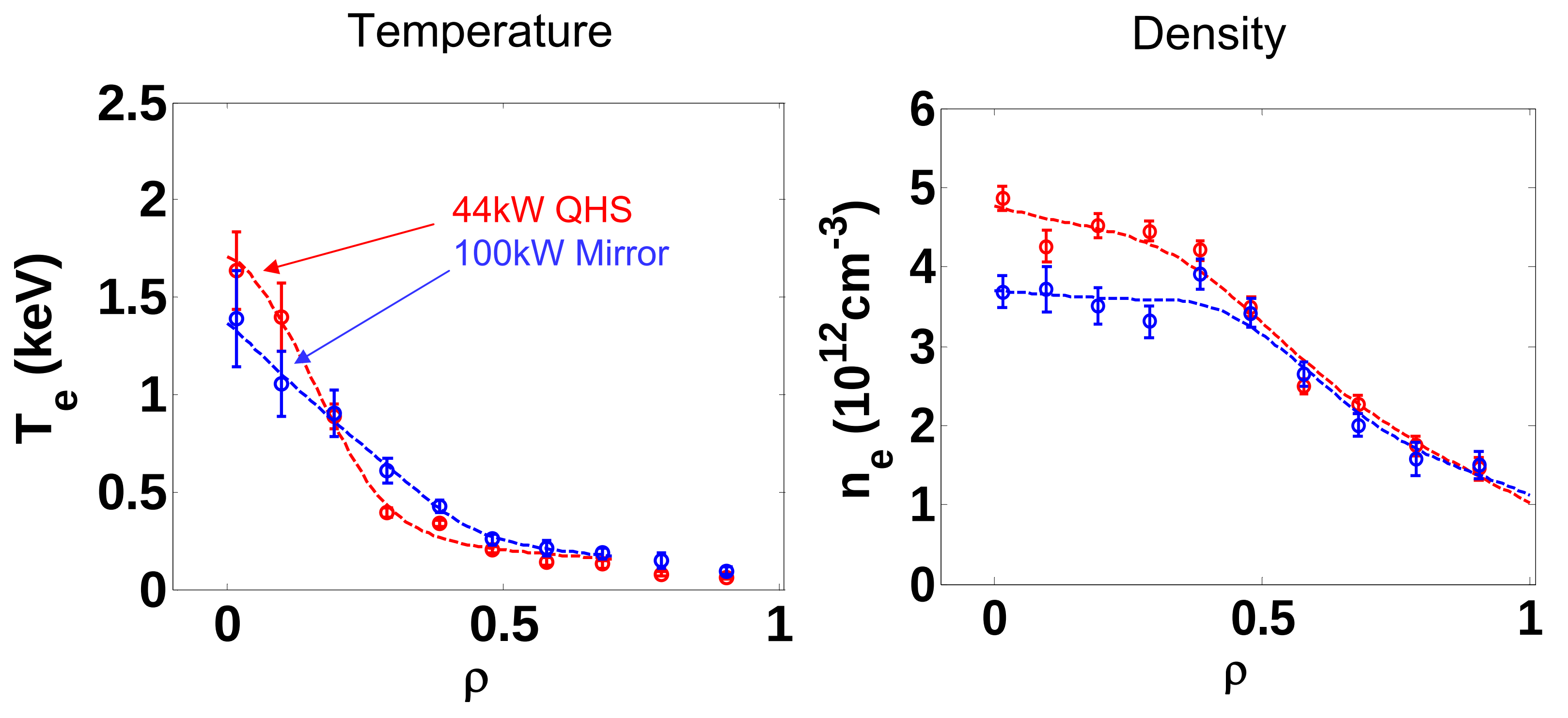
- Little difference in anomalous transport between QHS and Mirror

ECH at B = 1.0 T



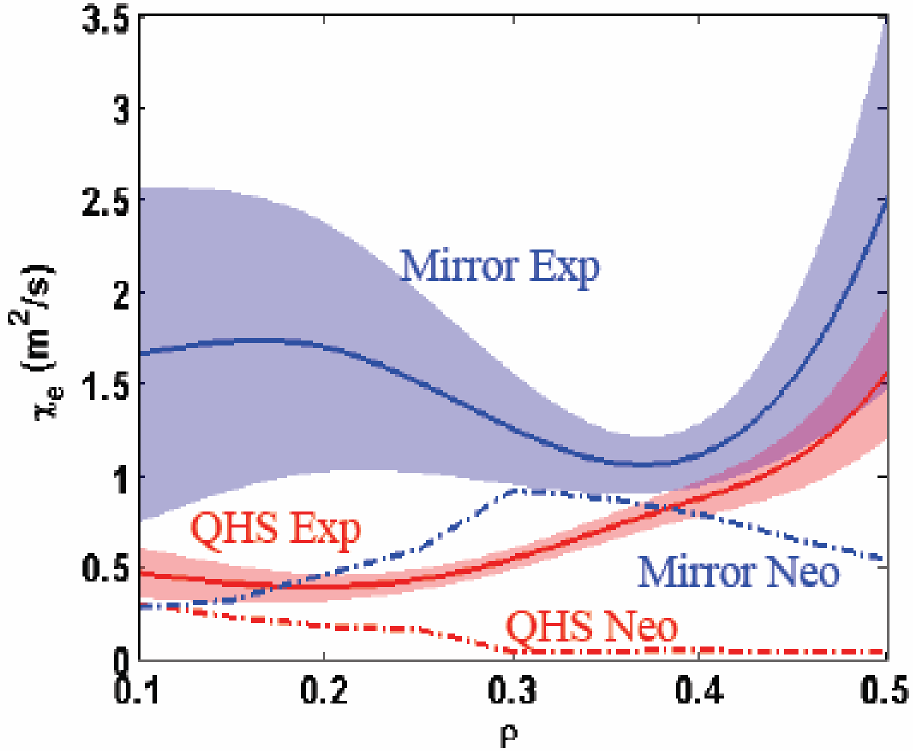
- Good agreement between kinetic and diamagnetic stored energy ➔ minimal nonthermal contribution
- Core T_e about twice as large in QHS as Mirror configuration
- Mirror density profile more hollow as T_e gradient increases

Minimum difference profiles to compare transport at B = 1.0 T



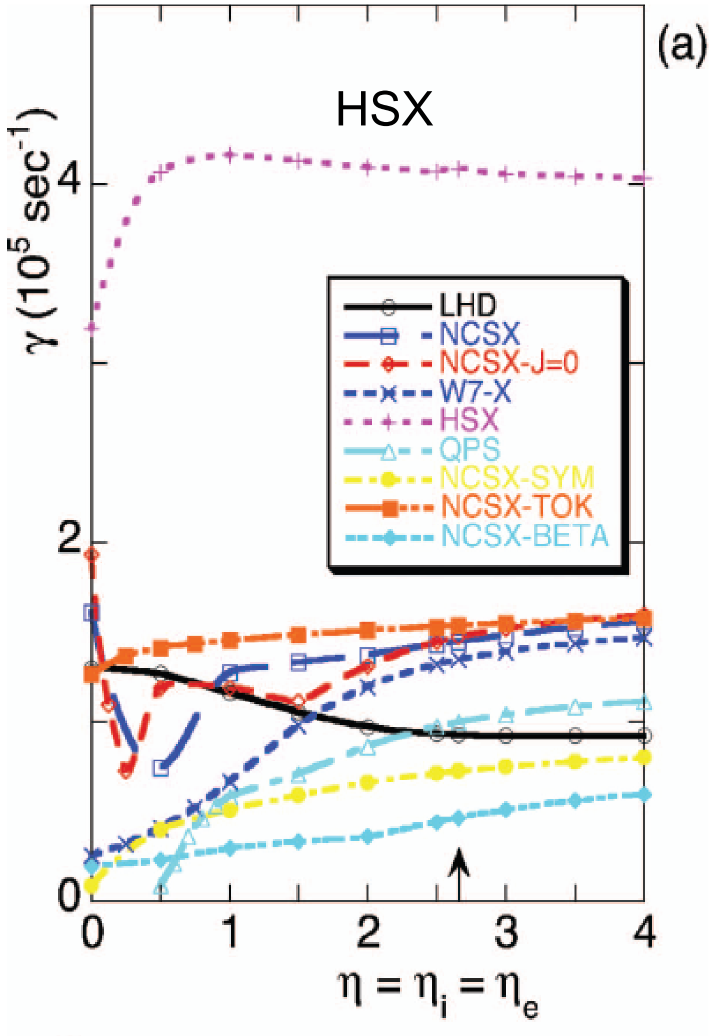
- More than twice the power in Mirror configuration to approximate the temperature profile
- Density profile still slightly more peaked in QHS than Mirror

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:
- Neoclassical calculation is being redone using Spong's PENTA code

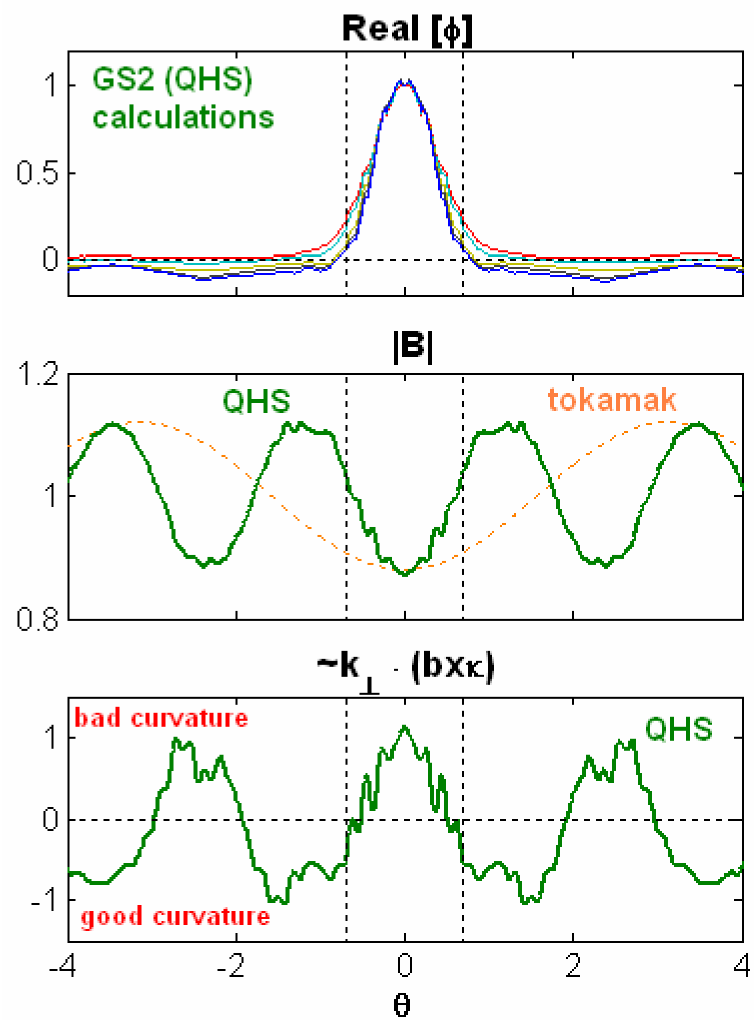
Can we model anomalous transport in HSX?



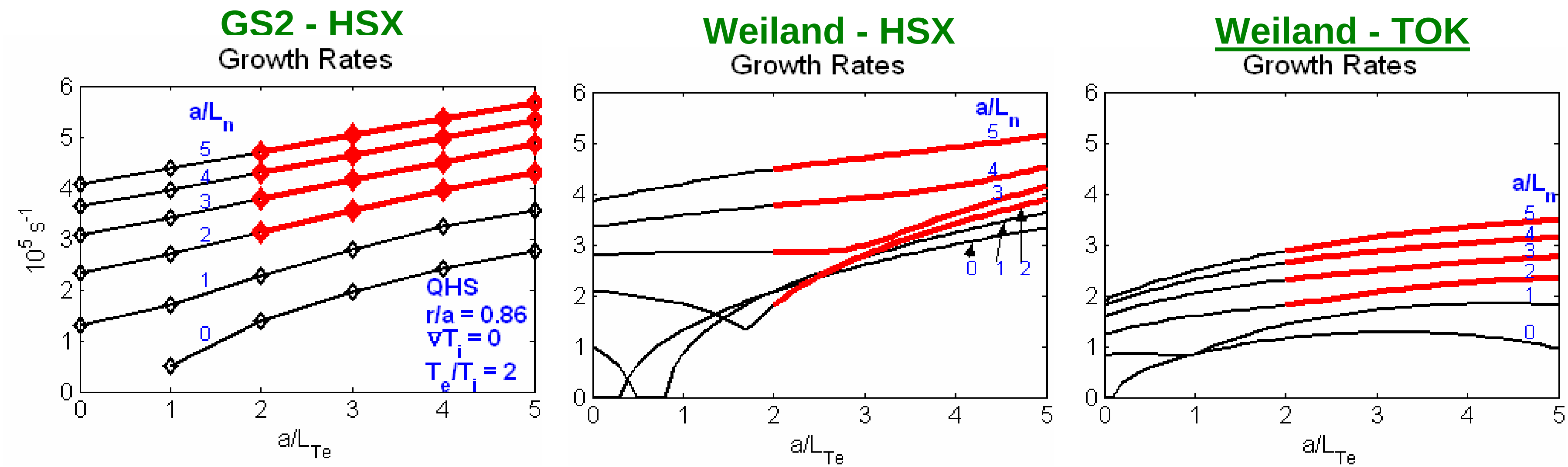
- Rewoldt '05 using FULL code showed HSX had largest linear growth rate to ITG/TEM modes compared to LHD, W7-X, NCSX, QPS
- Goal is to apply predictive transport modeling to HSX using multi-mode approach
- Neoclassical transport based on DKES, anomalous transport based on Weiland analytic model

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 ($0.14 \cdot r/a = 1.4 \cdot r/R$)
- 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 $\rightarrow$ 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, $R/L \rightarrow (R/3)/L$



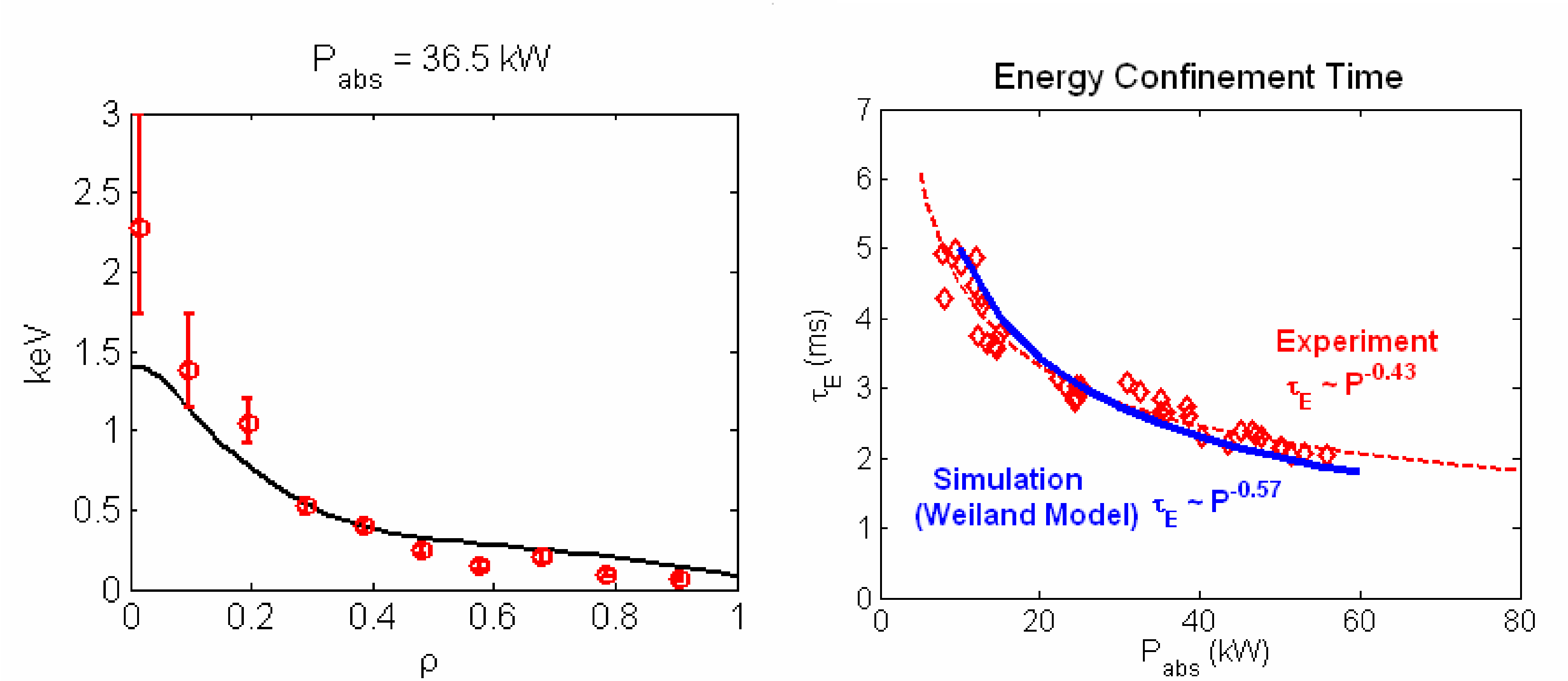
Weiland model with simplified assumptions benchmarked against GS2 code



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

- Weiland growth rates 2$\times$ smaller without “quasisymmetric” approximation

Model predicts gross features of T_e profile and confinement scaling



- Weiland model, with geometry approximations, gives reasonable fit to temperature profile.
- Captures the scaling and magnitude of confinement times at B = 1.0 T

Near Term Plans

• Emphasis in near term will be to measure flows and radial electric field and compare to neoclassical modeling ➔ diagnostic neutral beam mounted on HSX for CHERS

• Compare experimental data to Spong's PENTA code. How important is it to solve 2 momentum balance equations on flux surface for a quasisymmetric plasma? How do changes in effective ripple affect E_r?

• Compare reflectometer measurements of turbulence at plasma core for QHS versus Mirror at 1 T. How important are differences in trapped particle fraction and E x B shear?

• Novel low-cost HIBP system being developed with RPI

• Model time evolution of neoclassical currents and compare to measurements for different magnetic geometries.

• Obtain ion root plasma for Mirror to maximize differences with QHS configuration of neoclassical and possibly anomalous transport

Conclusions

- Lack of toroidal curvature verified by
  - grad-B drift of passing particle
  - 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

Conclusions

- ECH at B = 0.5 T
  - Reduction of particle, momentum and heat transport with quasisymmetry
  - Large themodiffusive flux in Mirror yields hollow density profiles, reduction of neoclassical in QHS results in peaked density profile.
- ECH at B = 1.0 T
  - Nonthermal component is small
  - T_e up to 2.5 keV is observed
  - Multi-mode model of neoclassical + modified Weiland for anomalous agrees well with temperature profile and confinement time.

➔Quasihelically symmetric configuration improves neoclassical transport. Initial results suggests anomalous transport may be high.