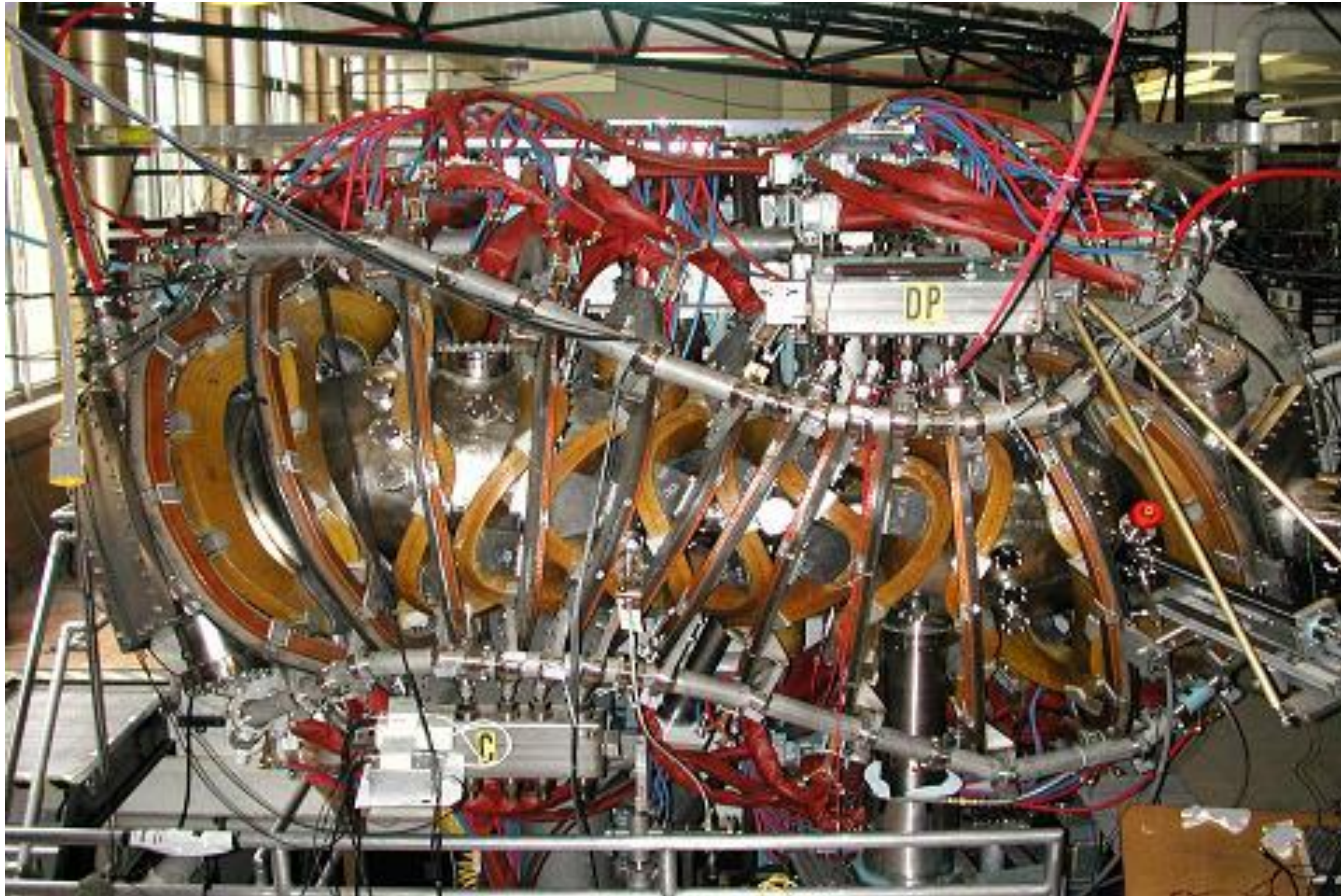


Experimental Tests of Quasisymmetry in HSX

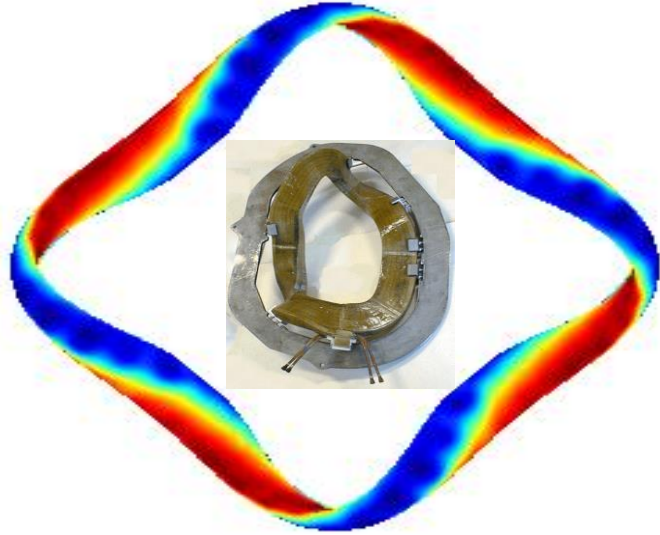


J.N. Talmadge
*HSX Plasma Laboratory
UW-Madison*

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 simulation → Large curvature drives TEM
 - ❑ Good model for temperature profile and confinement scaling
- Future Plans and Conclusions

Quasihelical stellarators have high effective transform



Quasihelical: Fully 3-D, BUT

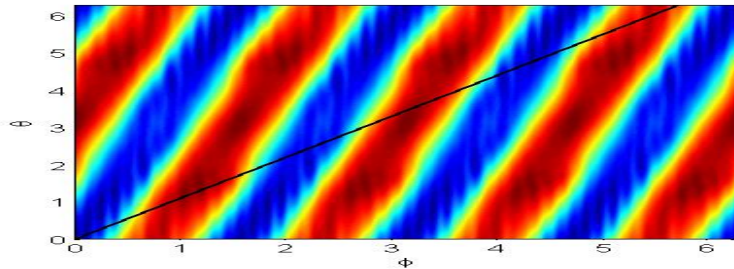
Symmetry in $|B|$: $B = B_0 [1 - \varepsilon_h \cos(N\phi - m\theta)]$

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

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

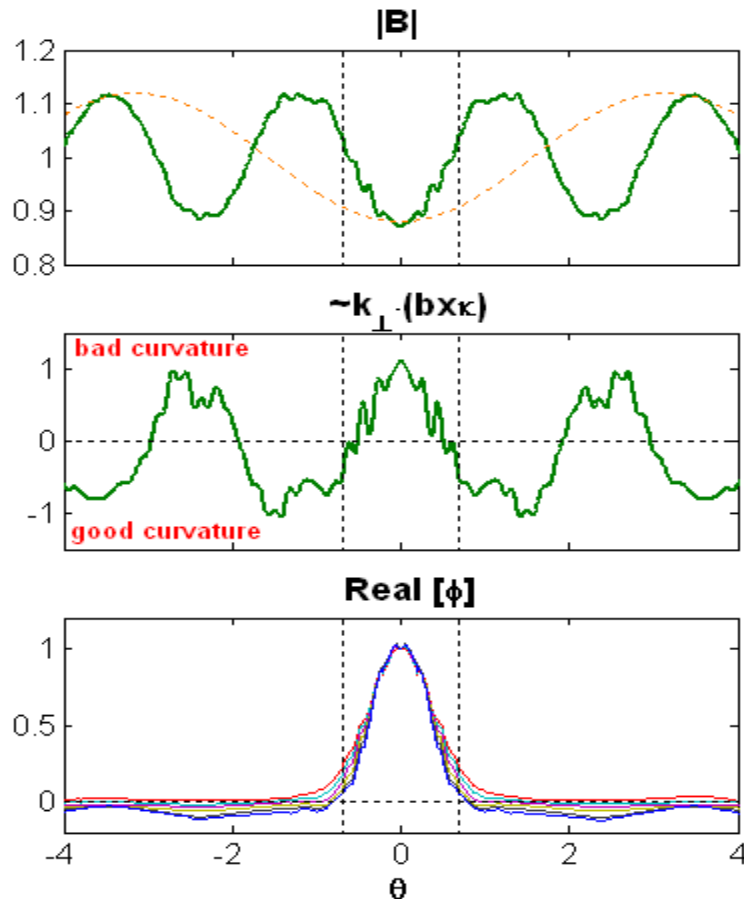
In HSX: $N=4$, $m=1$, and $\iota \sim 1$

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



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

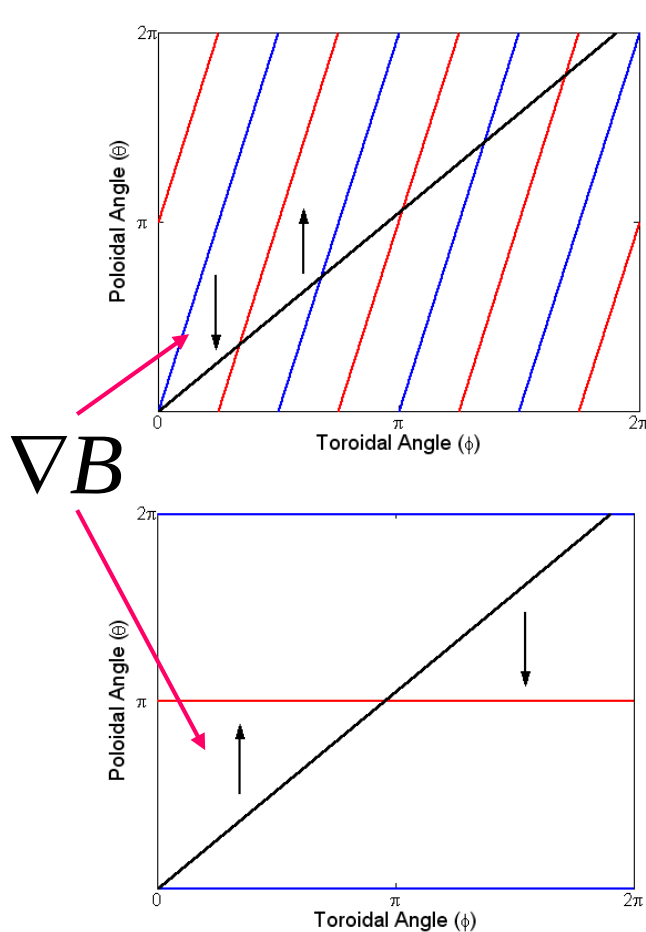
High effective transform is beneficial for neoclassical – how does it affect anomalous transport?



Consequences of high effective transform:

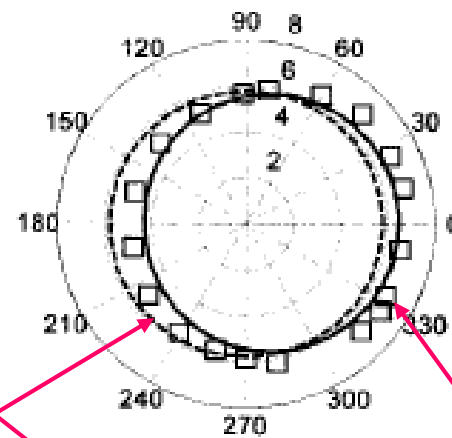
- Small drift of passing particles from flux surface
- Pfirsch-Schlüter and bootstrap currents are reduced in magnitude
- Easy to achieve low collisionality plasmas
- Small banana orbits; very low neoclassical transport
- Large curvature, short connection length
➔ is there evidence that anomalous transport might be large?

Lack of toroidal curvature verified by passing orbit measurements



HSX

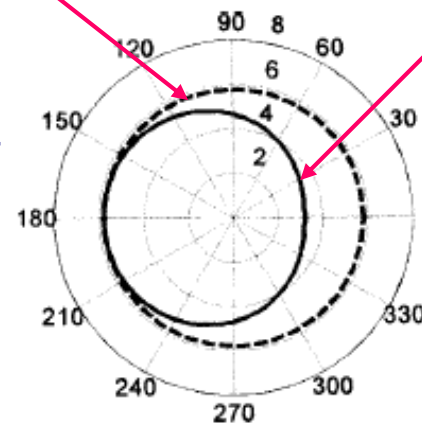
Equivalent Tokamak



Electron orbits mapped into Boozer coordinates

Flux Surface

Drift Orbit



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

High effective transform reduces Pfirsch-Schlüter and bootstrap current

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).

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

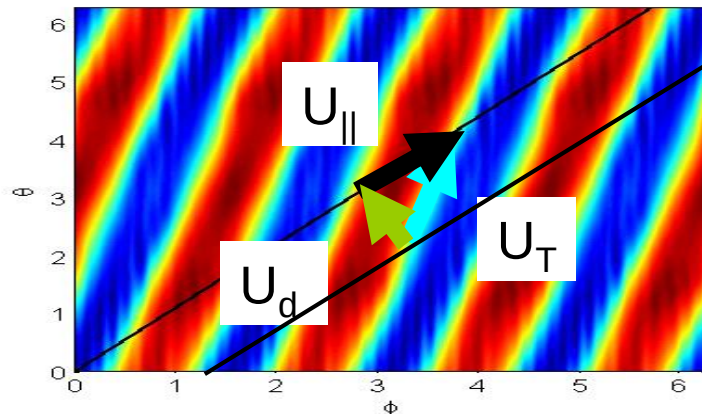
Bootstrap current:

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

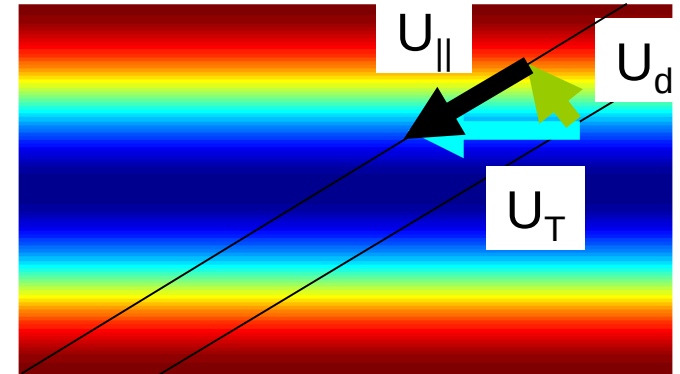
$$J_B \sim 1.46 \sqrt{b_{nm}} \frac{m}{n - m\iota} \frac{g}{B_0} [\text{gradients}]$$

Boozer, '82 '92

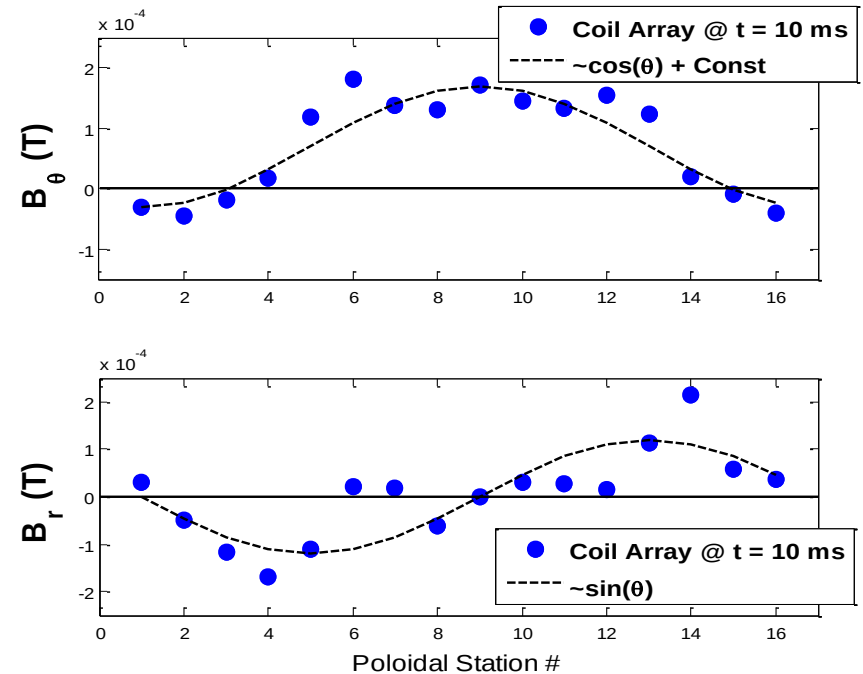
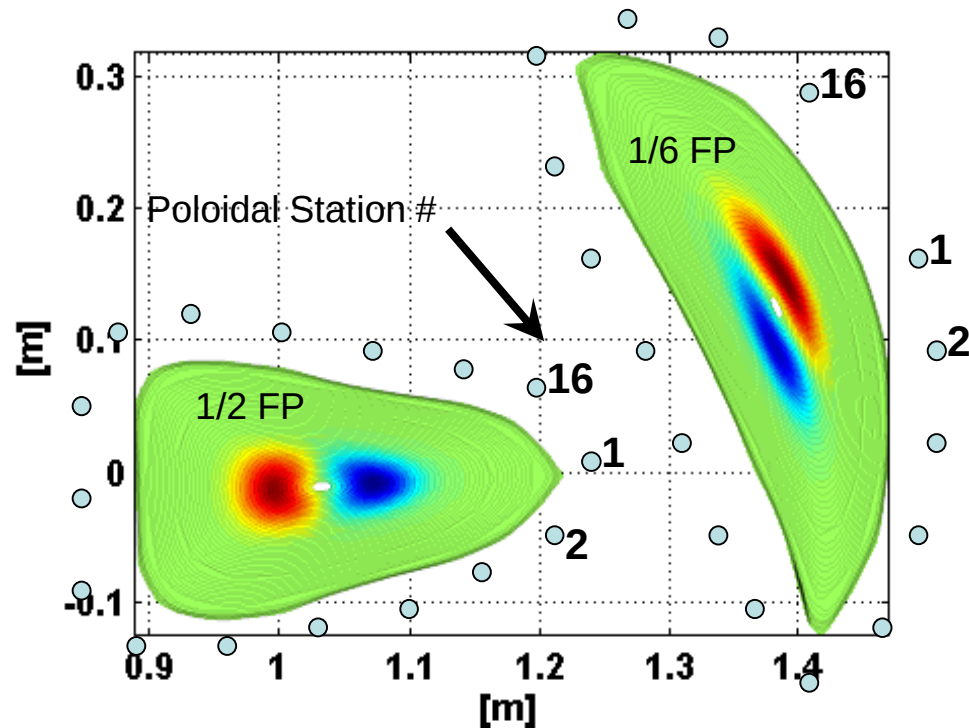
HSX



Tok

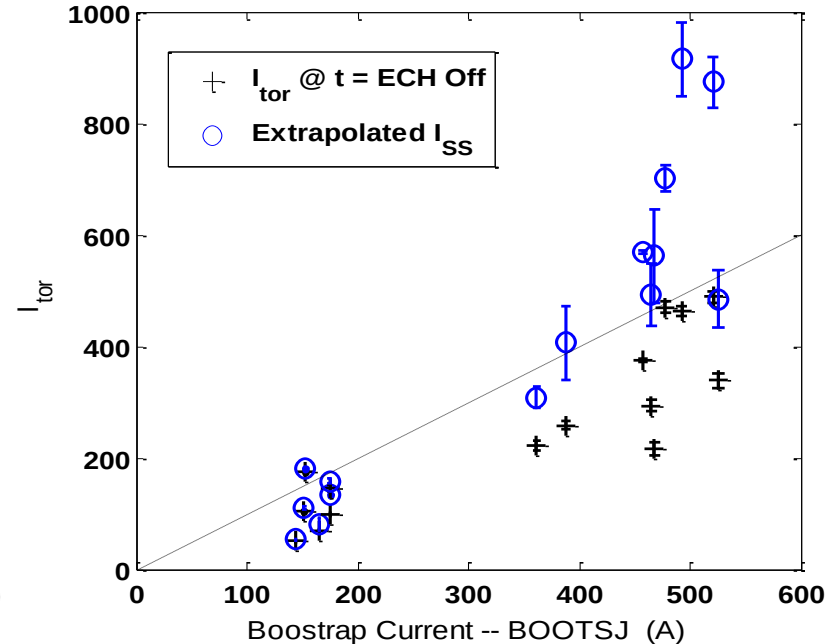
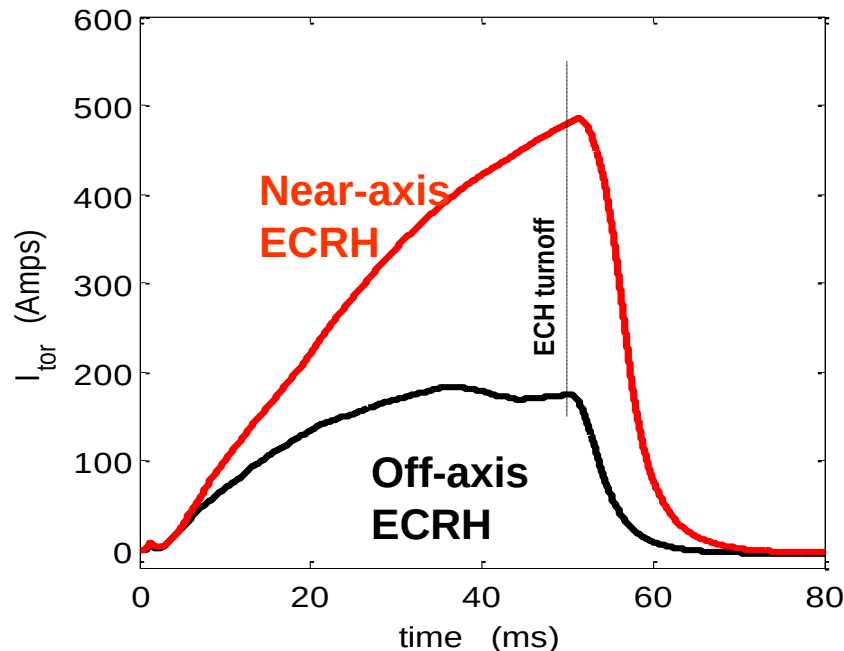


3 axis coils measure current evolution at two toroidal locations



- 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 $B_r \sim \sin \theta$

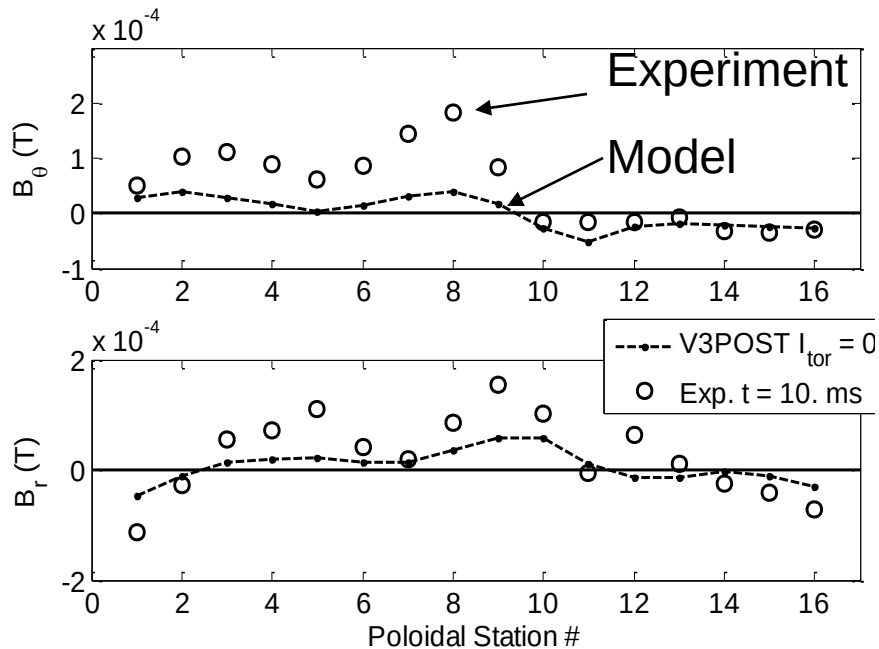
Rogowsky confirms bootstrap current unwinds transform



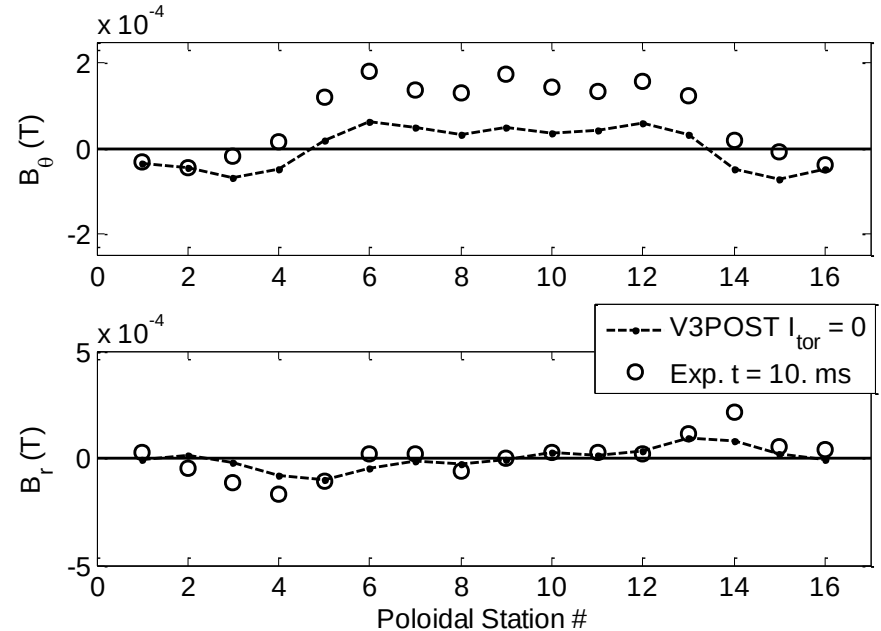
- For on-axis heating, bootstrap current rises during 50 ms ECH
- Colder plasmas with off-axis heating show saturation
- Good agreement with BOOTSJ (ORNL) for extrapolated currents
- Current direction consistent with lack of toroidal curvature

Coil array shows Pfirsch-Schlüter current dominant early in time

1/6 Field Period



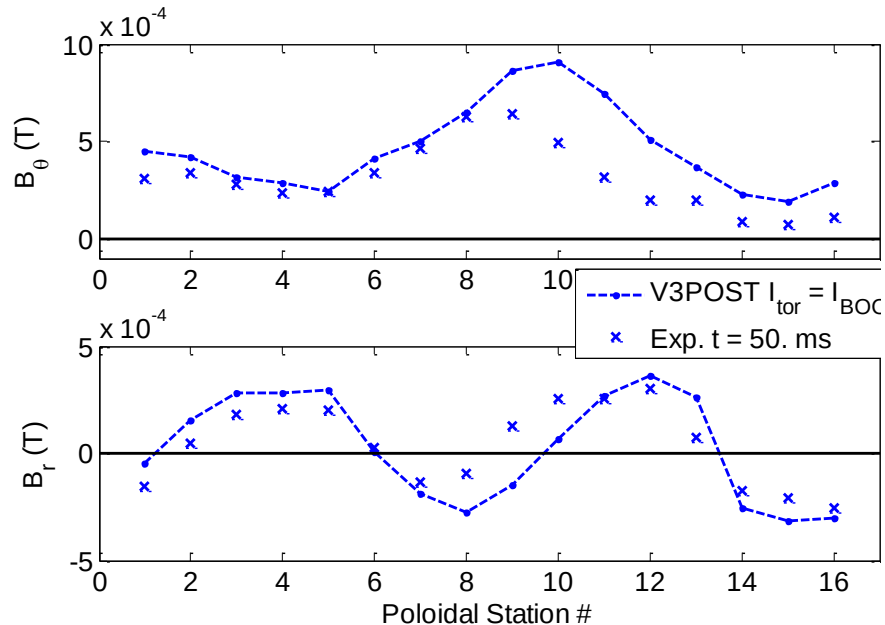
1/2 Field Period



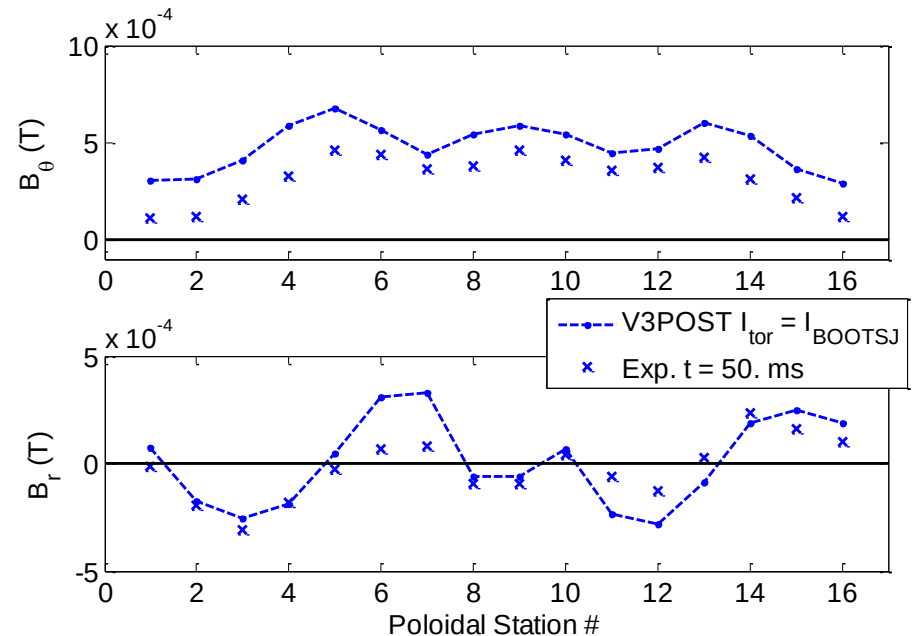
- Early time $t = 10$ ms $\rightarrow I_B = 0$ in model
- Bootstrap current probably underestimated

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 $\rightarrow I_B = \text{BOOTSJ}$ value (overestimated)
- Helical PS current evident in reversal of B_r

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

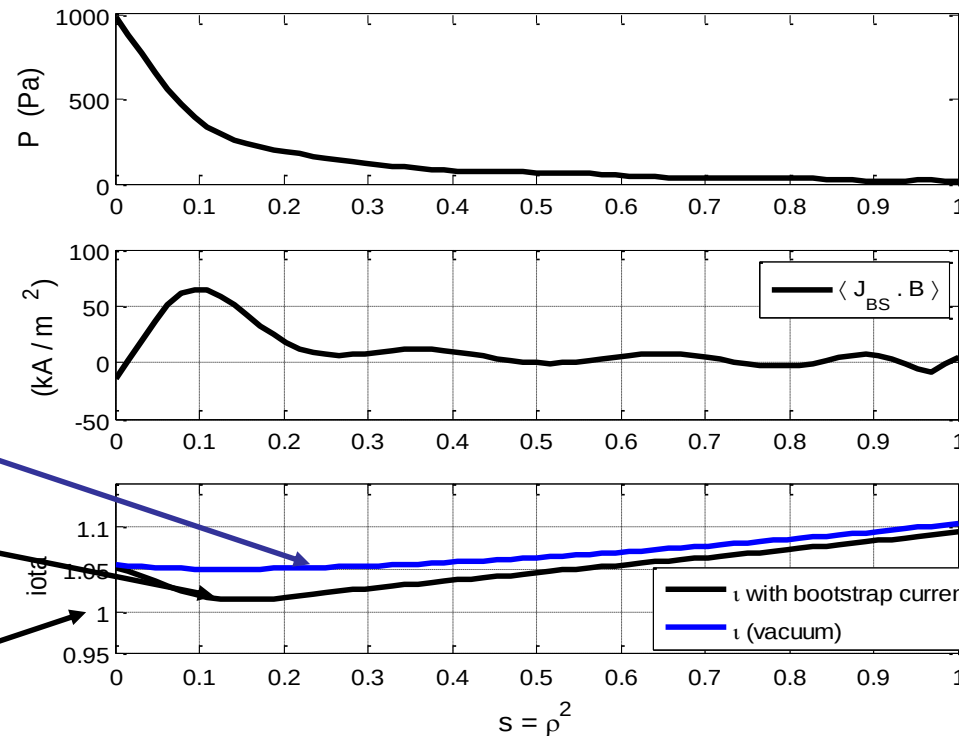
Bootstrap current decreases transform in HSX

See Schmitt poster
Wednesday

Vacuum Transform

Transform with
Bootstrap Current

$\iota = 1$



Pressure

Bootstrap
Current
Density

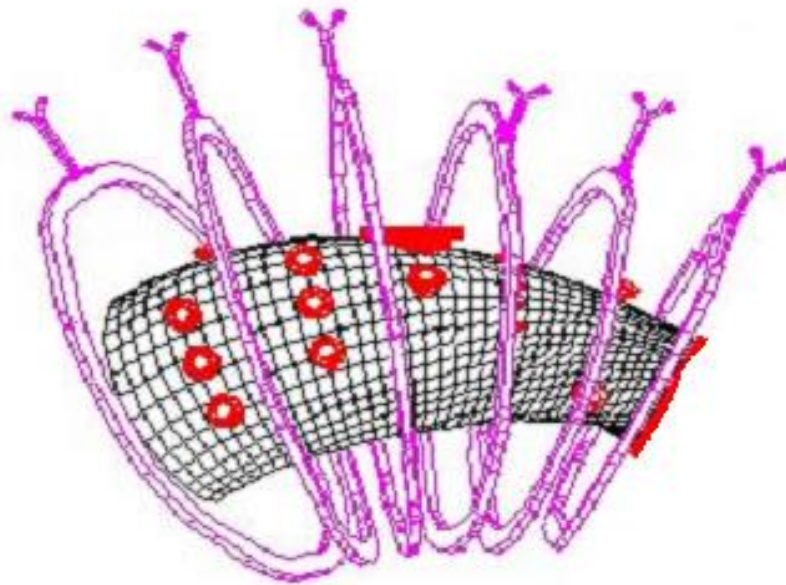
Transform
Profile

- Pressure profile from TS; current density profile from BOOTSJ
- Pressure and Current density profiles in VMEC → transform profile
- With 500 A, ι 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



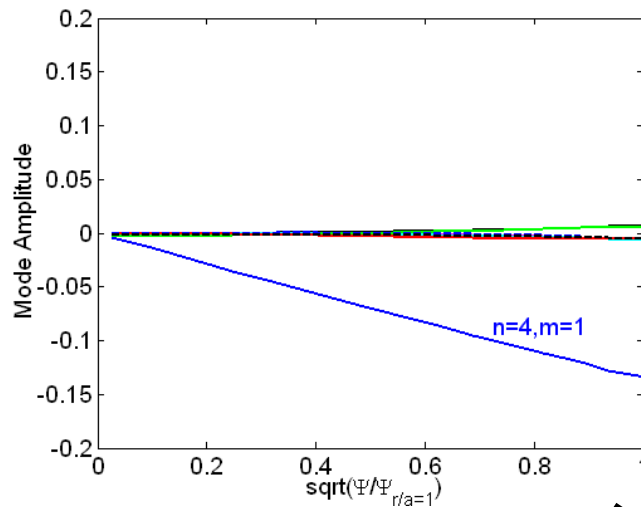
1 2 3 4 5 6

Minimal displacement
of magnetic axis at
ECH and TS ports

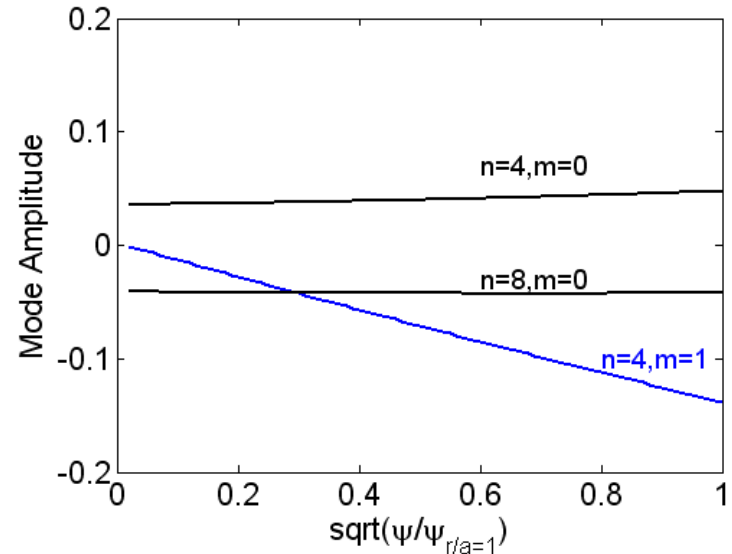
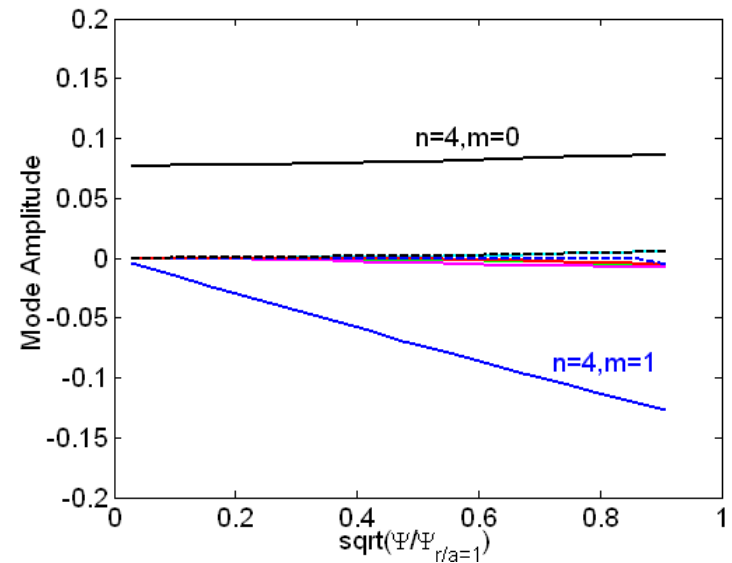
'New' mirror excites $n = 4$ and $8, m=0$ modes

'Old' Mirror

QHS

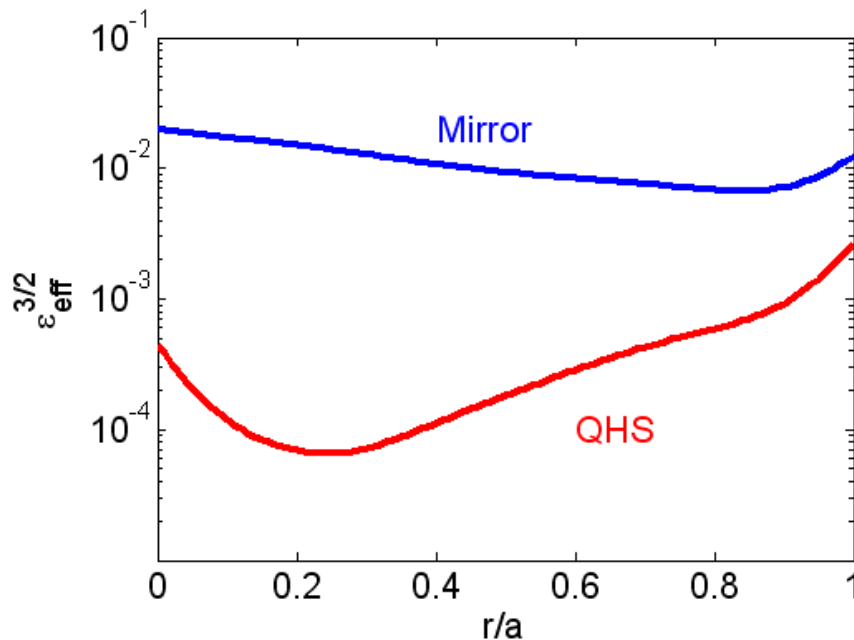


'New' Mirror

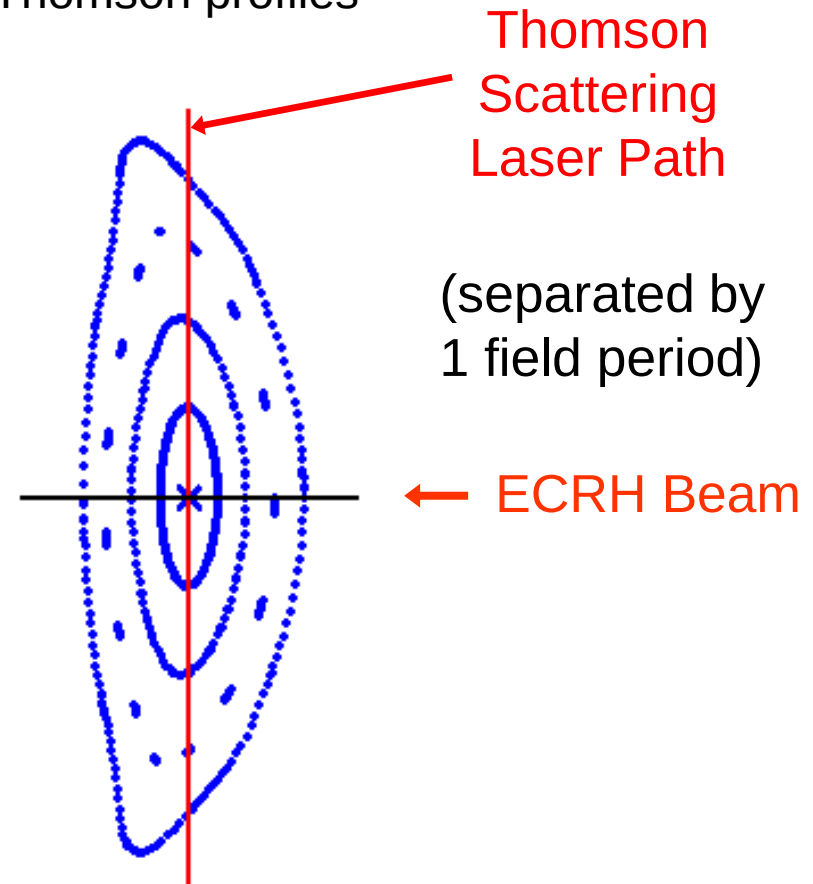


New mirror configuration increases effective ripple while keeping magnetic axis stationary

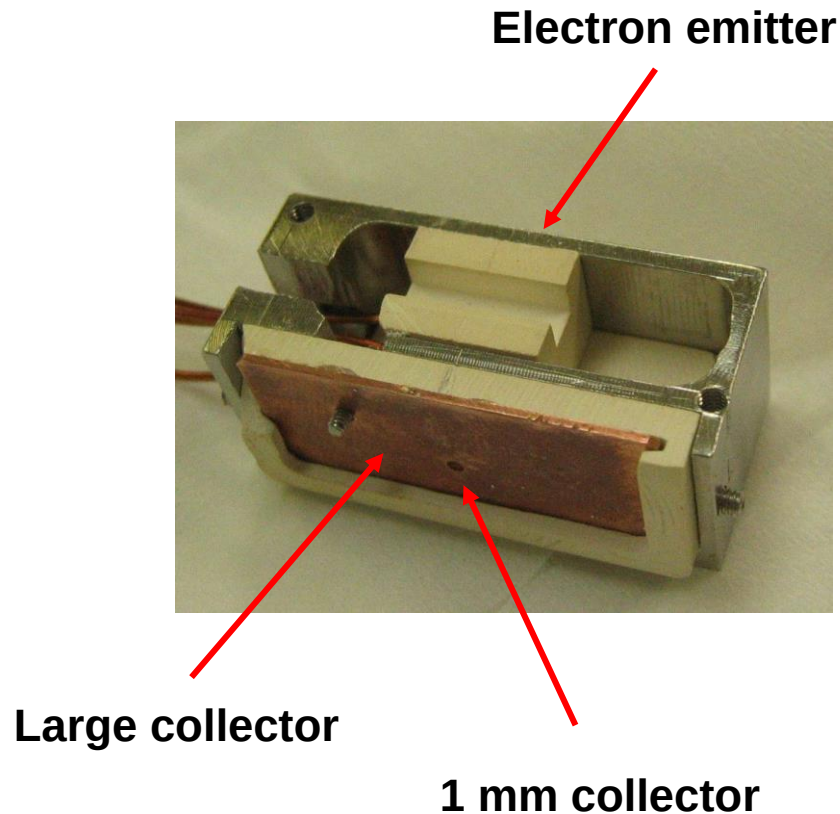
ϵ_{eff} increases by factor of 8
at $r/a \sim 2/3$



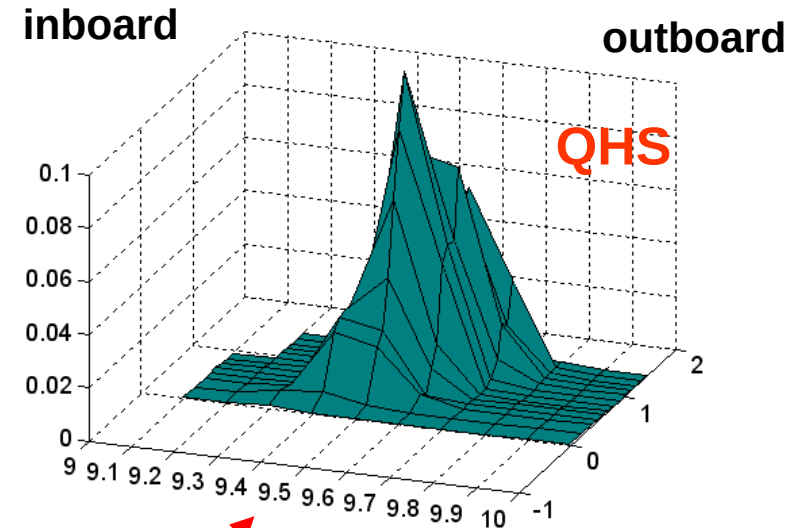
New Mirror Configuration allows for
both on-axis heating and on-axis
Thomson profiles



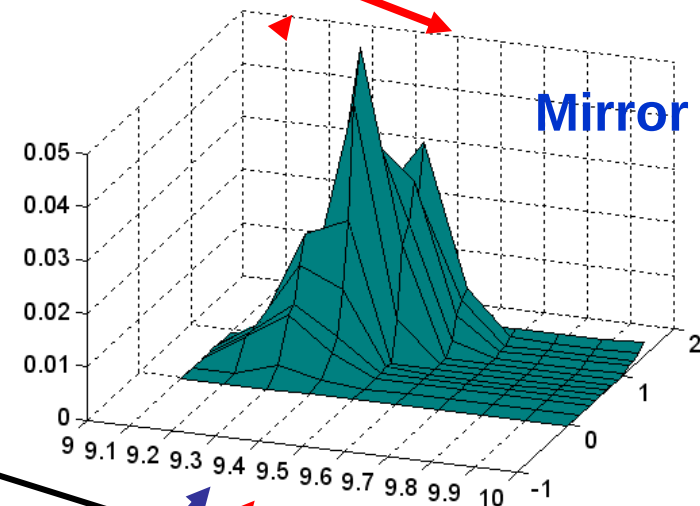
Verification of ~ 1 mm shift in magnetic axis



1 mm Shift



QHS peak

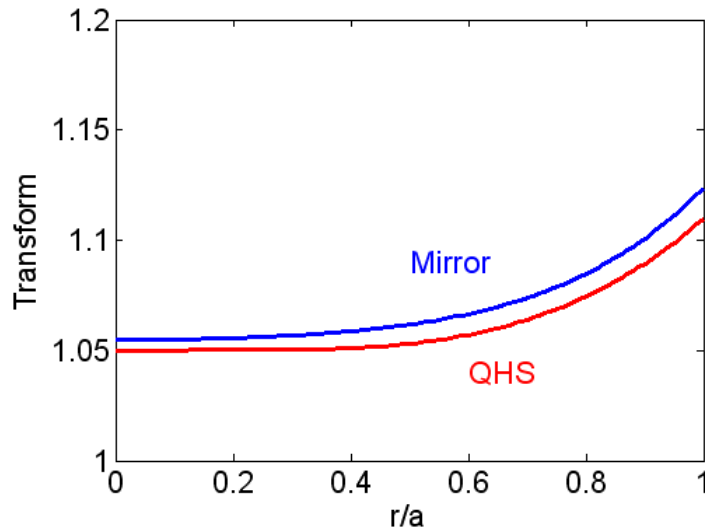


Mirror peak

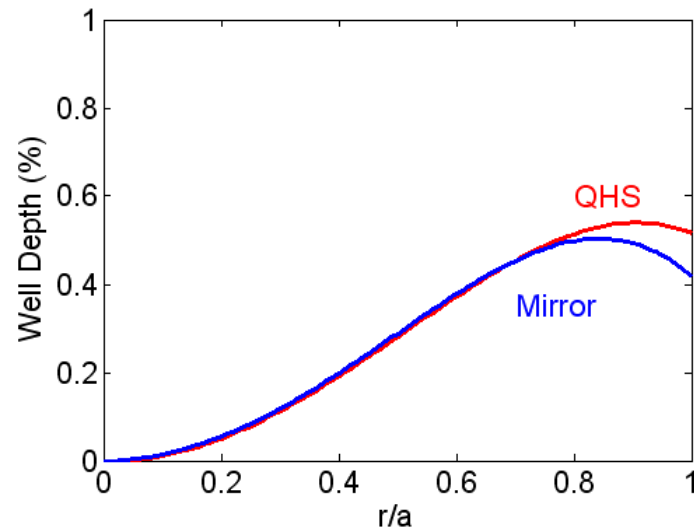
QHS peak

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

Rotational Transform



Well Depth



	QHS	'New' Mirror
Transform ($r/a = 2/3$)	1.062	1.071
Volume (m^3)	0.384	0.355
Axis location (m)	1.4454	1.4447
ϵ_{eff} ($r/a = 2/3$)	0.005	0.040

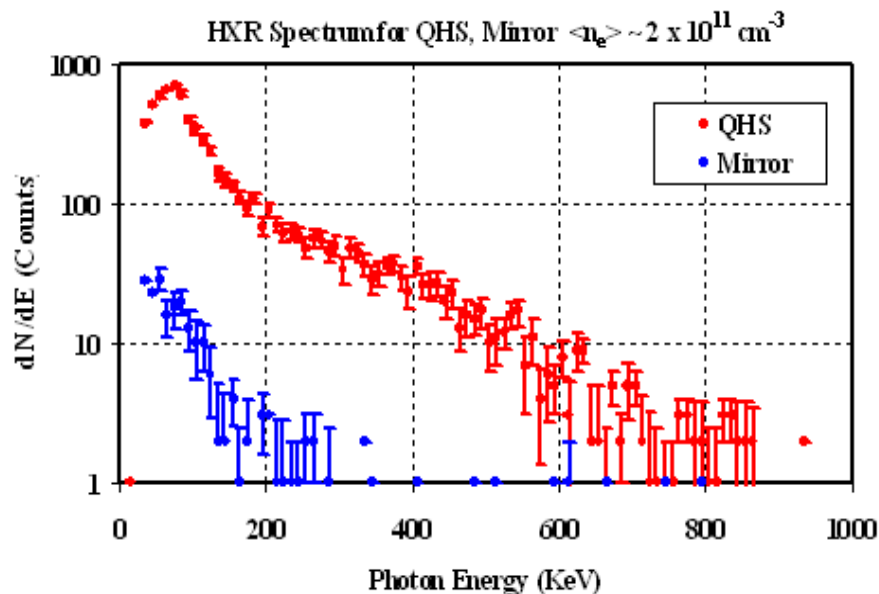
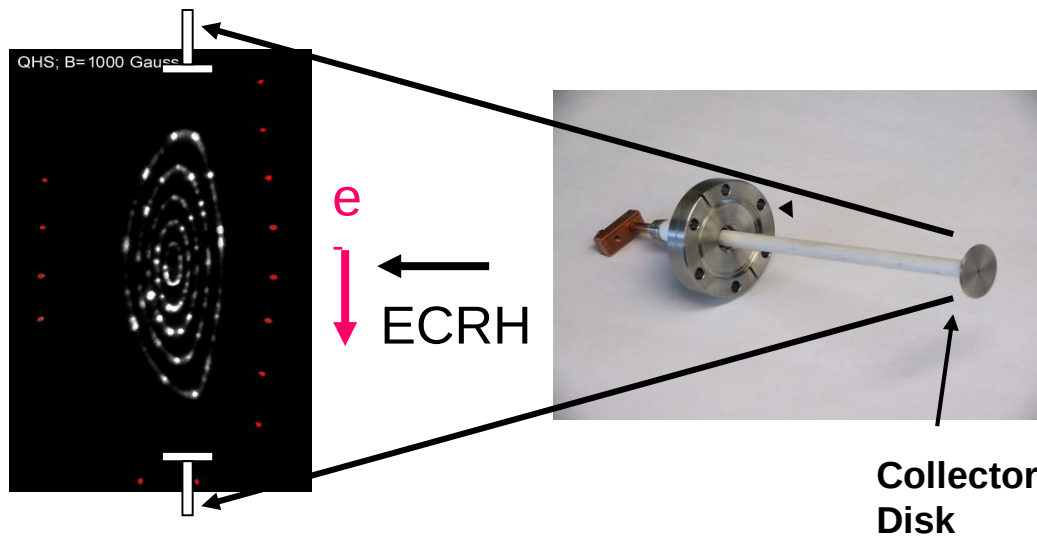
< 1%

< 10%

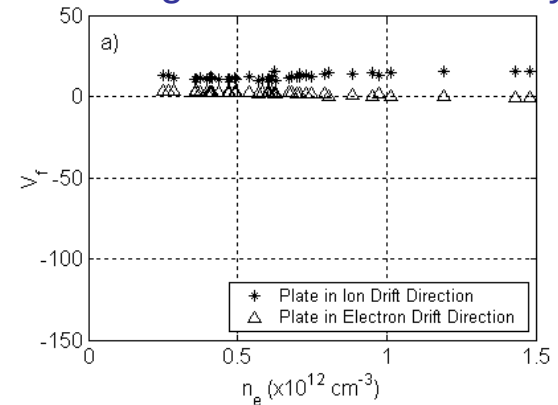
< 1 mm shift

factor of 8

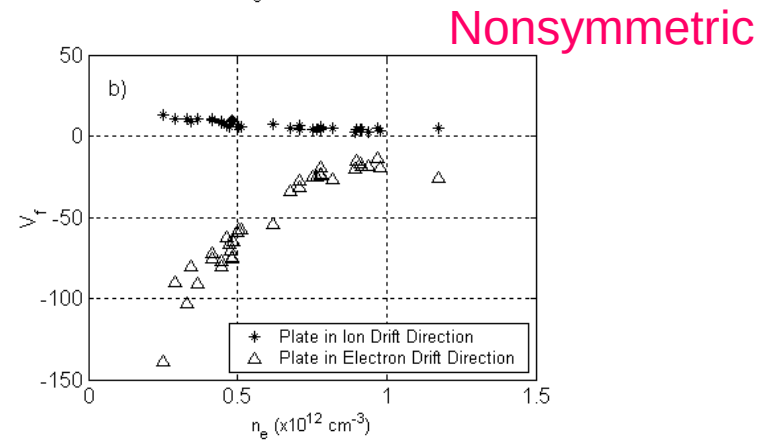
Good confinement of trapped particles



Floating Potential vs Density



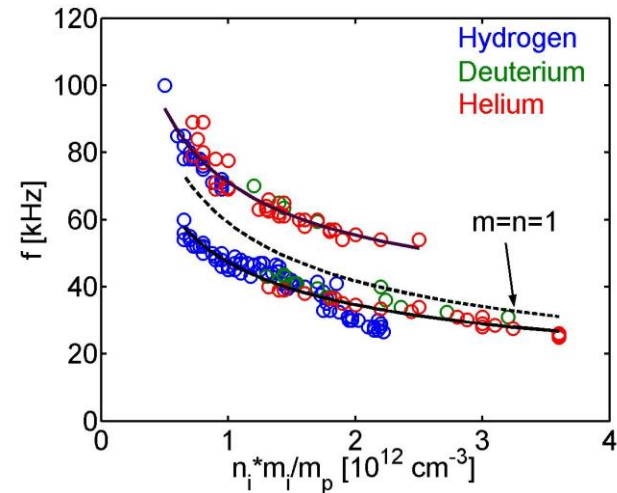
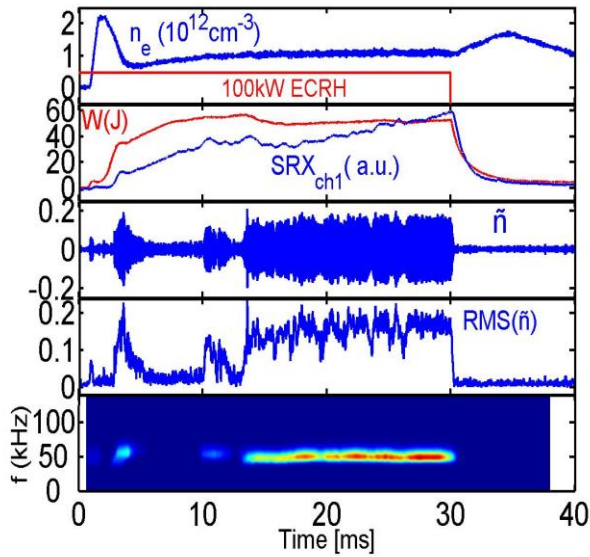
QHS



Nonsymmetric

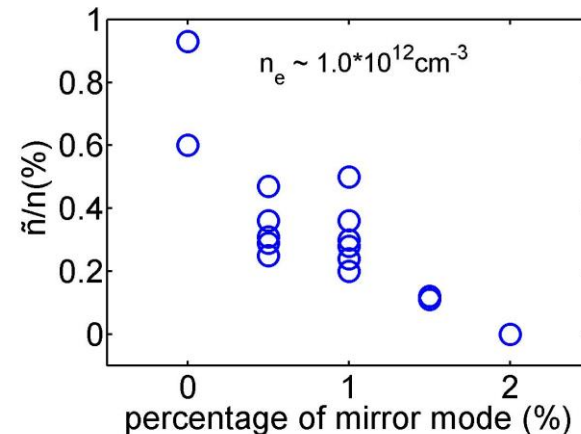
- Collector plate in direction of electron ∇B drift shows large negative potential when quasisymmetry broken.
- Larger HXR flux in QHS configuration.

BUT ... global coherent mode observed at 0.5 T



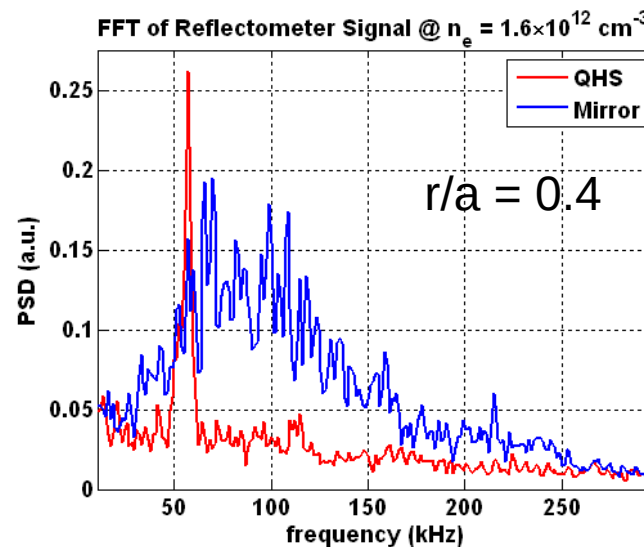
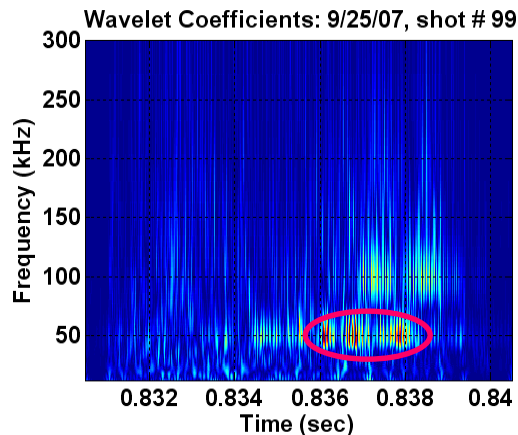
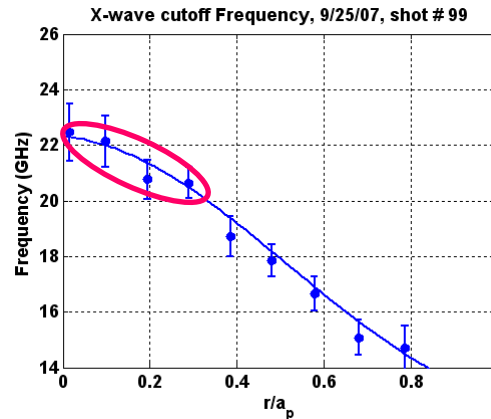
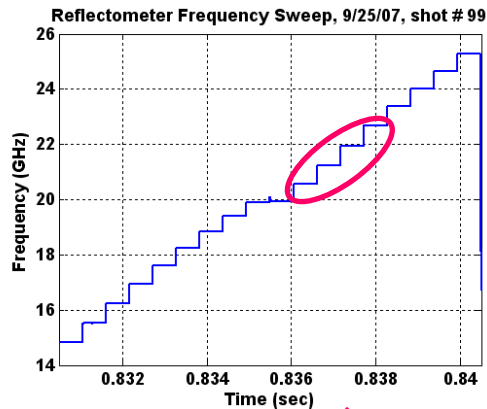
$$\omega_{GAE} \leq k_{//} v_A = \frac{(m\ell - n)}{R} \frac{B}{\sqrt{4\pi n_i m_i}}$$

- 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

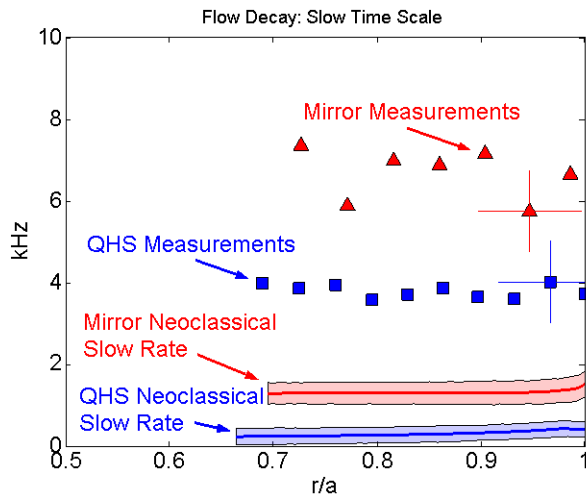


See Likin poster
Wednesday

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

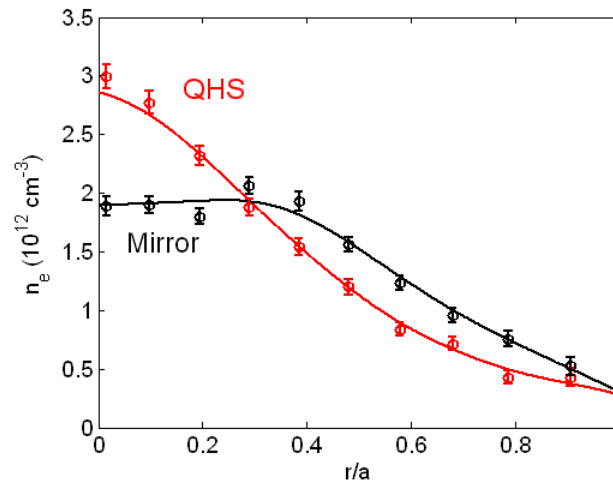
Momentum



Larger flows in QHS with equivalent torque

→ Lower parallel viscous damping

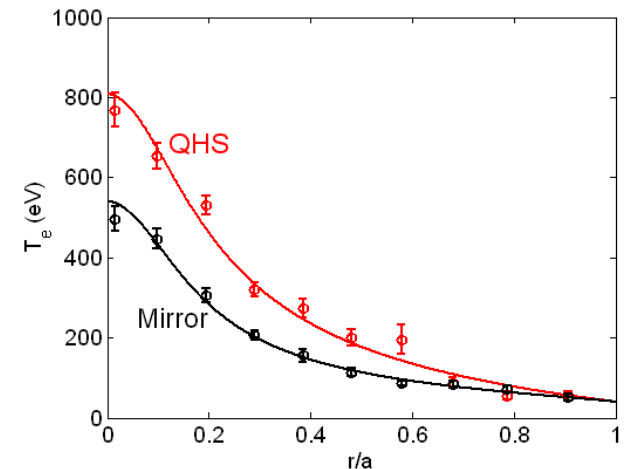
Particle



Peaked density profiles in QHS

→ Reduced thermodiffusion

Heat

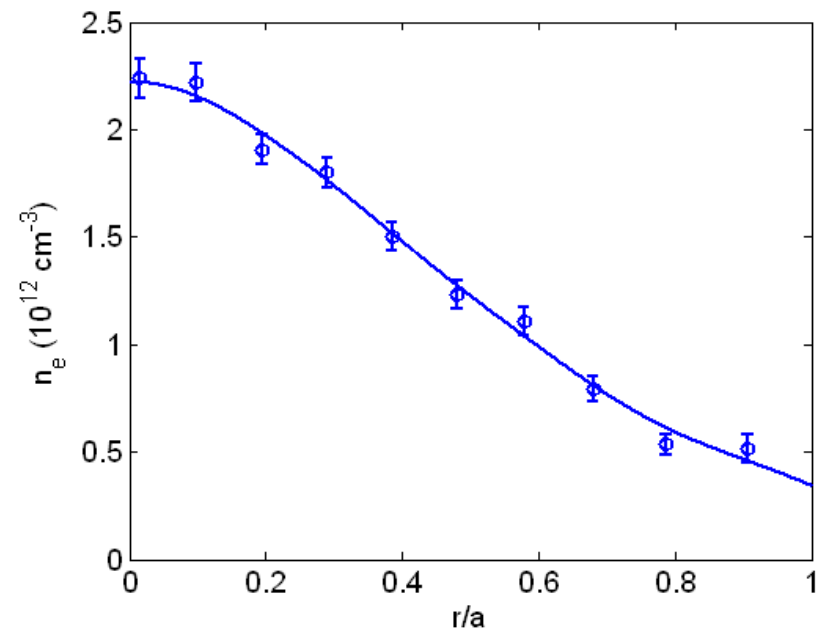
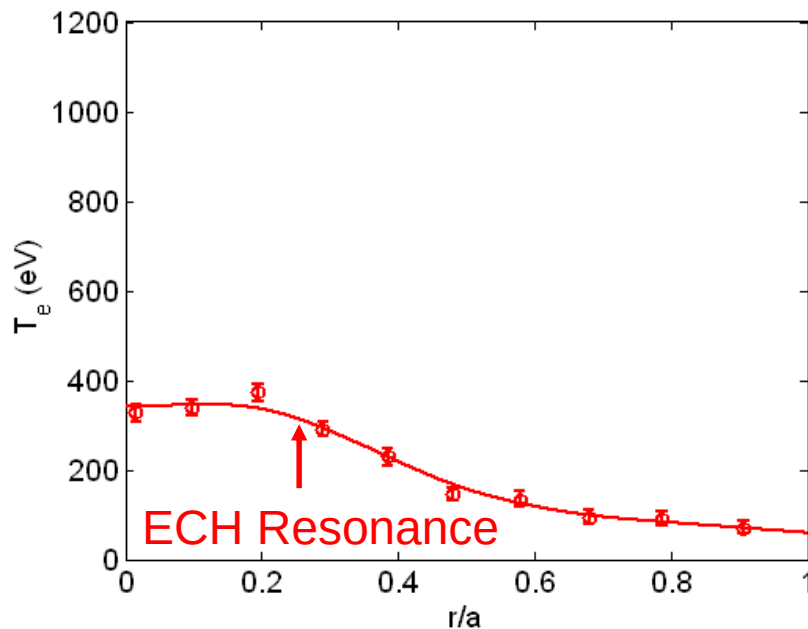


Higher T_e in QHS with same absorbed power

→ Lower χ_e

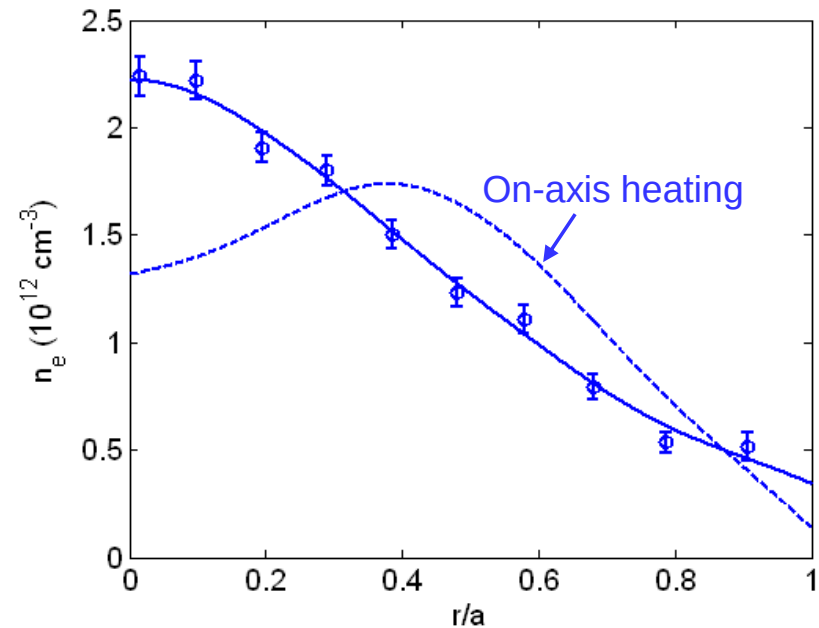
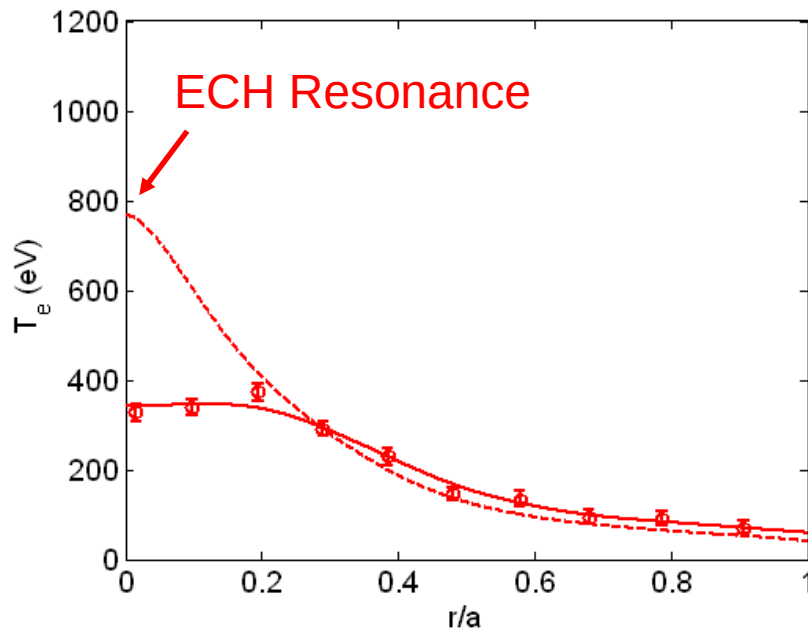
Off-axis Heating Confirms Thermodiffusive Flux in Mirror

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



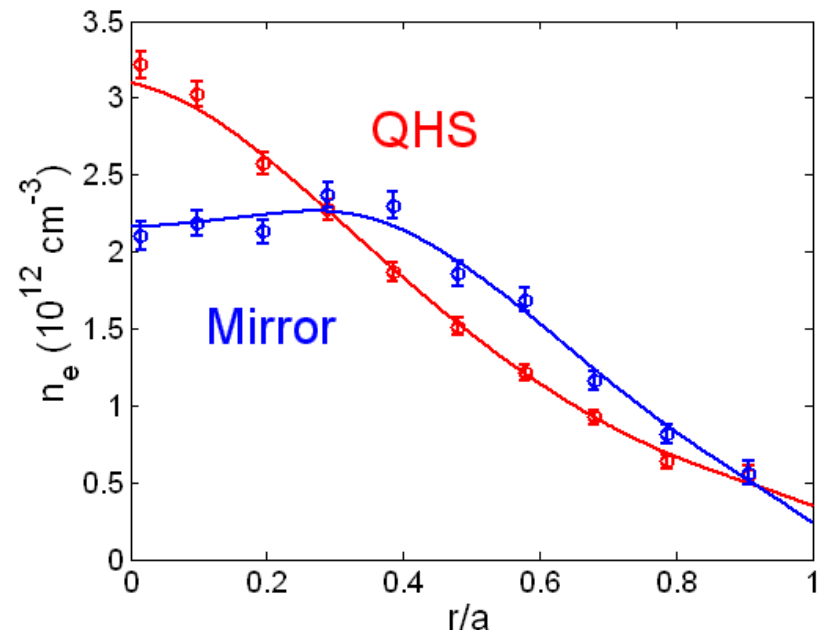
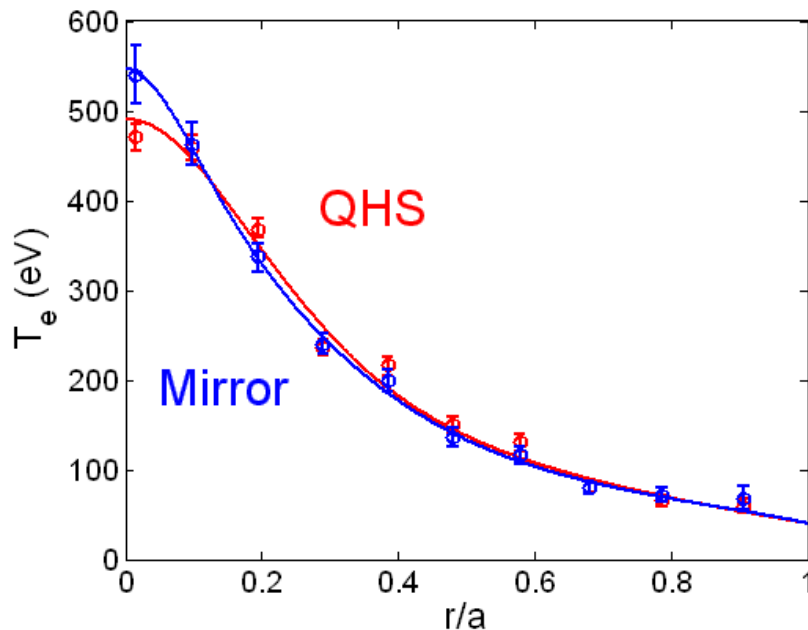
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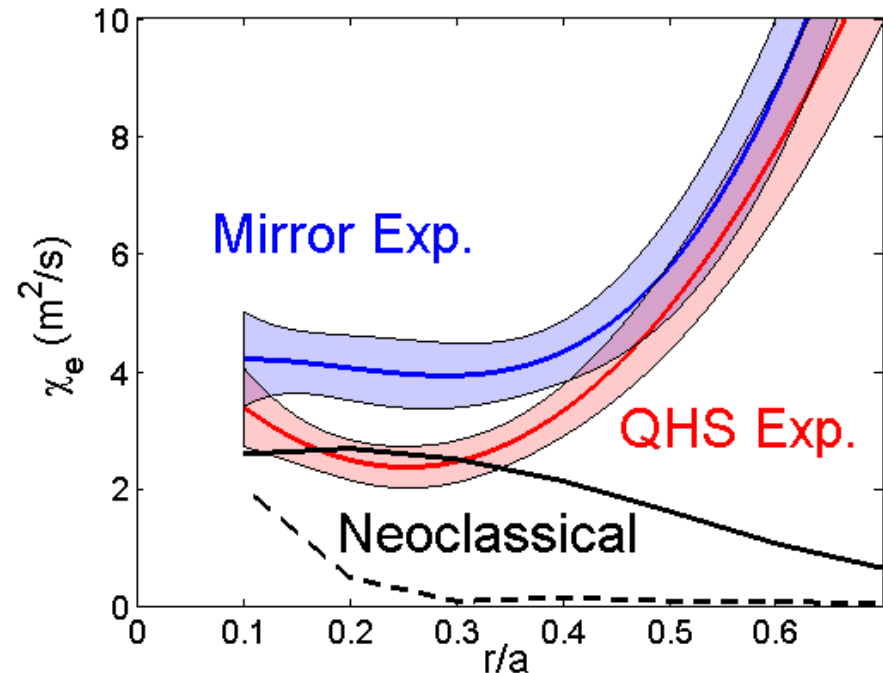
Electron temperature profiles can be well matched between QHS and Mirror

- 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

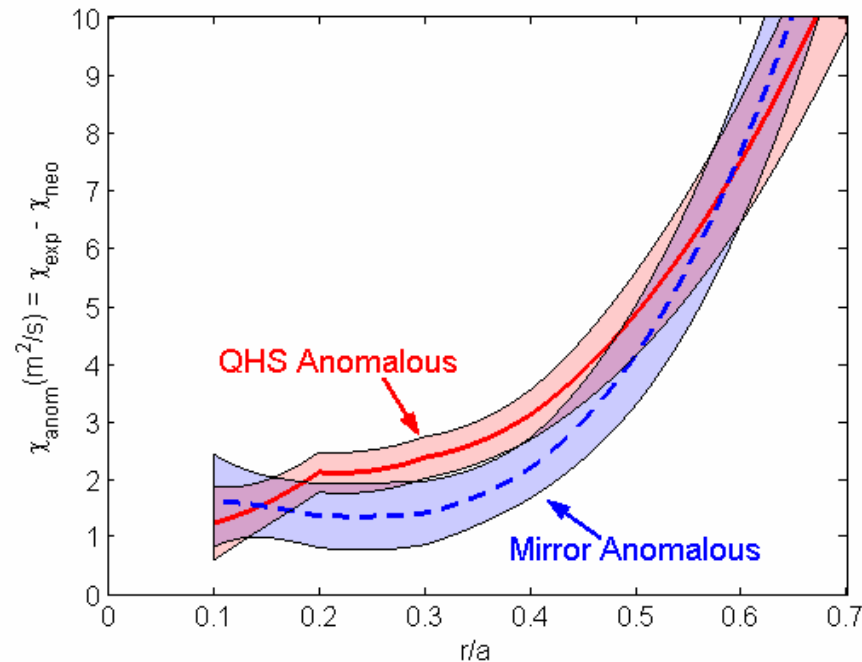


Thermal Diffusivity is Reduced in QHS

- QHS has lower core χ_e
 - At $r/a \sim 0.25$, χ_e is 2.5 m²/s in QHS, 4 m²/s in Mirror
 - Difference is comparable to neoclassical reduction (~ 2 m²/s)
- Two configurations have similar transport outside of $r/a \sim 0.5$

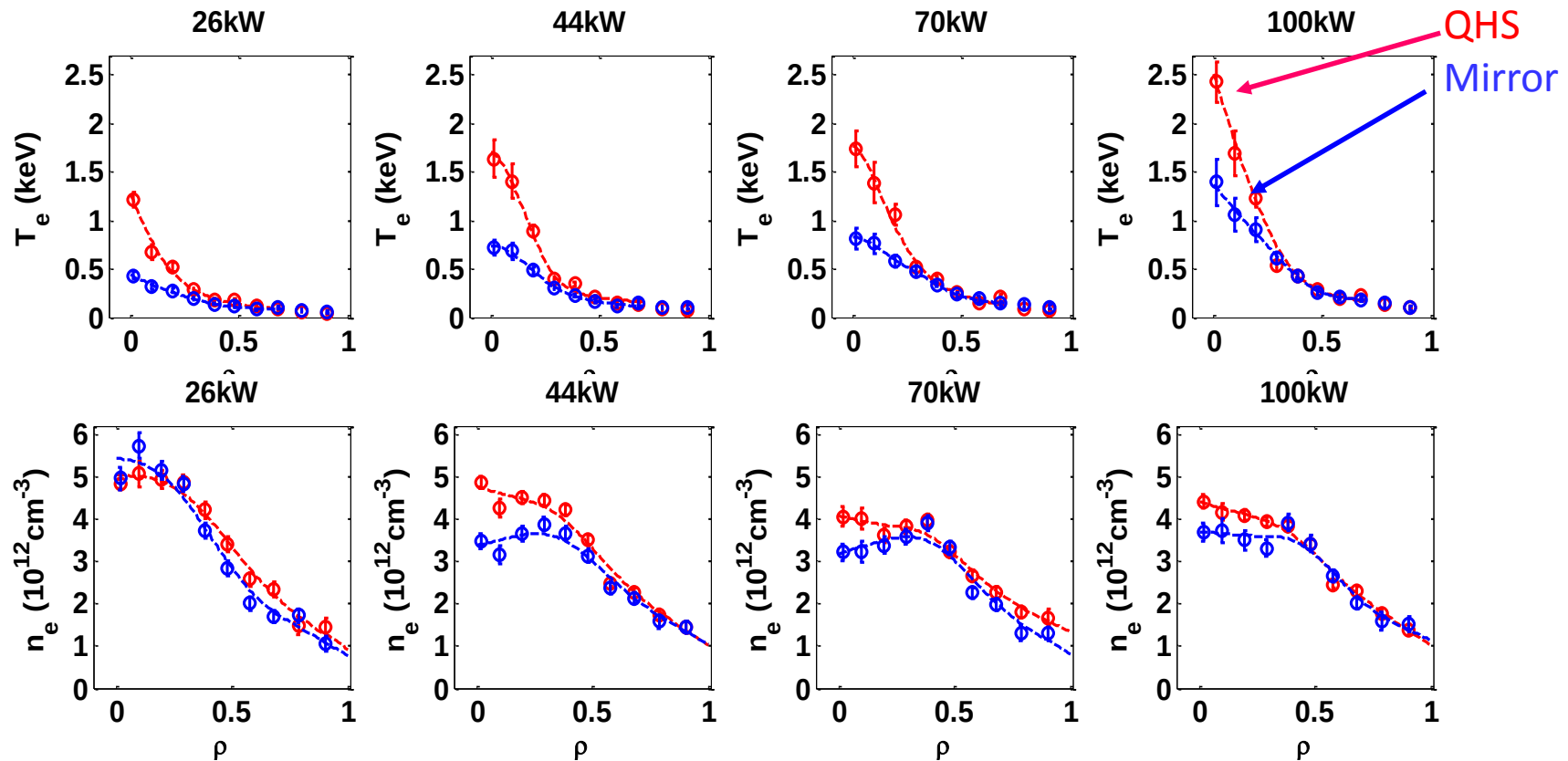


Anomalous conductivity is difference between experimental and neoclassical



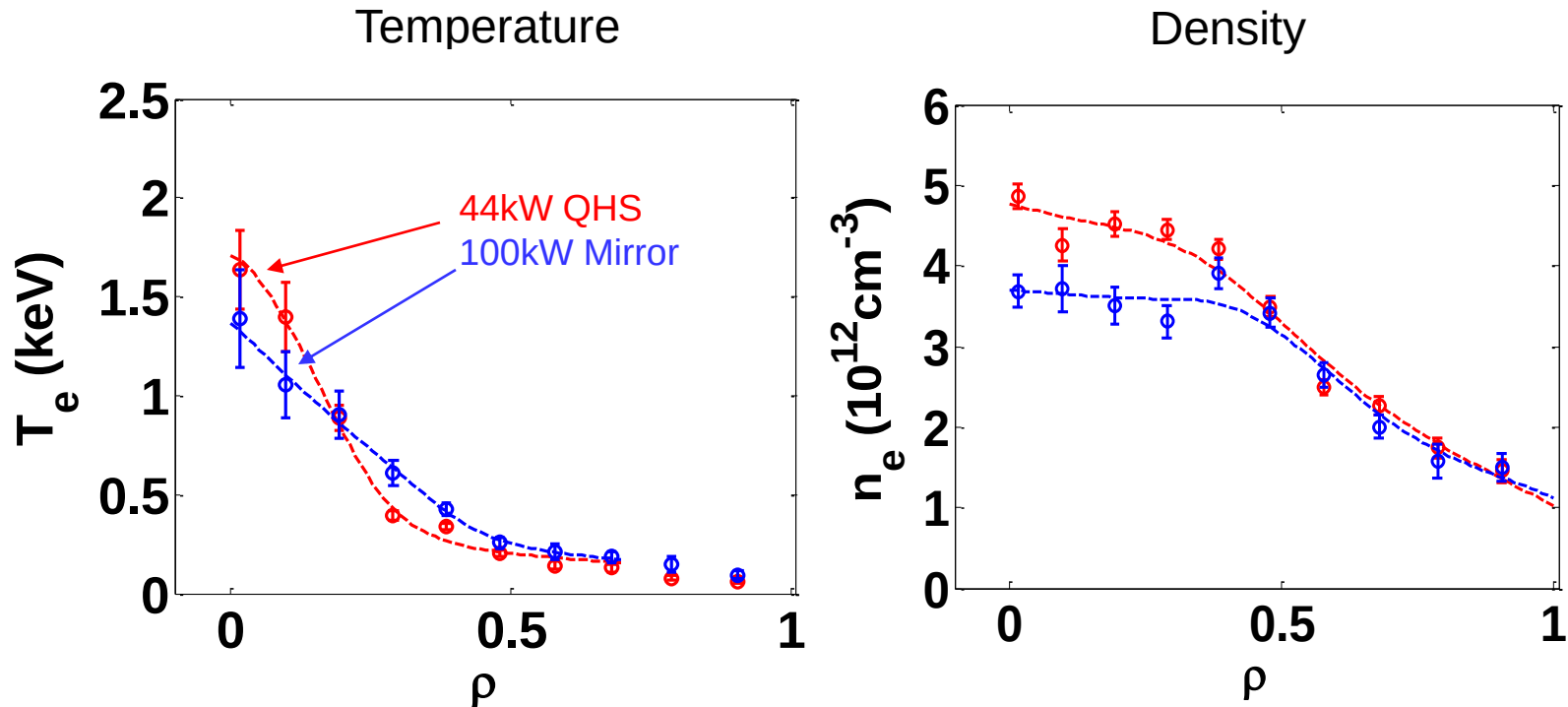
- Little difference in anomalous transport between QHS and Mirror

ECH at B = 1.0 T



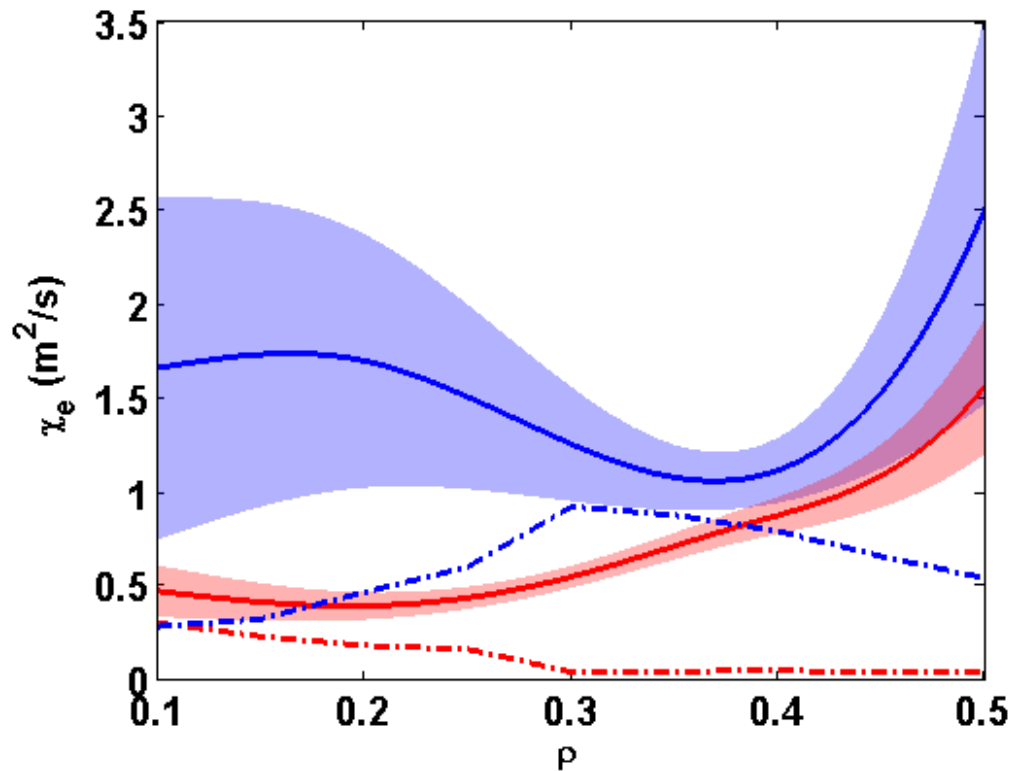
- Good agreement between kinetic and diamagnetic stored energy
➔ minimal nonthermal contribution
- Core T_e about twice as large in QHS as Mirror configuration
- Mirror density profile more hollow as T_e gradient increases

Minimum difference profiles to compare transport at $B = 1.0$ T



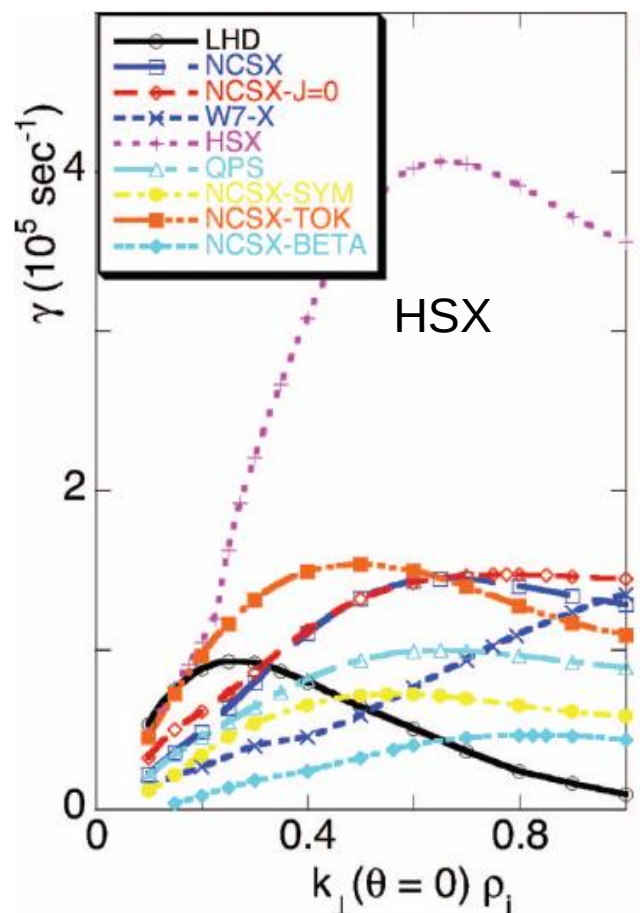
- More than twice the power in Mirror configuration to approximate the temperature profile
- Density profile still slightly more peaked in QHS than Mirror

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:
- Possibility that anomalous lower in QHS, but this needs more conclusive data

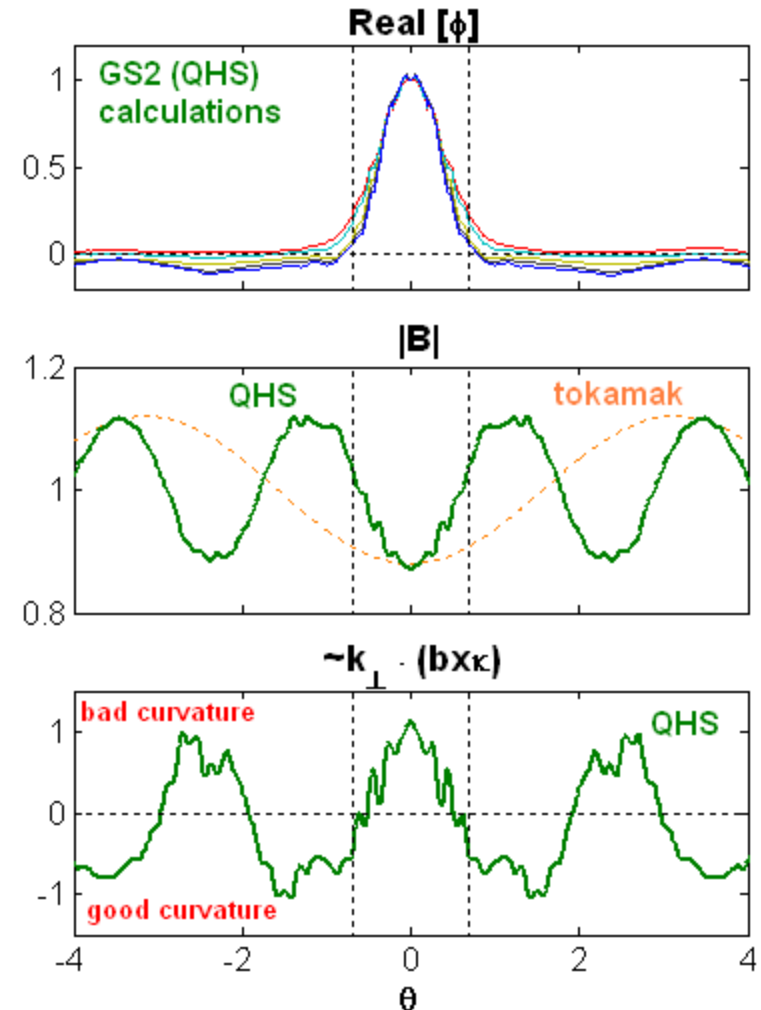
Can we model anomalous transport in HSX?



- 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

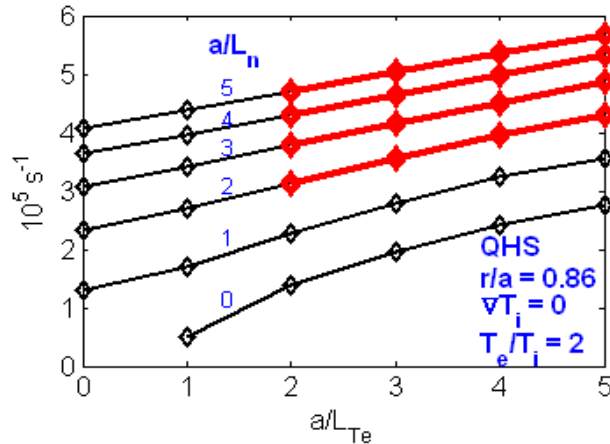
Microstability estimates using axisymmetric models with “quasisymmetric” approximation

- 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 ($0.14 \cdot r/a = 1.4 \cdot r/R$)
- Reduced connection length, $L_c = q_{\text{eff}} R = R/|N-m_I| \approx R/3$, leads to very low collisionality electrons across the minor radius $\rightarrow$ TEM ($T_e \gg T_i$)
- Normal curvature rotates helically, with bad curvature following the location of low field strength
- $\kappa_{N,\text{max}} \sim 1/45 \text{ cm}^{-1} \neq 1/R$ ($R=120 \text{ cm}$)
- To account for toroidal drifts in drift wave models, $R/L \rightarrow (R/3)/L$

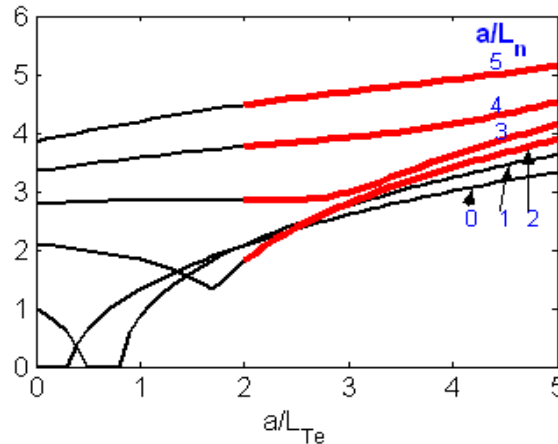


Weiland model with simplified assumptions benchmarked against GS2 code

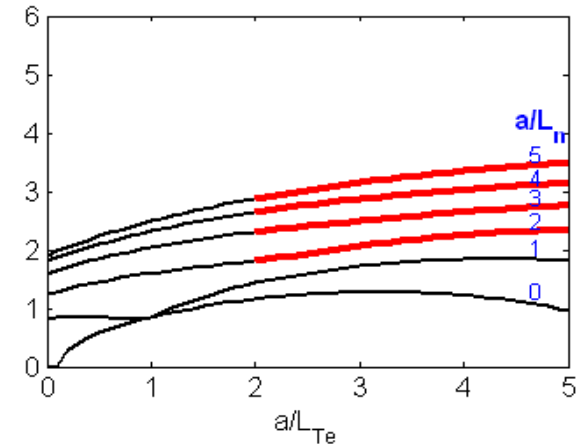
GS2 - HSX
Growth Rates



Weiland - HSX
Growth Rates

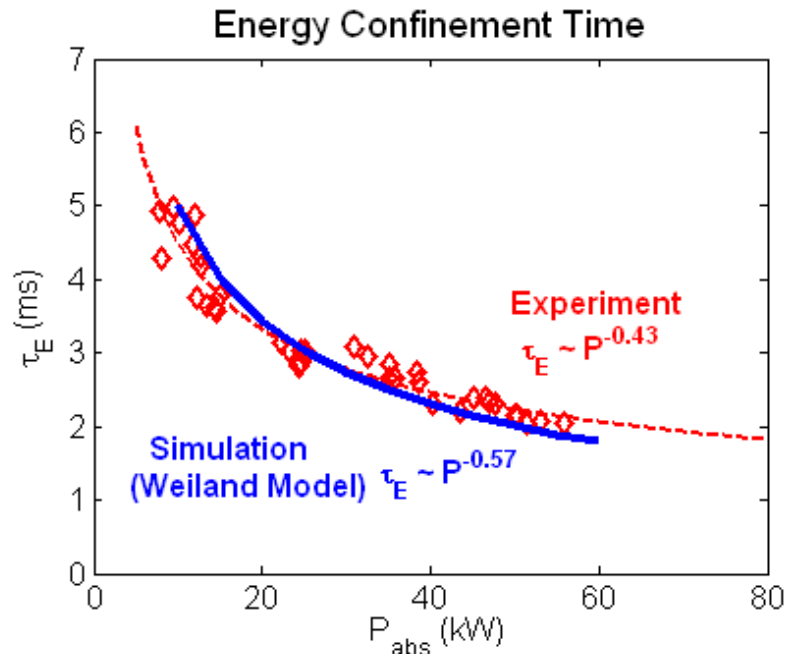
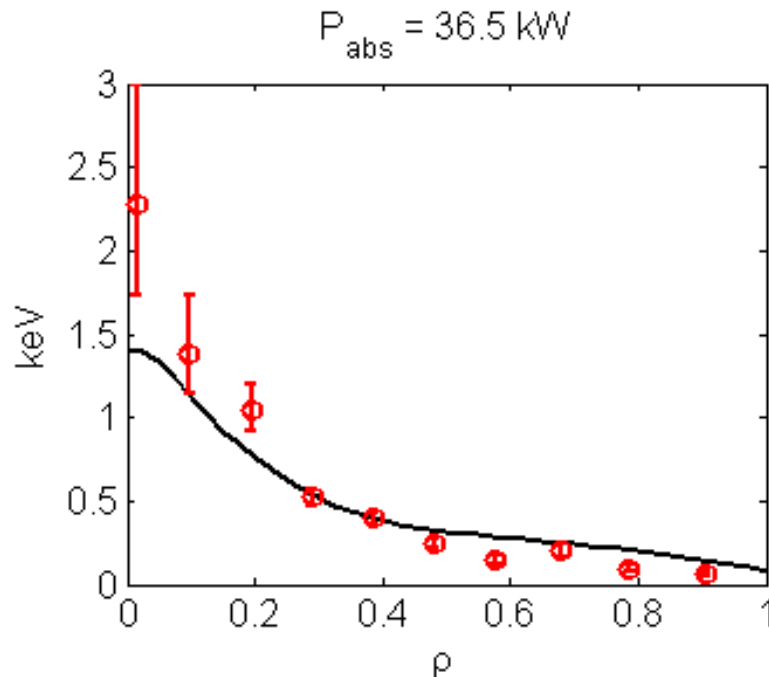


Weiland - TOK
Growth Rates



- 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 $\sim 30\%$)
- Weiland growth rates $2\times$ smaller without “quasisymmetric” approximation

Model predicts gross features of T_e profile and confinement scaling



See Guttenfelder talk,
Wednesday morning

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

Future plans

- 16 channel ECE system to be installed soon
- Need to measure radial electric field → diagnostic neutral beam mounted on HSX for CHERS
- Novel low-cost HIBP system being developed with RPI
- Second 28 GHz gyrotron for additional heating, pulse propagation and Bernstein wave heating
- ICRF to heat ions into low collisionality regime → Obtain ion root plasma for Mirror to maximize neoclassical and possibly anomalous differences with QHS configuration

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 $B = 0.5 \text{ T}$
 - Reduction of particle, momentum and heat transport with quasisymmetry
 - Large thermodiffusive flux in Mirror yields hollow density profiles, reduction of neoclassical in QHS results in peaked density.
 - $\chi_e (r/a = 0.25)$ is $4.0 \text{ m}^2/\text{s}$ in Mirror, $2.5 \text{ m}^2/\text{s}$ in QHS
 - ECH at $B = 1.0 \text{ T}$
 - Nonthermal component is small
 - T_e up to 2.5 keV is observed
 - $\chi_e (r/a = 0.25)$ is $1.5 \text{ m}^2/\text{s}$ in Mirror, $0.5 \text{ m}^2/\text{s}$ in QHS
 - Weiland model with geometric approximations gives reasonable fit to anomalous transport
- ➔ High effective transform is good for neoclassical transport, perhaps not so good for anomalous