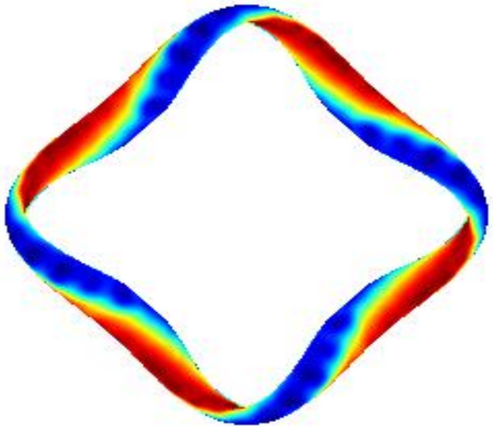
Measurements of bicoherence and long-range correlations during biasing in the HSX stellarator



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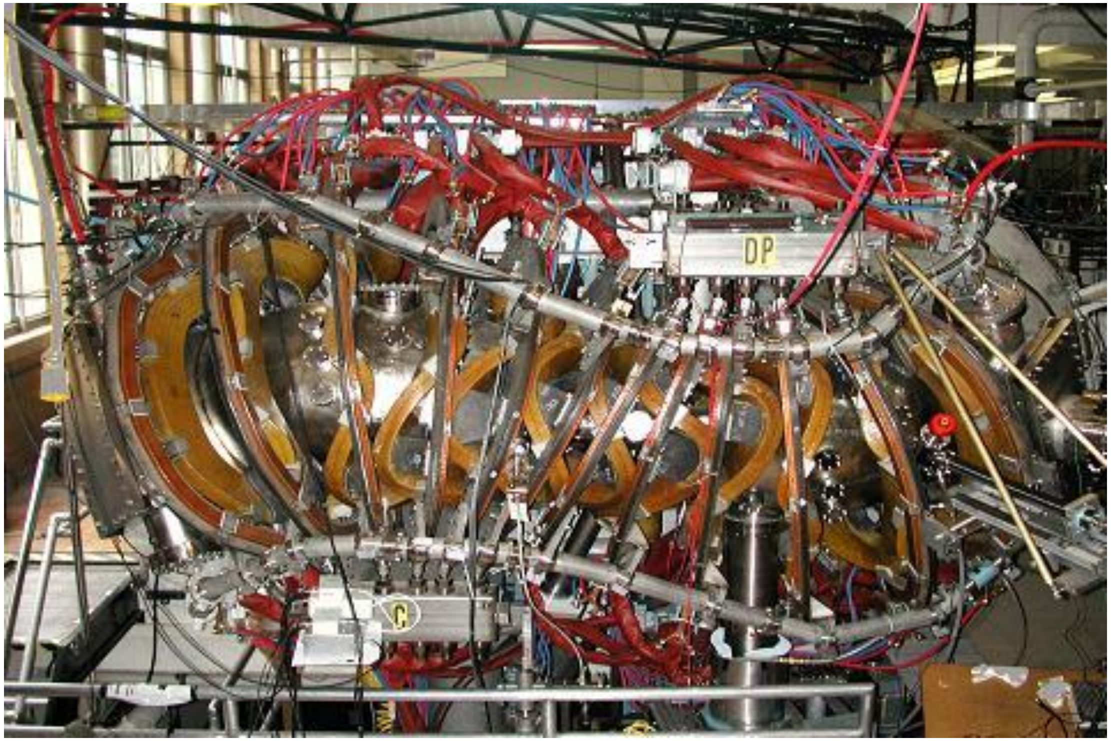


Transport Task Force Workshop
San Diego, CA, April 6-9, 2011

Thanks to Boudewijn van Milligen, Carlos Hidalgo, and the HSX team for their contributions to this work

Outline

- The HSX stellarator
  - QHS and Mirror configurations
    - Neoclassical transport increased with aux coils
  - Enhanced zonal flow response with quasi-symmetry?
  - Edge biasing and Langmuir probes
- Bicoherence of E_θ fluctuations during biasing
  - Broadband 3-wave coupling in poloidal plane during bias
  - Radial extent consistent with region of increased E_r
- Measurements of long-range correlations during bias
  - Zero-phase, high coherence potential fluctuations measured between multiple toroidally spaced probes

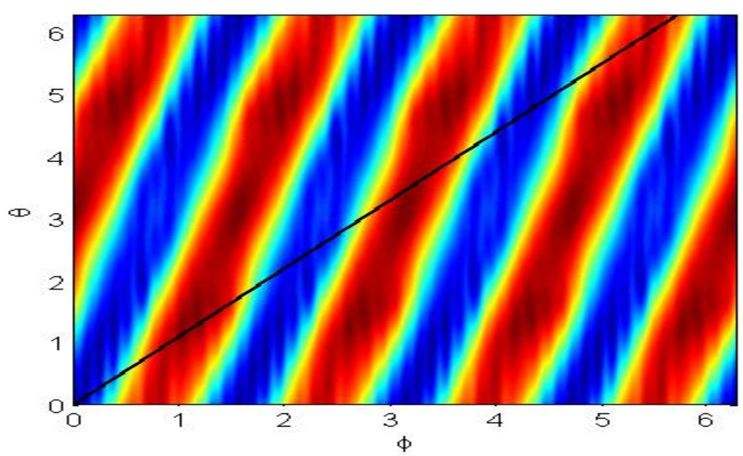
HSX is the first quasi-symmetric stellarator

- HSX has quasi-helical symmetry: |B| is symmetric in the helical direction (n=4, m=1)
- This gives tokamak-like neoclassical transport properties

Tokamak: $B/B_0 = 1 - \varepsilon_t \cos \iota\phi$

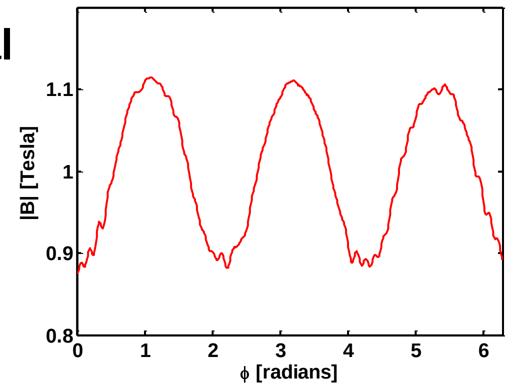
QHS: $B/B_0 = 1 - \varepsilon_h \cos(n - m\iota)\phi$

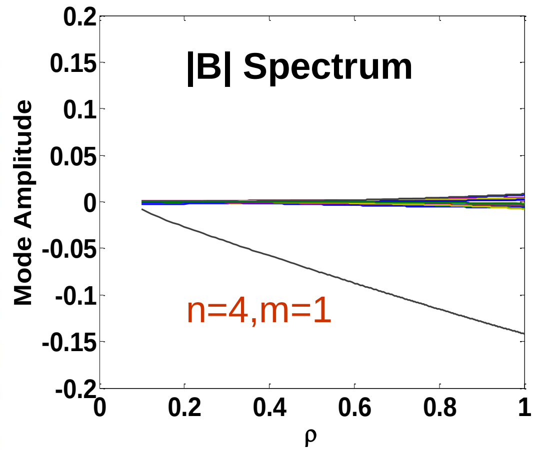
$\iota_{eff} \sim 3$



QHS

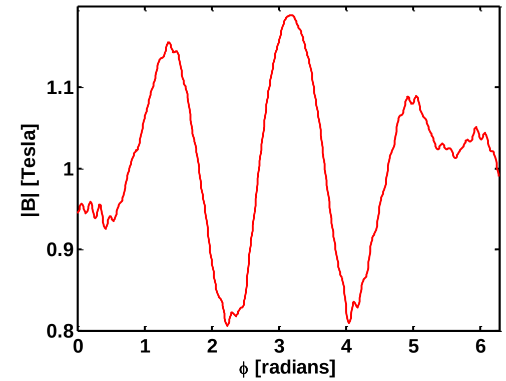
|B| along field line

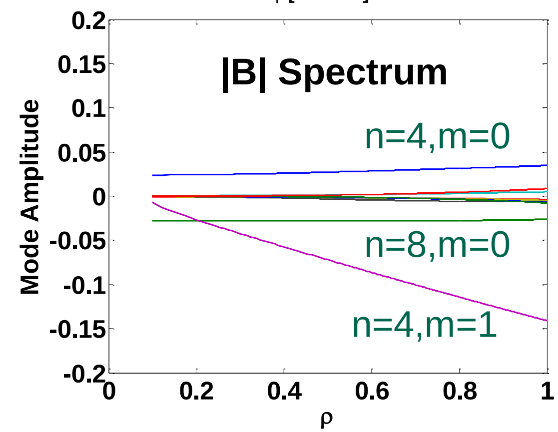




Mirror

|B| along field line





Neoclassical transport can be varied with auxiliary coils

Enhanced levels of zonal flows are expected in HSX due to neoclassical optimization

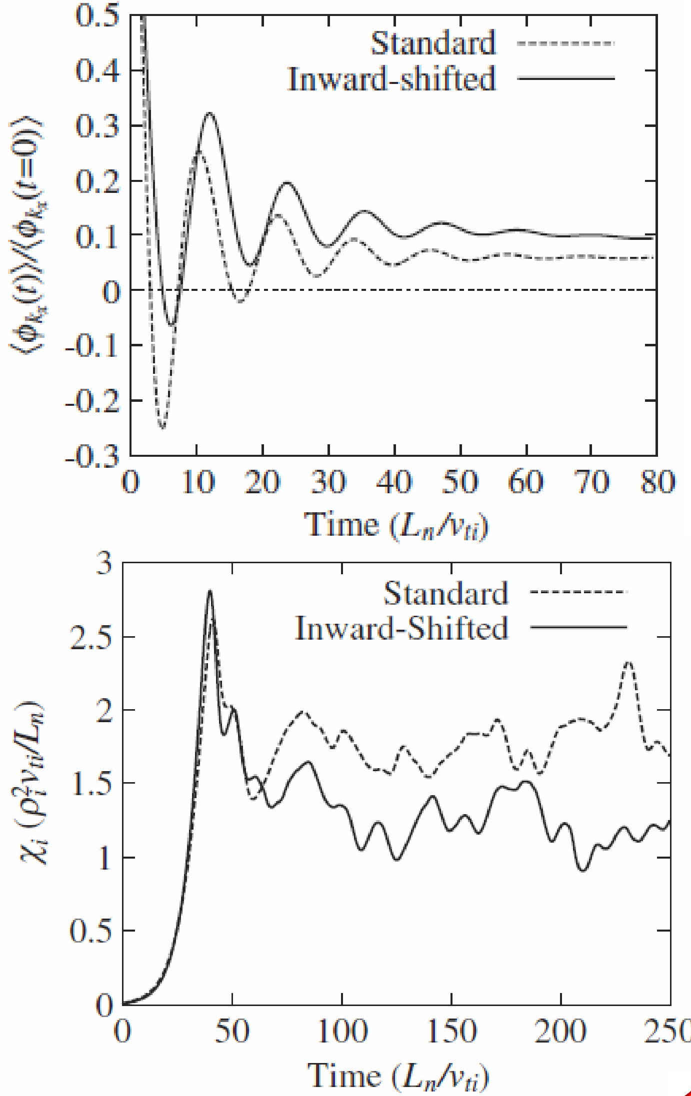
Prediction was made that optimizing magnetic configurations for reduction of the neoclassical ripple transport may simultaneously lower the anomalous transport through enhancing the zonal-flow level. [Sugama and Watanabe, PRL 2005]

LHD sees reduction in anomalous transport in their inward-shifted configuration which was optimized to reduce neoclassical transport, despite larger linear growth rates [Yamada et al, PPCF 2001; Watanabe et al., PRL 2008]

Neoclassically optimized configurations have reduced drift polarization shielding, resulting in a larger zonal flow amplitude [Mynick and Boozer, PoP 2007]

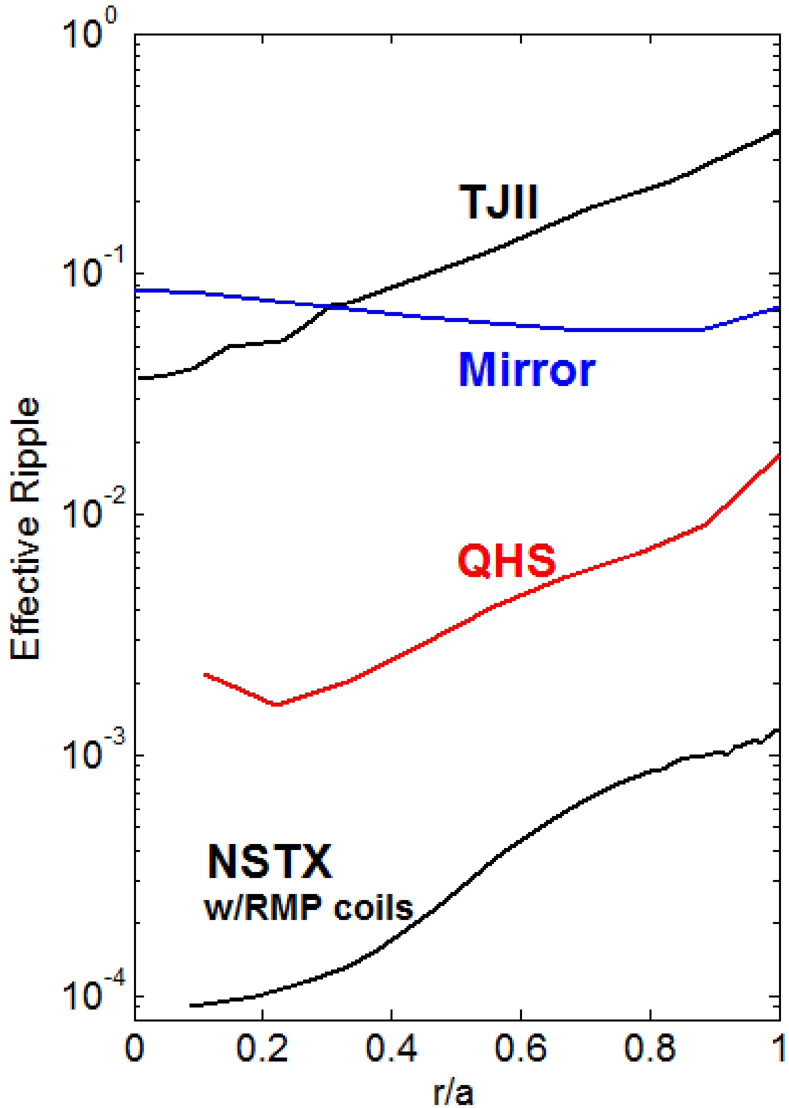
→ Does a quasi-helically symmetric configuration show signs of stronger zonal flows than one in which the symmetry is broken?

LHD FSA potential response and χ_i



[Watanabe et al., PRL 2008]

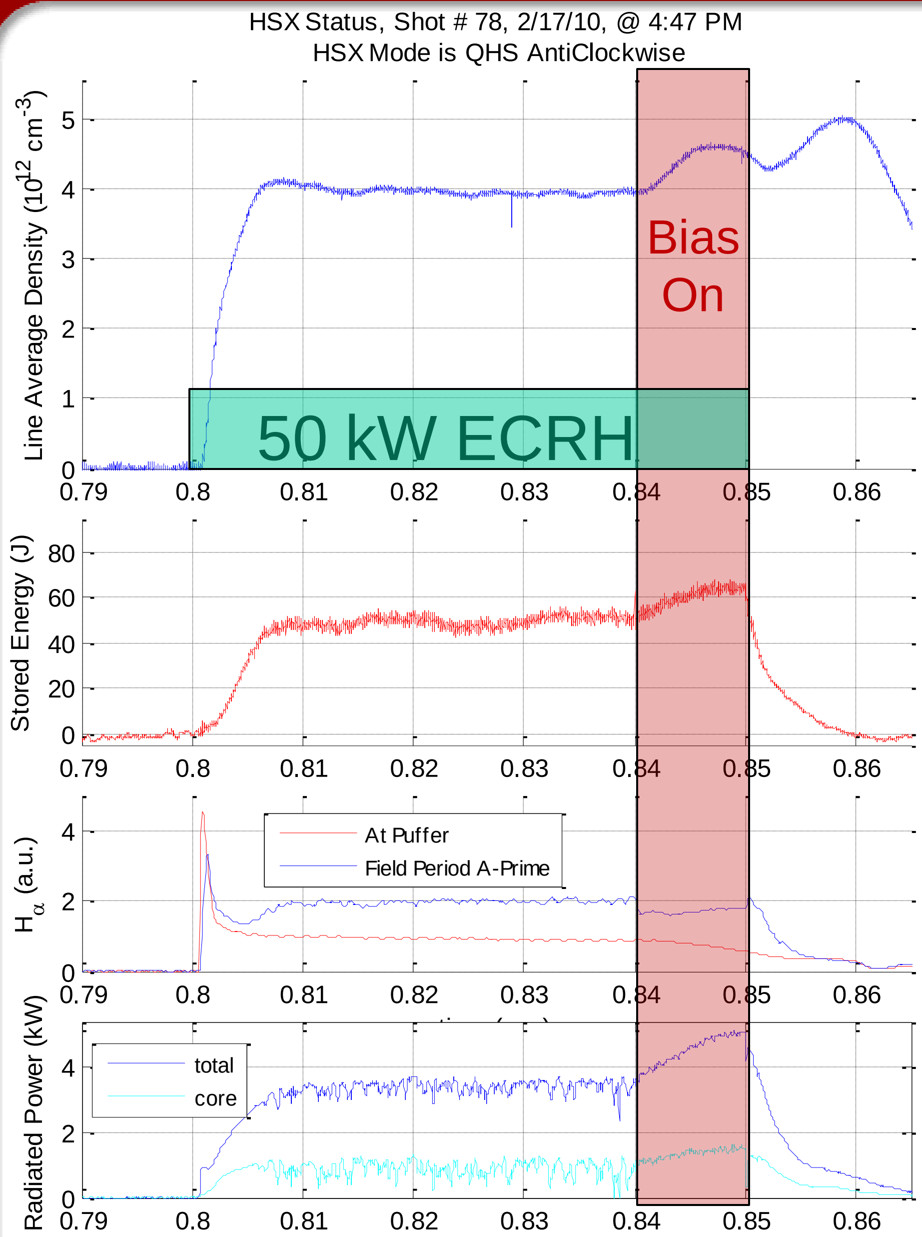
Symmetry breaking and its resulting neoclassical transport can be characterized by the effective ripple



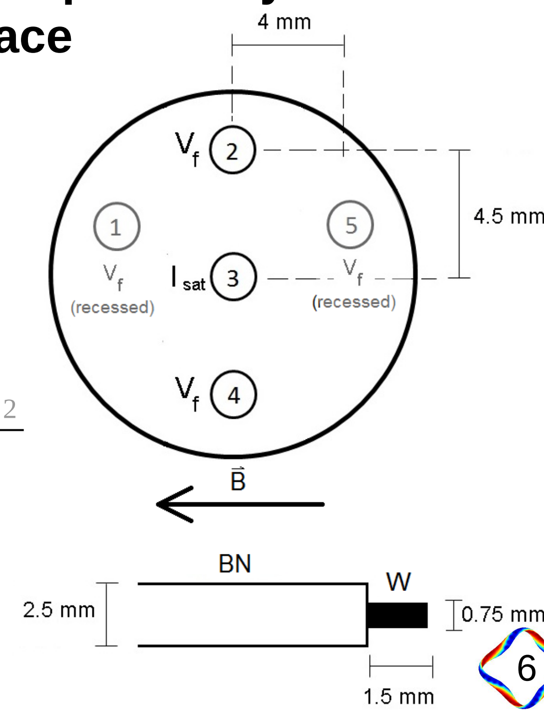
TJII ε_{eff}: Seiwald et. Al, JCP 2008
NSTX ε_{eff} calculations courtesy of John Canik, ORNL

- **Effective ripple (ε_{eff}) is a measure of the neoclassical optimization, and is finite in all real magnetic confinement devices**
  - **Sources like RMP coils, TF ripple, field errors in tokamaks**
- **The 1/υ transport scales with $\varepsilon_{eff}^{3/2}$ for zero radial electric field in the low collisionality regime.**
- **HSX probe measurements taken for r/a > 0.8, where the difference between configurations is not as large as further in**

Fluctuations are measured using Langmuir probes during edge biasing, when improved particle confinement is observed



- **Bias probe inserted to r/a=0.75, charged to 260V relative to a limiter positioned 1 cm outside the last closed flux surface**
- **3 Langmuir probe pins configured to measure I_{sat}, V_{float} to infer density, E_θ fluctuations**
- **Pins aligned poloidally on the same surface**

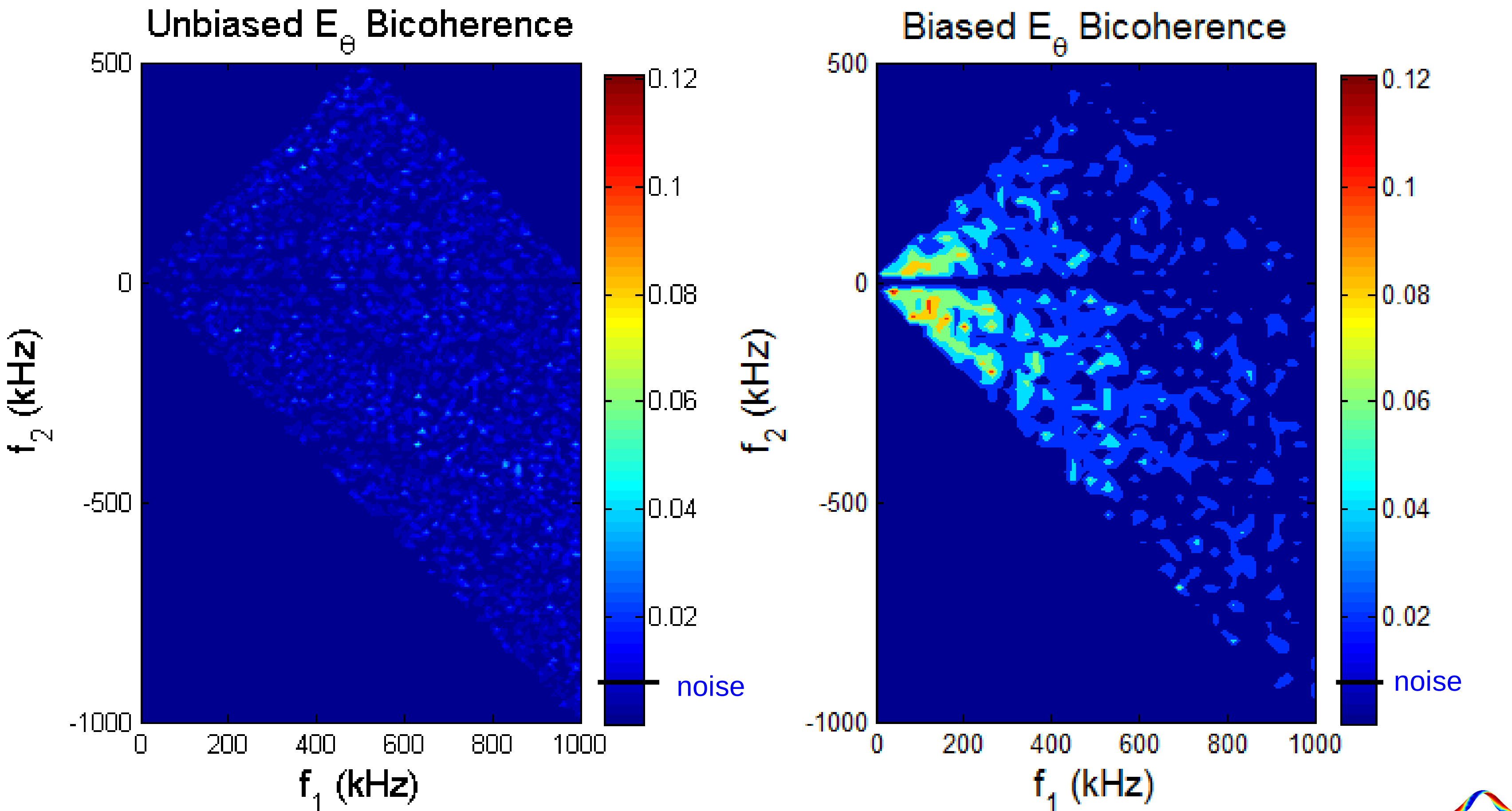


$$E_\theta = \frac{V_{f,4} - V_{f,2}}{|x_4 - x_2|}$$

Bicoherence analysis indicates strong 3-wave coupling between E_θ fluctuations over a broad band of frequencies

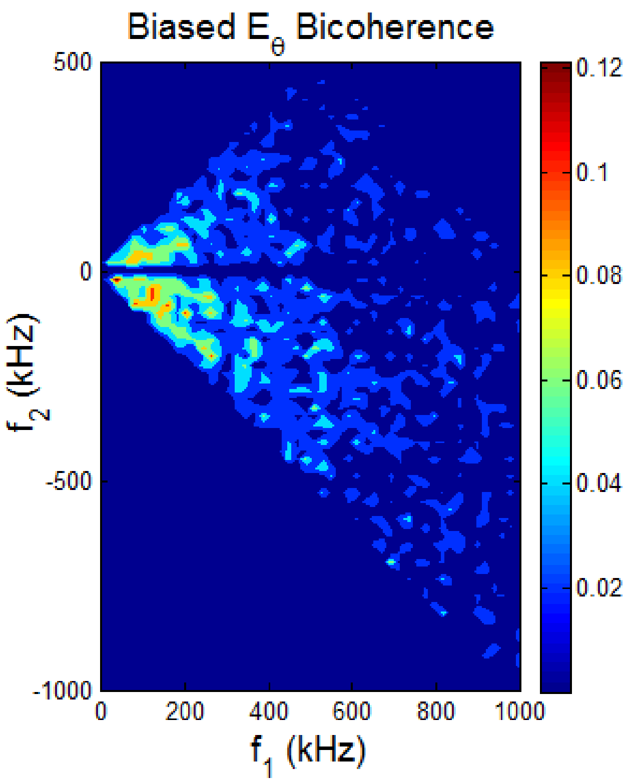
$$b_g^2(\omega_1,\omega_2) = \frac{\left\langle \left| \hat{g}(\omega_1)\hat{g}(\omega_2)\hat{g}^*(\omega_1+\omega_2) \right|^2 \right\rangle}{\left\langle \left| \hat{g}(\omega_1)\hat{g}(\omega_2) \right|^2 \right\rangle \left\langle \left| \hat{g}(\omega_1+\omega_2) \right|^2 \right\rangle}$$

Here $g=E_\theta$ → auto-bicoherence of E_θ is plotted

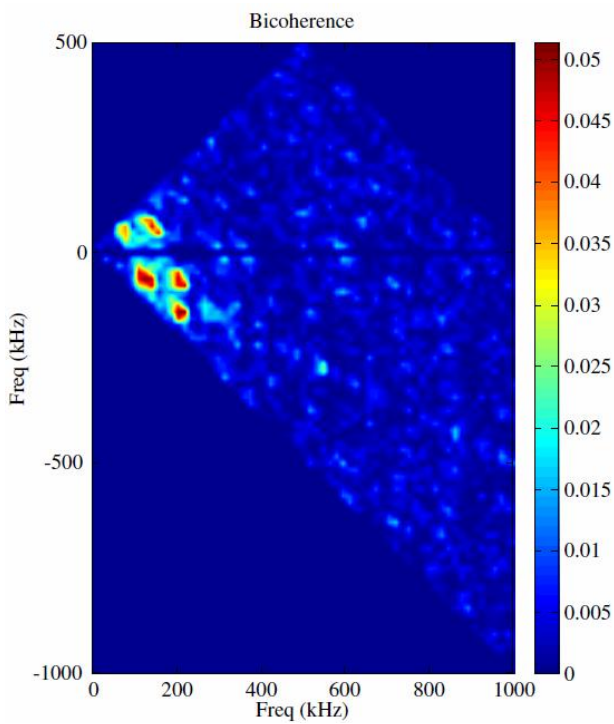


HSX measurements are consistent with TJ-II results during biased discharges, and distinct from spontaneous confinement transitions

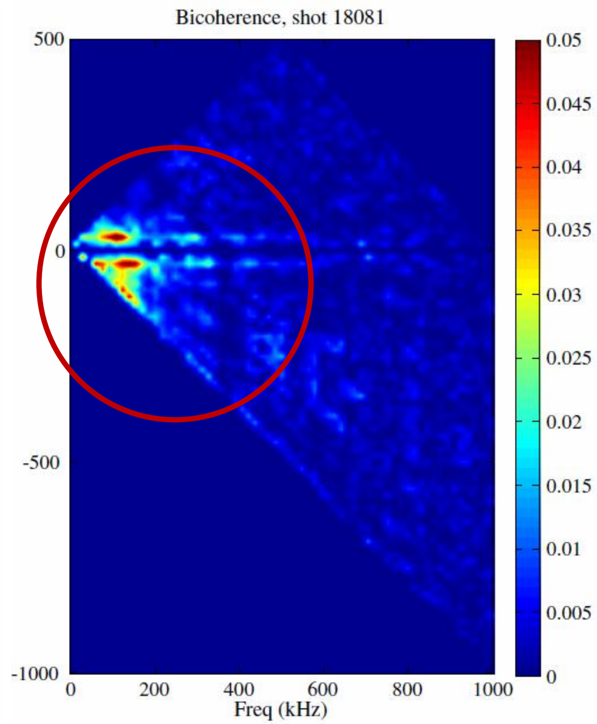
HSX biased discharge



TJ-II biased discharge



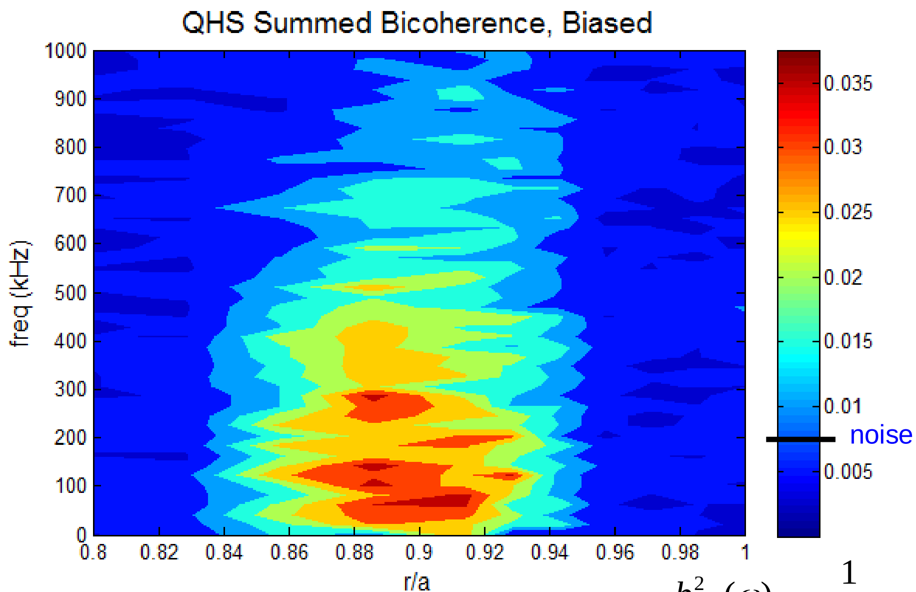
TJ-II spontaneous confinement transition

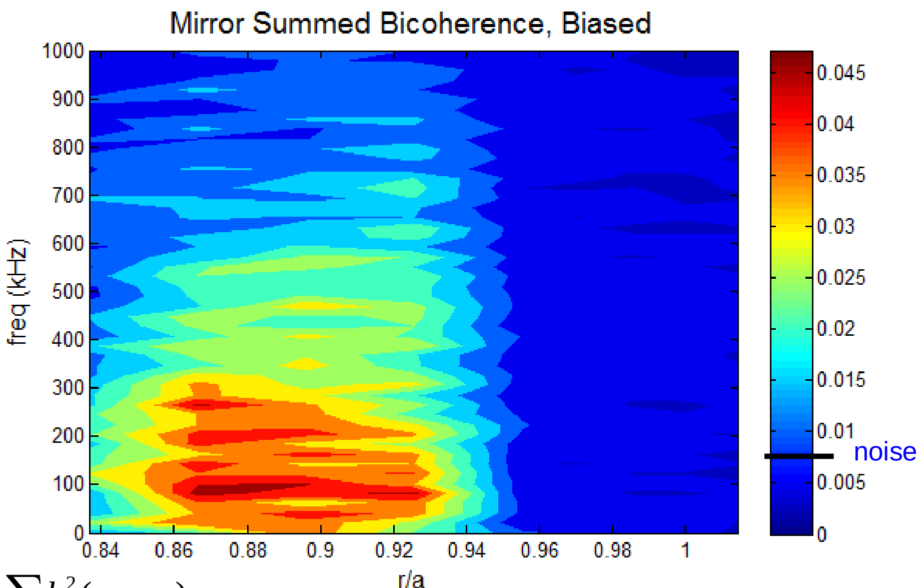


[van Milligen et al, NF 2008]

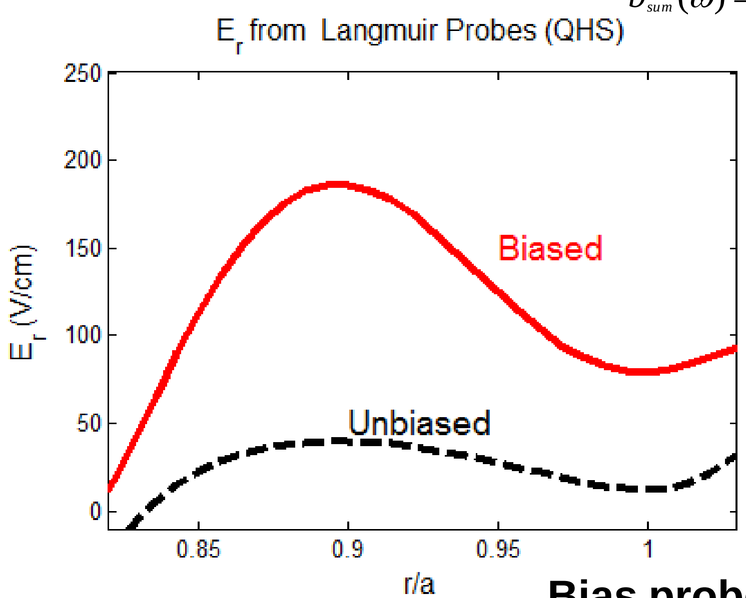
Bands in frequency space are indicative of direct coupling from high frequency fluctuations to near-zero frequency zonal flows

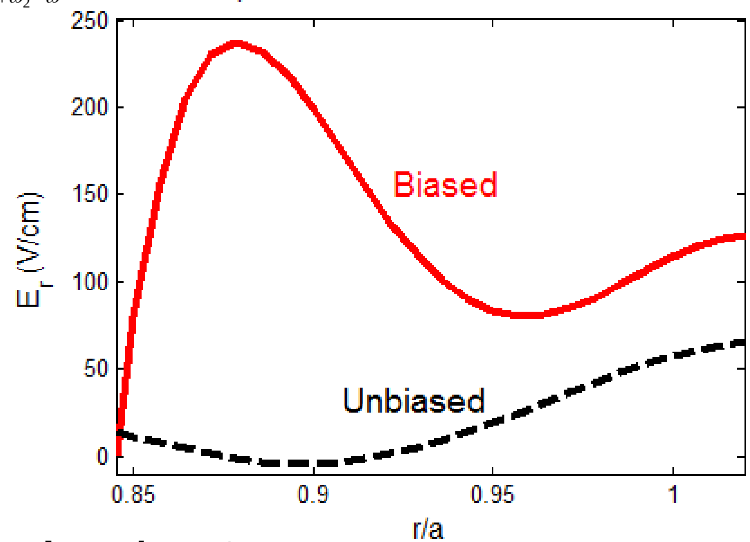
Radial region of increased bicoherence corresponds to region of large bias-induced E_r





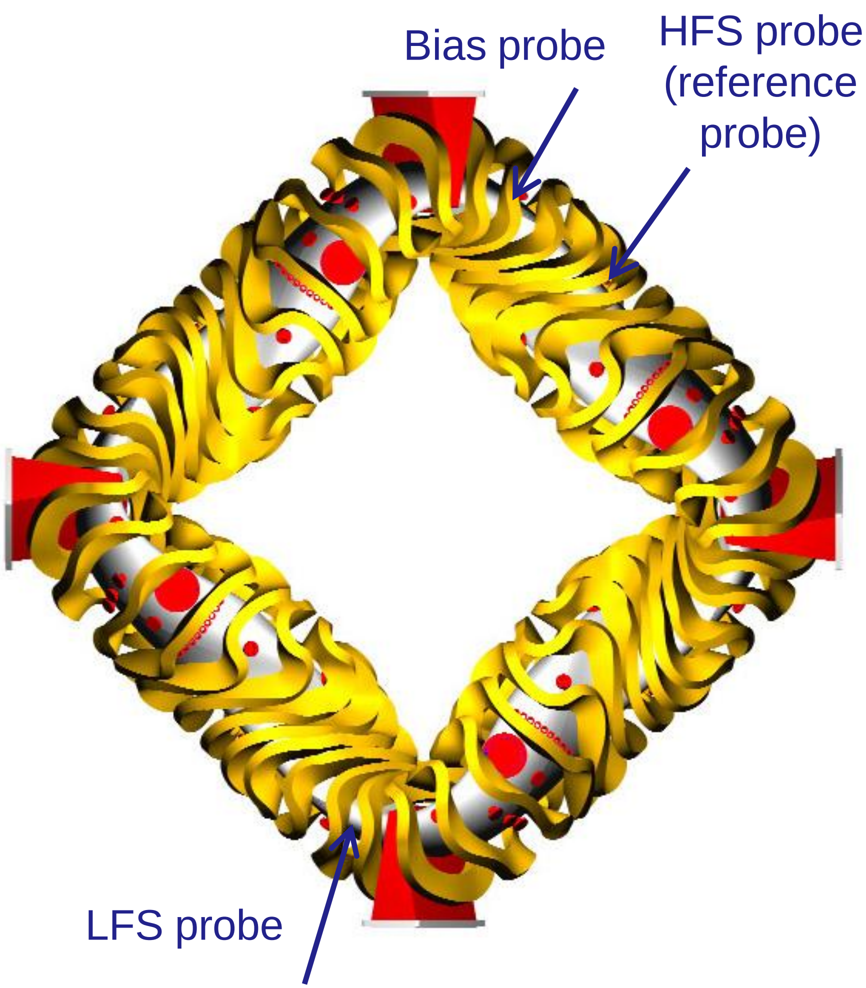
$$b^2_{sum}(\omega) = \frac{1}{N(\omega)} \sum_{\omega_1+\omega_2=\omega} b^2(\omega_1,\omega_2)$$





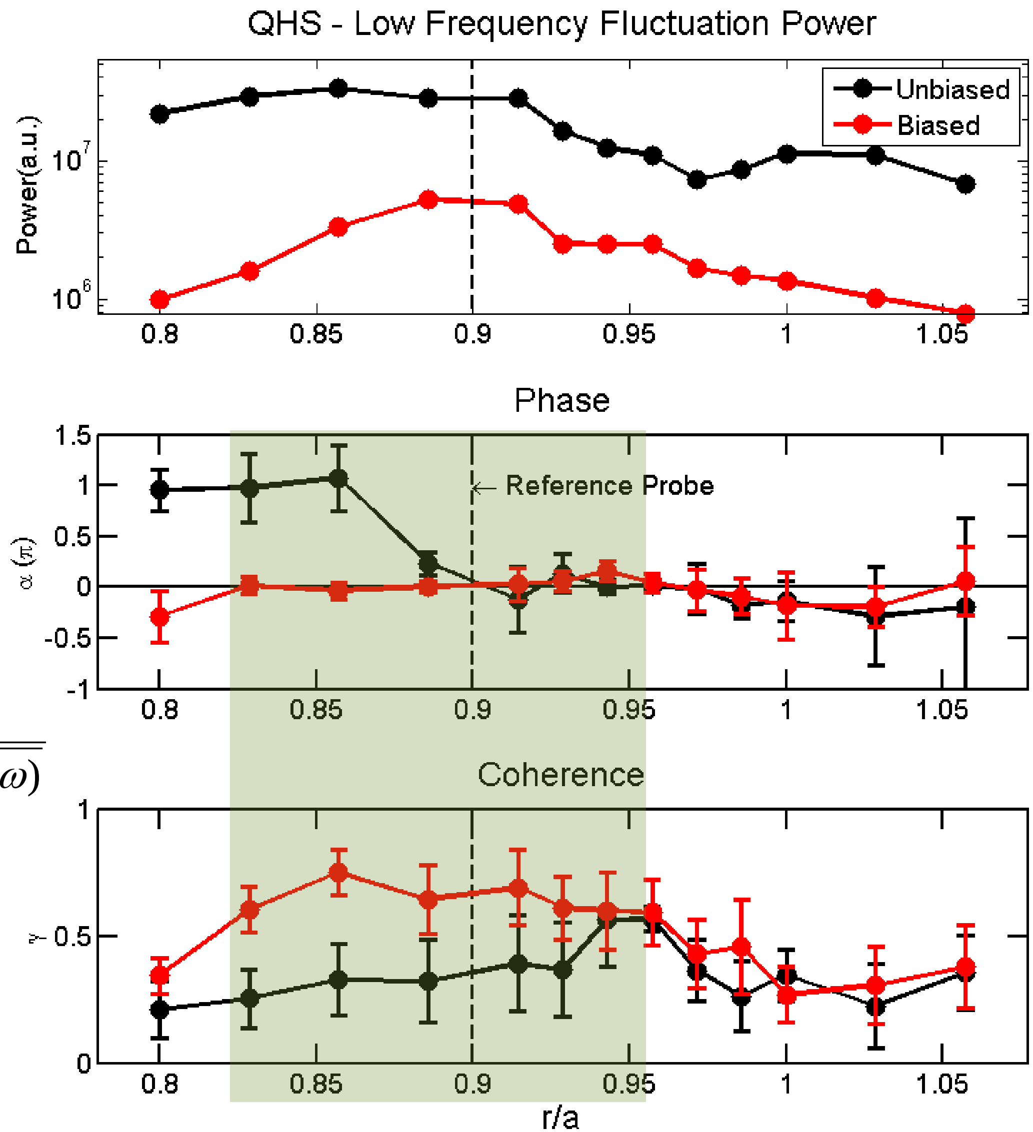
Bias probe located at r/a = 0.75

An experiment was performed to measure long-range correlations during biasing



- **Use two probes toroidally separated by $\phi \approx 3\pi/4$, both on outboard side, but one on high-field side and one on low-field side**
- **Leave the probe on the high-field side stationary while scanning the low-field side probe radially on a shot-by-shot basis**
- **Look for correlations of low-frequency potential fluctuations with zero phase and high coherence**

In QHS configuration, the phase of potential fluctuations goes to zero while coherence > 0.5 where E_r is large

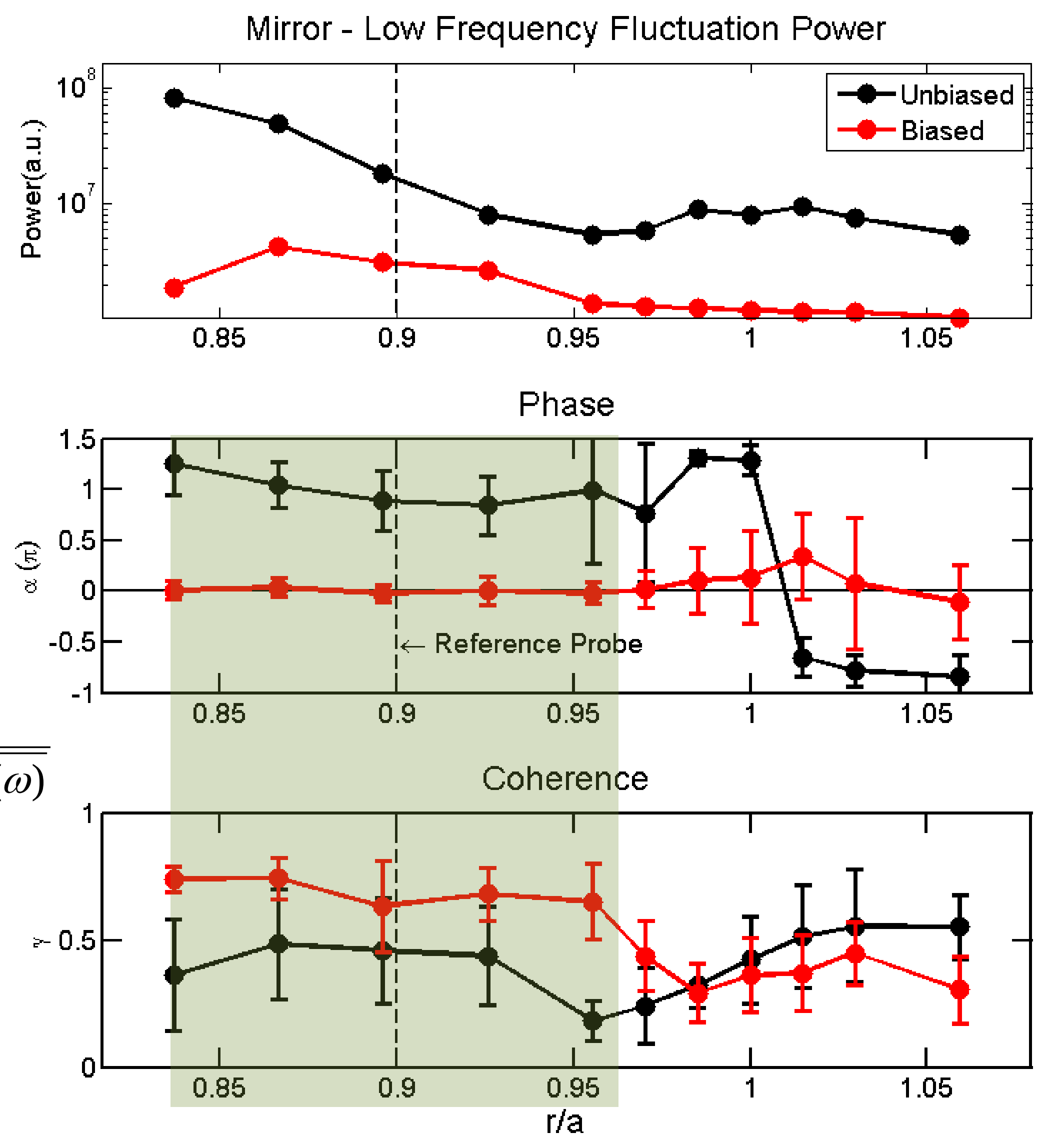


$$\gamma(\omega) = \frac{|P_{xy}(\omega)|}{\sqrt{P_{xx}(\omega)P_{yy}(\omega)}}$$

Zero phase and high coherence seen across similar radial region as bicoherence and high E_r

A similar characteristic is not seen in the density fluctuations, only in the potential

Results are similar with symmetry broken in Mirror configuration



$$\gamma(\omega) = \frac{|P_{xy}(\omega)|}{\sqrt{P_{xx}(\omega)P_{yy}(\omega)}}$$

Summary

- Experiments have been performed to investigate the role of neoclassical transport optimization in zonal flow formation
- During biasing, bicoherence in E_θ fluctuations measured in region with large imposed E_r
- Coupling is strongest where E_r is largest
- Broadband bicoherence observations are similar to those in TJ-II during biased confinement transitions, but distinctly different from measurements during spontaneous confinement transitions
  - No bands in frequency space indicative of direct coupling from high frequency fluctuations to near-zero frequency zonal flows
- Long-range potential correlation measurements in HSX reproduce TJ-II results of zero phase and high coherence during bias
- Results for both experiments (bicoherence and long-range correlations) are similar in QHS and Mirror configurations