Measurements of Long-range Correlations and Bicoherence during Biasing in HSX

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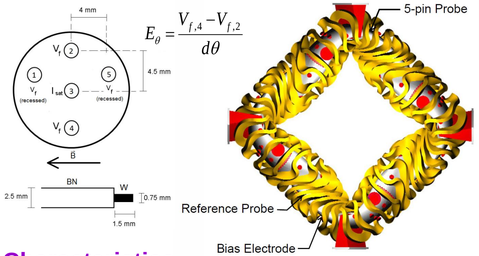
Overview

- This work is part of a collaboration with the TJ-II group in Madrid regarding zonal flows in stellarators
- Our goal is to find differences in zonal flow formation in HSX between a configuration optimized for neoclassical transport and one with the optimization intentionally broken
- Using Langmuir probes at the edge, an increase in the bicoherence of E_θ fluctuations was measured during biasing in the region of strong induced E_r
- Long-range correlations are also observed in the potential fluctuations of spatially separated probes while biasing, but not between density fluctuations
- These observations are consistent with those in other devices, especially during confinement transitions, and are generally seen as indications of zonal flow formation
- Changing the degree of quasi-symmetry has no significant effect on these results

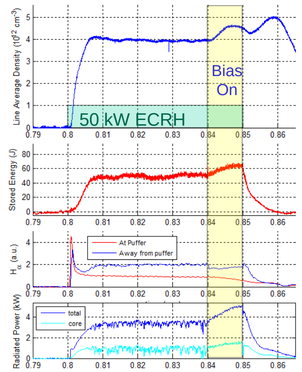
Langmuir Probes and Biasing

- 5-pin Langmuir probe configured to measure floating potential and ion saturation current
- Tungsten probe tips insulated by boron nitride tubes extend from bulk BN to minimize perturbations
- Signals passed through optically isolated amplifiers, sampled at 2MHz
- Probes scanned radially on a shot-by-shot basis
- Bicoherence measured using the floating potential of 2 pins of the 5-pin scanning probe
- Long-range correlations measured with respect to a fixed reference probe located ϕ≈3π/4 toroidally from 5-pin probe

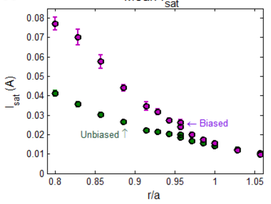


$$E_\theta = \frac{V_{f,4} - V_{f,2}}{d\theta}$$

Biased discharge Characteristics



- Bias probe inserted to r/a = 0.75, biased at 260V relative to a carbon limiter placed just outside the last closed flux surface
- Gas puffing stopped during bias
- Radial electric field is set by bias, probe floating potentials and ion saturation current reach a steady state in <100μs
- Particle transport barrier created by induced flows, as measured by Thomson scattering and Langmuir probes
- Density and stored energy rise during bias
- H_α signals drop
- Radiated power increases as impurities accumulate
- Core temperature increases gradually, possibly due to impurities

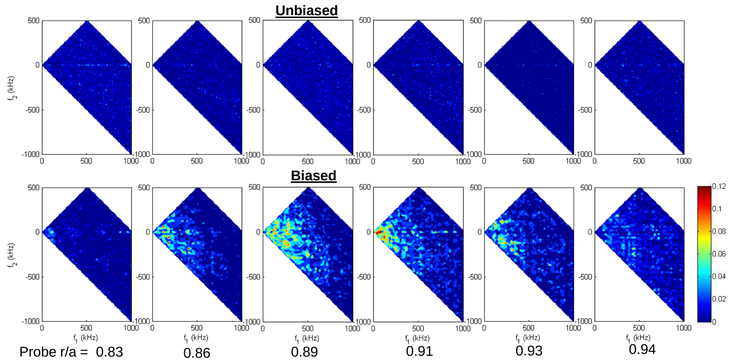


E_θ Bicoherence

- Bicoherence measures 3-wave coupling between single or multiple signals, and is used as a tool to analyze zonal flow drives [1]
- Often measured during transitions to improved confinement regimes
- Plots indicate amount of coupling between fluctuations of frequencies f_1, f_2, and $f_3=f_1+f_2$
- Plots are bounded by the Nyquist frequency on top, left and right, and by symmetry where $f_1=f_2$ and $f_1=-f_2$

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

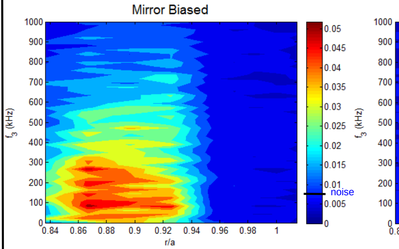
Here f=E_θ → auto-bicoherence of E_θ is plotted

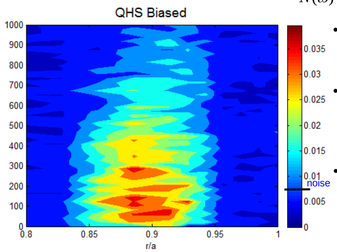


Probe r/a = 0.83 0.86 0.89 0.91 0.93 0.94

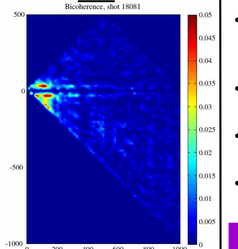
Summed Bicoherence

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





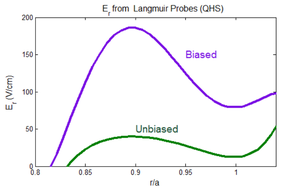
- Increase in auto-bicoherence of E_θ fluctuations well above the noise level is measured when bias is applied
- Broadband coupling is consistent with results from biased discharges in other devices, TJ-II [2] and CCT [3]
- Measurements during spontaneous, unbiased L-H transitions in TJ-II showed more preferential coupling of like frequencies to near-zero frequency modes (more clearly indicative of zonal flows)



[2]

Breaking the Quasi-symmetry

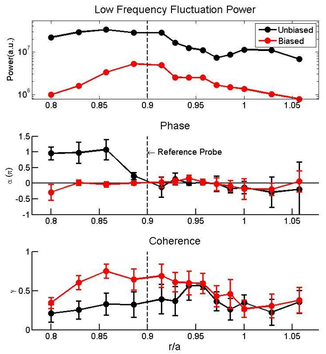
- HSX has a direction of symmetry in the magnetic field strength, |B|
- Auxiliary coils can be energized to introduce additional terms into the |B| spectrum, without significantly changing the mean field strength, well depth, or rotational transform
- Results in this configuration (Mirror) were qualitatively similar to those in the symmetric configuration (QHS)
- Small quantitative differences are assumed to be due to experimental differences between the two configurations when biasing is applied



- Radial electric field found by fitting a curve of the shot-by-shot floating potential profile
- Measured bicoherence is highest in the region where the induced radial electric field is the largest
- This is consistent with results from other devices that measure bicoherence when biasing
- Suggests a link between mean radial electric fields and zonal flow drive

Long-range Correlations

- Zonal flows are expected to be electric field perturbations with zero frequency and a finite spectral width (δf), determined by collisional damping
- Low-frequency (<10kHz) potential fluctuations are measured by 2 spatially separated probes, one stationary and one scanning across the minor radius
- When a bias is applied, correlations between the two fluctuation measurements become in-phase and have higher coherence across a large radial region
- The radial extent of the long-range correlations is similar to that of the bicoherence



- Long-range correlations are not observed in ion saturation signals
- This is consistent with results from TJ-II in both biased and spontaneous L-H transitions, both of which were attributed to zonal flows [4]
- Coupling to zonal flows is predicted to be stronger in neoclassically optimized configurations like QHS [5]
- LHD has simulated and measured reduced anomalous transport in their inward-shifted configuration designed to reduce neoclassical transport [6]

Summary

- Bicoherence of E_θ and long-range correlations of low-frequency potential fluctuations are measured in the region of strong radial electric field during biasing in the HSX stellarator
- This is consistent with previous experiments, in both tokamaks and stellarators, and is generally interpreted as an indication of zonal flows
- Little difference is seen between a configuration with the quasi-symmetry intact and one with it intentionally broken
- Future work will be performed to investigate radial electric field threshold for these observations

References

1) C. P. Ritz et al., *Physics of Fluids B* 1 (1989) 153.
2) B. P. van Milligen et al., *Nuclear Fusion* 48 (2008) 115003.
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4) M.A. Pedrosa et al, *Physical Review Letters* 100 (2008) 215003.
5) H. Sugama et al., *Physical Review Letters* 94 (2005) 115001.
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