

Abstract

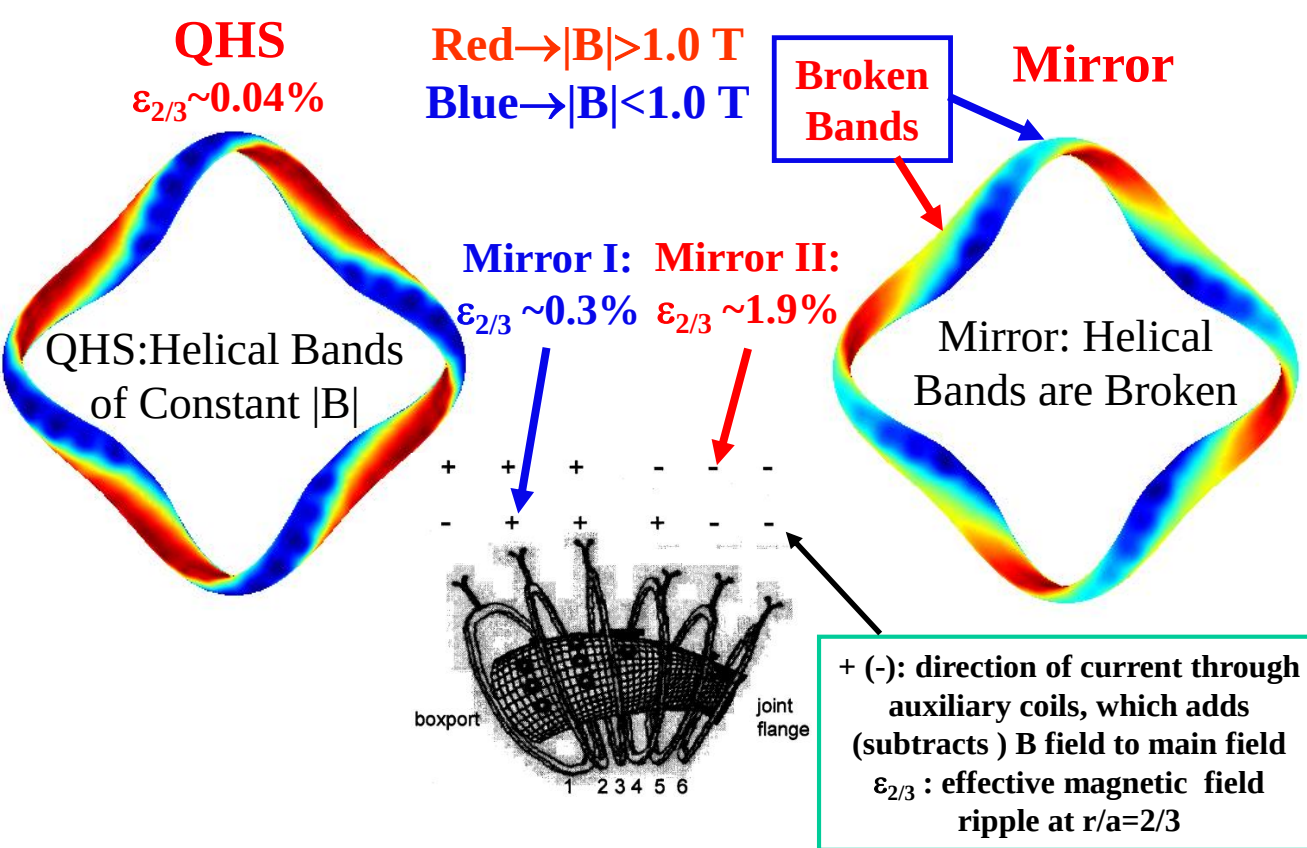
Density fluctuations are measured in the core of the HSX stellarator using a non-perturbing, multi-channel, interferometer system. Measurements show that broadband density turbulences with $k_{\perp} < 2 \text{ cm}^{-1}$, $f = (20-200) \text{ kHz}$ correlates with density gradient and plasma flow. The density fluctuation level is observed to decrease with increasing ECRH power as both the electron temperature, and its gradient, along with plasma flow increase. Electron temperature gradient is eliminated as drive for the observed turbulence. GENE simulations show that the density-gradient-driven TEM may be responsible for the observed density fluctuations. Low-frequency coherent modes are also observed in different magnetic configurations, mirror and QHS. The identifications of these coherent modes will be explored. *Supported by USDOE grants DE-FG03-01ER54615 and DE-FG02-93ER54222.

Outline

- HSX configurations: QHS, Mirror
- Density fluctuation measurement techniques
- Measurement Results:
 - Case I: Fluctuation changes with heating location and power
 - Case II: Fluctuations in QHS and Mirror I configurations
 - Case III: Fluctuations in QHS and Mirror II configurations
- Coherent fluctuations
- Summary and future plans

HSX Provides Access to Configurations With and Without Symmetry

QHS: helical axis of symmetry in $|B|$; predicted very low neoclassical transport
Mirror: quasi-helical symmetry broken by adding a mirror field.

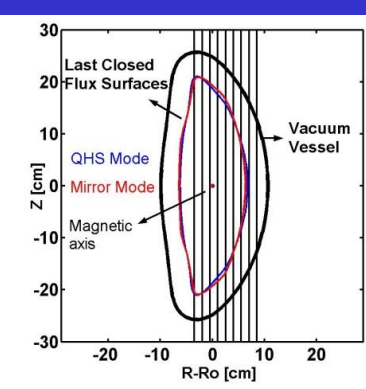


helical axis of symmetry, no toroidal curvature, no toroidal ripple

Conventional stellarators exhibit poor neoclassical transport in low-collisionality regime due to magnetic field ripple

Interferometry System

Flux Surface and Chord Positions



Interferometry (phase measurement)

$$\phi_{\text{Interferometry}}(x) = \int (n_o + \tilde{n}) dl$$

- 9 chords
- 1 MHz bandwidth
- 1.5 cm chord spacing, width
- $k_{\perp} < 2 \text{ cm}^{-1}$

Density fluctuations can be measured from information of:
(i) Amplitude
(ii) Phase
(iii) Differential

Far-forward Scattering- amplitude

$$P_{\text{scatt}} \sim P_{\text{inc}} \tilde{n}^2 \sim (\text{amplitude})^2$$

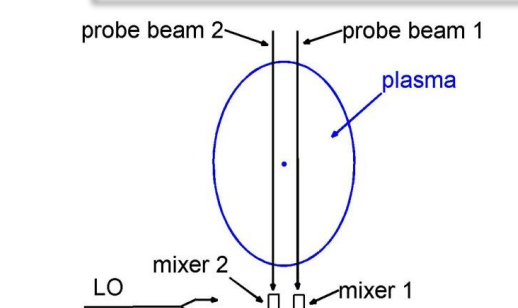
Differential Interferometry Measurement

- For density gradient and gradient fluctuations

$$\frac{d\phi(x)}{dx} = \frac{\phi(x_1) - \phi(x_2)}{x_1 - x_2} = \int \frac{\partial(n_o + \tilde{n})}{\partial r} \frac{x}{r} dl = \int \frac{\partial(n_o + \tilde{n})}{\partial r} \cos \theta dl$$

- For density gradient fluctuations

$$\frac{\partial \tilde{\phi}}{\partial x} = \int \frac{\partial \tilde{n}_e}{\partial r} \cos \theta dz$$



Geometrical weighting factor

central chords provide core localization

Case II: Comparison of QHS and Mirror I Plasmas

ECRH Power: 50kW

Heating locations: on axis

Two different configurations:

QHS: $\varepsilon_{2/3} \sim 0.04\%$

Mirror I: $\varepsilon_{2/3} \sim 0.3\%$

- Plasma stored energy reduced for Mirror I plasma
- Density fluctuations are quite similar for QHS and Mirror I plasmas.

Similar Density fluctuations for QHS and Mirror I

Line-integrated Interferometer measurements show:

Density fluctuations are similar for QHS and Mirror I plasmas, at plasma core and edge.

T_e and n_e for QHS and Mirror I Plasmas

- Significantly lower T_e (T_e gradients) and stored energy for Mirror configuration is caused by increased neoclassical transport.
 - Density profile is slightly hollow for Mirror configuration
- Data inconsistent with T_e drive for turbulence (similar to Case I)

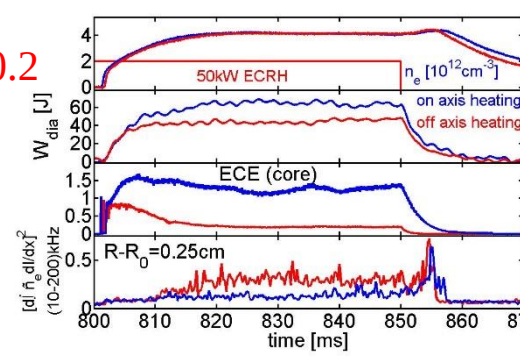
Case I: Density Fluctuations Increase for QHS Plasmas With Off-axis ECRH

QHS Plasma 50 kW ECRH

on-axis ECRH

off-axis ECRH, inboard $r/a=0.2$

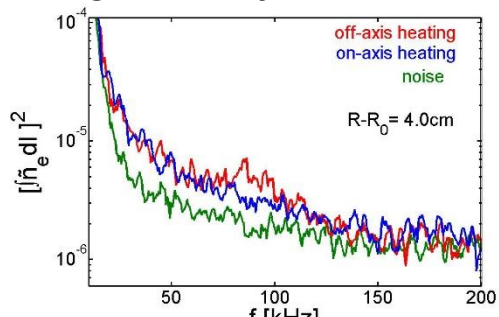
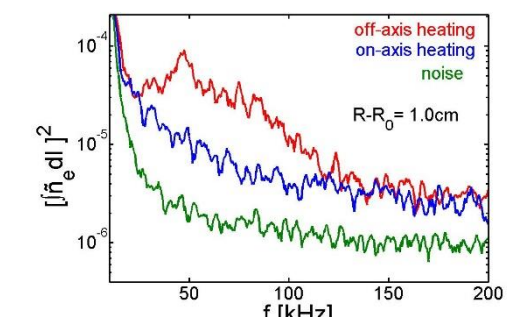
Significantly lower T_e and stored energy for off-axis heated plasma while measured density fluctuations have larger amplitude.



Core Density fluctuations increases with off-axis ECRH

Core density fluctuations

Edge density fluctuations



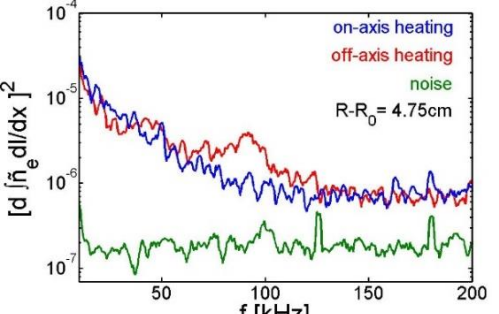
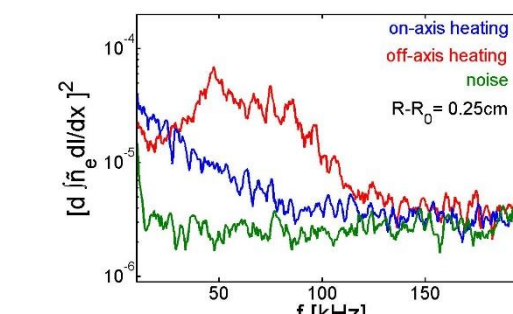
Interferometer measurement shows:

- Line-Integrated density fluctuations increase in amplitude for off-axis heating [ECRH inboard at $r/a \sim 0.2$]
- Increased fluctuation levels observed on central chords, not edge chords, indicating change in core turbulence

Differential interferometer measurement confirms: density fluctuations increase is from turbulence in plasma core, not edge.

Core density gradient fluctuations

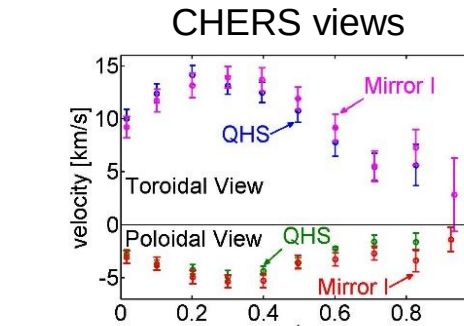
Edge density gradient fluctuations



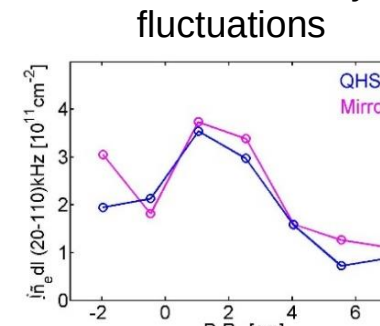
Case II: Comparison of QHS and Mirror I Plasmas

Plasma flow unchanged between QHS and Mirror I

Velocity measured by CHERS views



Profile of density fluctuations

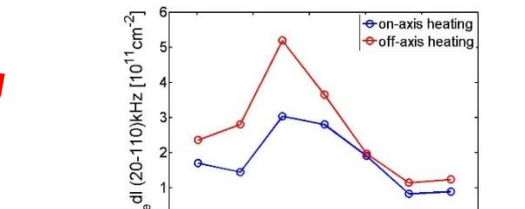


- QHS: transport dominated by anomalous effects (suppressed neoclassical transport)
 - Mirror I: transport dominated by neoclassical effects
 - Plasma turbulence and flow are little changed between the 2 different magnetic configurations
- Similarity of fluctuations, density gradient and flow consistent with Case I picture

Density fluctuations from all interferometer viewing chords.

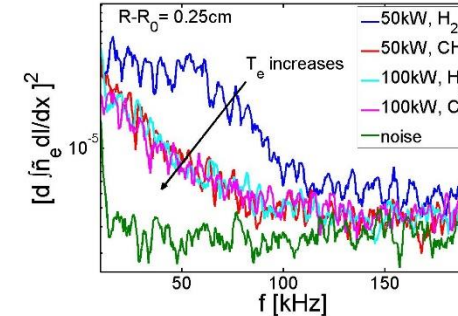
Largest fluctuation change observed on central chords indicating a change in core turbulence

Profiles of density fluctuations in frequency range of (20-110)kHz

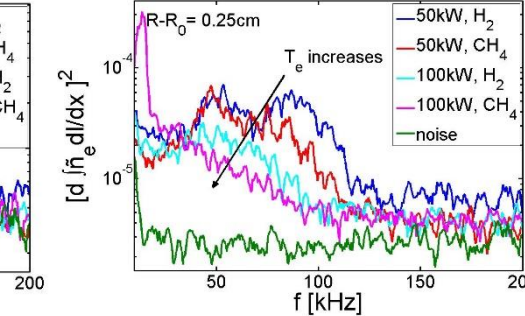


Core density fluctuations vary inversely with P_{ECRH}

On-axis heating



Off-axis heating (inboard)

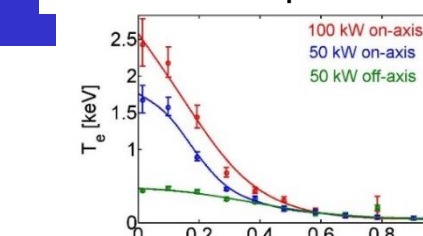


For both on-axis and off-axis ECRH: core density fluctuations are reduced in amplitude with increased heating

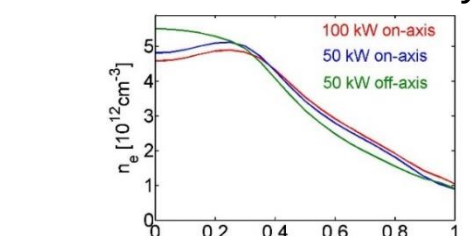
- inconsistent with T_e drive for turbulence.
- is density gradient playing a role?

Temperature and Density Response to ECRH

Electron temperature



Electron density



- Electron temperature highest for 100kW on-axis heating.
 - Density profiles appear quite similar (peaking near magnetic axis)
 - Plasmas with largest T_e and T_e gradients have the lowest fluctuation amplitudes ----- inconsistent with T_e drive for turbulence
 - Plasma stored energy is largest for plasmas with high T_e and reduced core fluctuations
- Core density gradient may be playing a role....

Case III: Comparison of QHS and Mirror II Plasmas

QHS:

$\varepsilon_{2/3} \sim 0.04\%$

Mirror II:

$\varepsilon_{2/3} \sim 1.9\%$

Core density fluctuations

Edge density fluctuations

QHS (x=5.5cm)

Mirror II (x=6.5cm)

noise

Plasma Stored energy 25% lower than that in QHS plasma

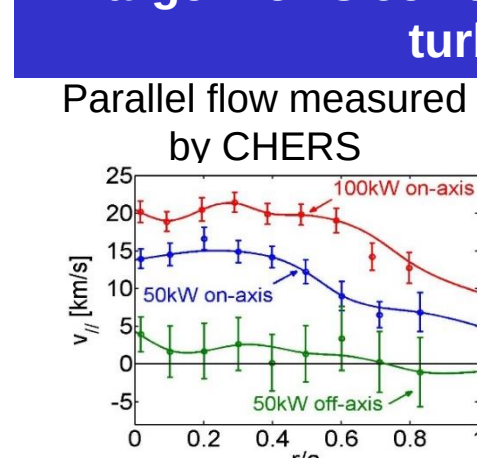
Broad band fluctuations do not have much differences at edge and core, but coherent mode appears for Mirror II plasma

CHERS measurement shows faster flow in Mirror II

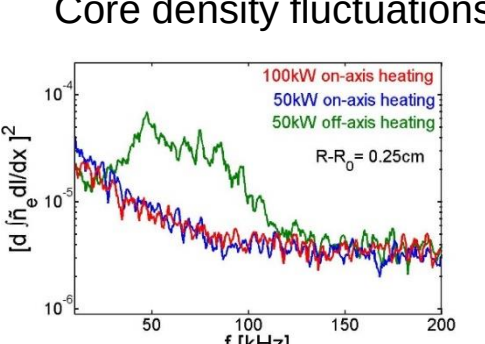
consistent with Case I picture

Large Flows correlate with lower density turbulence!

Parallel flow measured by CHERS



Core density fluctuations

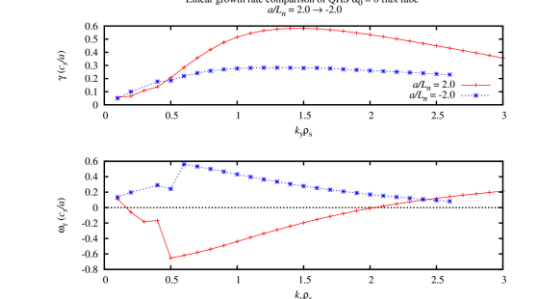


- Flow (parallel) is largest for on-axis power.
 - Doppler shift from plasma flow cannot account for higher frequency density fluctuations with off-axis heating — lower flow but higher fluctuation frequency
 - Density turbulence largest for case with reduced flow (off-axis heating or lower power) and lower stored energy.
- Data suggest large parallel flows may be associated with reduced core plasma density turbulence!!!

Linear GENE simulations show reduced growth rate with hollow density profiles

Linear growth rate is reduced with hollow density profile

$$\omega_e^* \cdot \bar{\omega}_d < 0$$



Coherent Modes in HSX

Coherent mode in QHS plasma

- Coherent mode (density fluctuation) is observed with slight ($r/a \sim 0.05$) inboard offset of heating location
 - Coherent magnetic fluctuations observed on some Mimov coils
 - ECE signals reduced when coherent mode present
 - No change in $n_e(r)$
 - Mode unknown....
- Coherent mode is sensitive to ECRH location

Coherent modes in Mirror I plasma

- Coherent mode observed in Mirror Plasma for $B_{\text{pol}} = 1 \text{ T}$ (ccw)
 - Mode observed in density, not in magnetic signals
 - Density window for mode is narrow: $(3.8-4.5) \times 10^{12} \text{ cm}^{-3}$
 - Decrease in ECE emission suggests decrease in energetic electron confinement.
- Coherent mode is sensitive to electron density

Coherent modes in Mirror II plasma

- Mode at $f = (20-30) \text{ kHz}$ is observed on interferometer, magnetic pick-up coils and Langmuir probes
 - Mode is intermittent, coherent
 - Mode not driven by energetic electrons (mode exists for 5ms after ECRH)
 - Strong bi-coherency observed on Langmuir probe signals
- Observed coherent may indicate existence of GAM

Coherent Modes in HSX With Bias

Biasing excites coherent mode in QHS plasmas

- Biasing excited coherent mode sensitive to bias voltage and electron density
- Bi-coherency is observed for this coherent mode on Langmuir probe signal.

Biasing enhance the coherent mode in Mirror I plasmas

- Biasing increases the coherent mode amplitude, but does not change mode frequency
- Coherent mode observed on magnetic probe when biasing

Summary: Coherent modes in HSX

- QHS: magnetic ripple $\varepsilon_{2/3} \sim 0.04\%$, mode observed when ECH at slightly inboard ($r/a \sim 0.06$), observed on density and magnetic signals, $f = (15-40) \text{ kHz}$, depend on heating locations and density;
- Mirror I: $\varepsilon_{2/3} \sim 0.3\%$, mode observed in certain density window $n_e \sim (3-5) \times 10^{12} \text{ cm}^{-3}$, $f = (20-30) \text{ kHz}$, observed only on density signals;
- Mirror II: $\varepsilon_{2/3} \sim 1.9\%$, $f = (20-30) \text{ kHz}$, mode observed on density and magnetic signals;
- When biased,
 - QHS: the $f = 15 \text{ kHz}$ mode is not affected by bias, but new coherent mode at $f = (10-40) \text{ kHz}$ is observed when electron density is lower than $3 \times 10^{12} \text{ cm}^{-3}$, and bias voltage is lower than 400V
 - Mirror I: coherent mode is enhanced, and magnetic feature is observed.

- Coherent modes appear more easily with higher magnetic ripple
- E_r from biasing affects the mode amplitude and frequency
- Mode frequency scales as acoustic velocity for QHS plasma, [not observed for coherent modes in Mirror I and II plasmas]

Summary and Future Plans

- Interferometry and Differential Interferometry are used to measure density fluctuations in HSX
 - Non-perturbing measurement
 - Line-integrated measurements; spatial information available by comparing chords
 - Differential interferometry is used to obtain core localized measurements
- For QHS plasmas
 - Significant changes (amplitude and frequency) of fluctuations are observed with changes in heating location and power
 - measured density fluctuation change consistent with density gradient drive (not T_e gradient)
 - Reduction of density fluctuations is accompanied by improved confinement and increased plasma flow.
- Mirror plasmas:
 - Coherent mode observed in density fluctuations (and magnetic fluctuations, depending on specific mirror configuration)
 - broadband fluctuations and plasma flow similar to those in QHS plasma.
- Coherent modes are observed for different configurations and plasma conditions

Future work will focus on identification of fluctuations and relation to transport and flows.