# Core Density Fluctuation Measurements by Interferometry in the HSX Stellarator

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## Abstract

The multichannel interferometer system on the HSX stellarator is optimized to measure electron density fluctuations by utilizing both phase and amplitude techniques Information on core and edge fluctuations can be realized by comparing chords at different locations or by use of the differential interferometry approach. Both coherent modes and broadband density fluctuations with frequency up to 250 kHz are measured. For quasi-helically symmetric plasmas with $B_T$=1.0 T, significant changes (both amplitude and frequency) in the turbulent density fluctuation spectrum are observed when heating location changes from on-axis to high field side. Density fluctuation amplitude and frequency decrease with increasing of ECRH power (Te). Changes in fluctuations will be compared with measurements of plasma flow (by CHERS) as well as electron density and temperature profile modifications. When HSX is operated without quasi-helical symmetry at $B_T$=1T and $n_e$= $4x10^{12}$ $cm^{-3}$, a coherent electrostatic mode at 28 kHz is observed. Fluctuation sensitivity to changes of heating location and ECRH power were not observed for these plasmas.

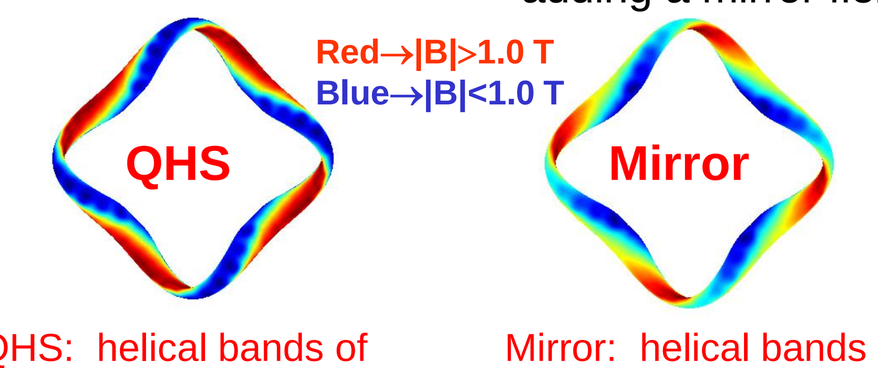
## HSX – Quasi-Helically Symmetry Stellarator

### HSX Provides Access to Configurations With and Without Symmetry

QHS: helical axis of symmetry in |B|

Mirror: quasi-helical symmetry broken by adding a mirror field

**major radius: 1.2 m**
**minor radius: 0.15 m**
**magnetic field: 1 T;**
**ECRH: 28 GHz ,**
**<150 kW**
**pulse length: < 50 ms**




QHS: helical bands of constant |B|

Mirror: helical bands are broken

## Interferometry System

### Measurement Techniques

1. **Interferometry (phase measurement)**

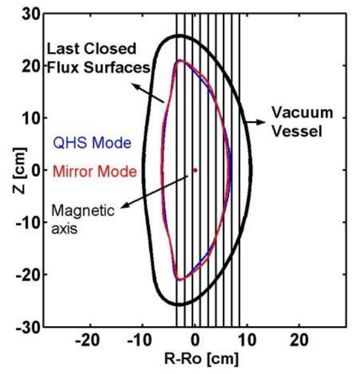
$$\phi_{Interferometry}(x)=\int(n_o+\tilde{n})dl$$

2. **Far-Forward Collective scattering**
   (a) **collective scattering within the divergence of the beam**
   (b) **amplitude measurement**

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

3. **Differential Inteferometry**

### Flux Surface and Chord Positions




Interferometer System:

1. 9 chords
2. 1 MHz bandwidth
3. 1.5 cm chord spacing, width
4. $k_\perp$ < 2 $cm^{-1}$

Density fluctuations can be measured from information of:

(i) Amplitude
(ii) Phase
(iii) Differential

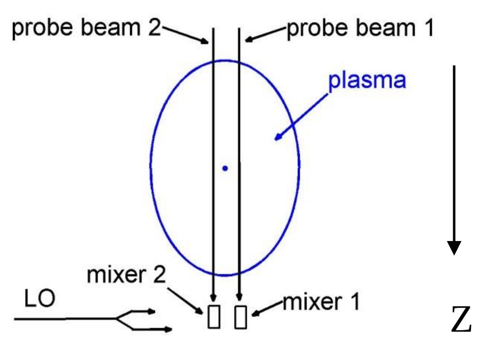
### Localized Density Fluctuation Gradient Measurement

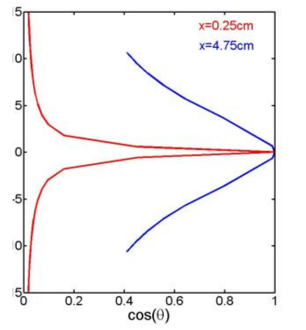
*(1) For density gradient and gradient fluctuations*
[differential interferometry]

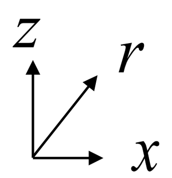
$$\frac{\partial\phi(x)}{\partial x}=\int_x\frac{\partial n_e(r)}{\partial r}\frac{\partial r}{\partial x}dz=\int_x\frac{\partial n_e(r)}{\partial r}\cos\theta dz$$

*(2) For density fluctuations (m=1)*
[standard interferometry]

$$\tilde{\phi}(x)=\int\tilde{n}_e(r)\cos\theta dz$$



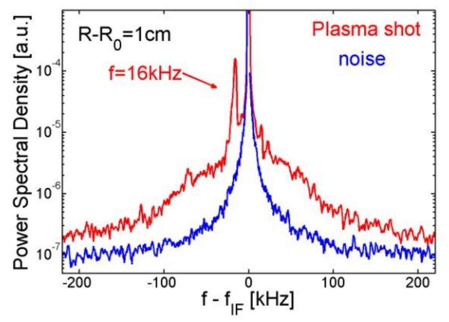



$$\cos\theta=\frac{x}{r}$$

## Results From Three Techniques

### Coherent and Broad Band Fluctuation Measured by Far-Forward Scattering

$$P_{scatt}\approx\tilde{n}^2$$




Plasma Conditions:
$B_T$=1T, Counter Clockwise, QHS
Main Field Current $I_B$=10891A
$n_e$=$4x10^{12}cm^{-3}$ , $P_{ECRH}$=50kW
Scattering measurements
R-$R_o$=1.0 cm

1. Broadband fluctuations
2. Coherent mode at 16 kHz (stronger on neg. side)
3. Coherent mode observed on magnetic coils

### Interferometer and Far-Forward Scattering Show Similar Results

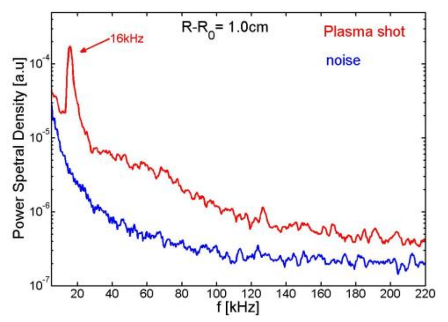
Far-Forward Scattering

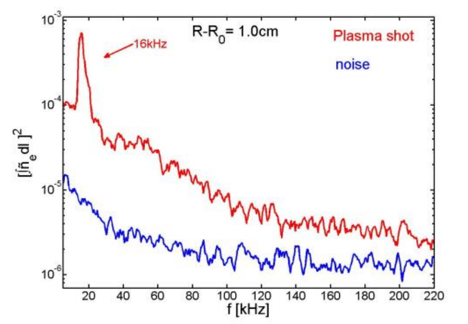
$$P_{scatt}\left[P_{scatt}^{+}+P_{scatt}^{-}\right]\approx\tilde{n}_{Total}^2$$

Interferometry

$$\tilde{\phi}=\int\tilde{n}dl$$

*PhaseFluctuation s* $\tilde{n}^2$

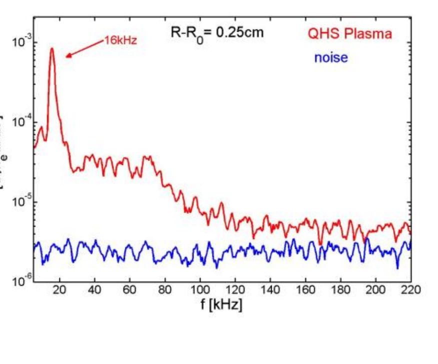


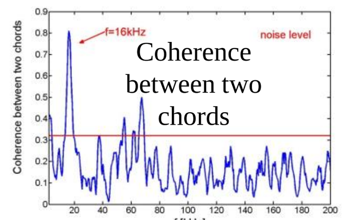

### Density Fluctuations from Differential Interferometry Measurement

$$\frac{d\tilde{\phi}(x)}{dx}=\int\frac{\partial\tilde{n}(x,l)}{\partial x}\frac{x}{r}dl$$

Provides measure of density gradient fluctuations




Directly measures phase difference between adjacent chords
[R-Ro: +1 and -0.5 cm]:



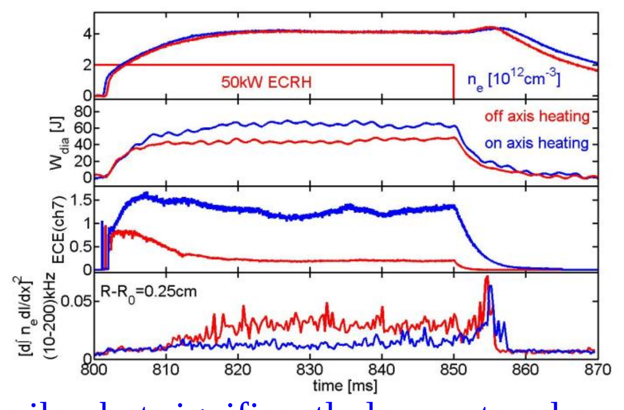

Lower noise level and core localization for differential interferometer measurement

## Density Fluctuations Increase with off-axis Heating (QHS plasma, Bt=1T in CCW)

### Plasma Parameter Time Traces

Plasma Parameters

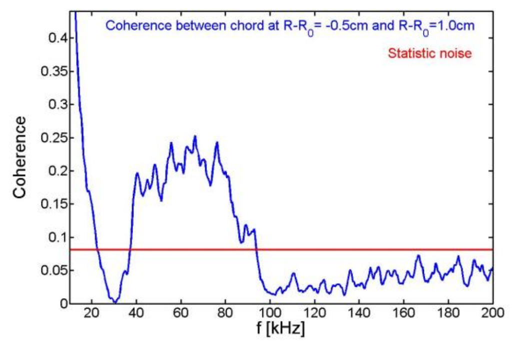
on axis heating:
$I_B$=11000A
off axis heating:
$I_B$=10600A

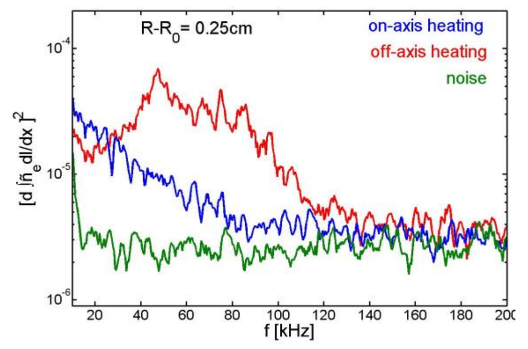


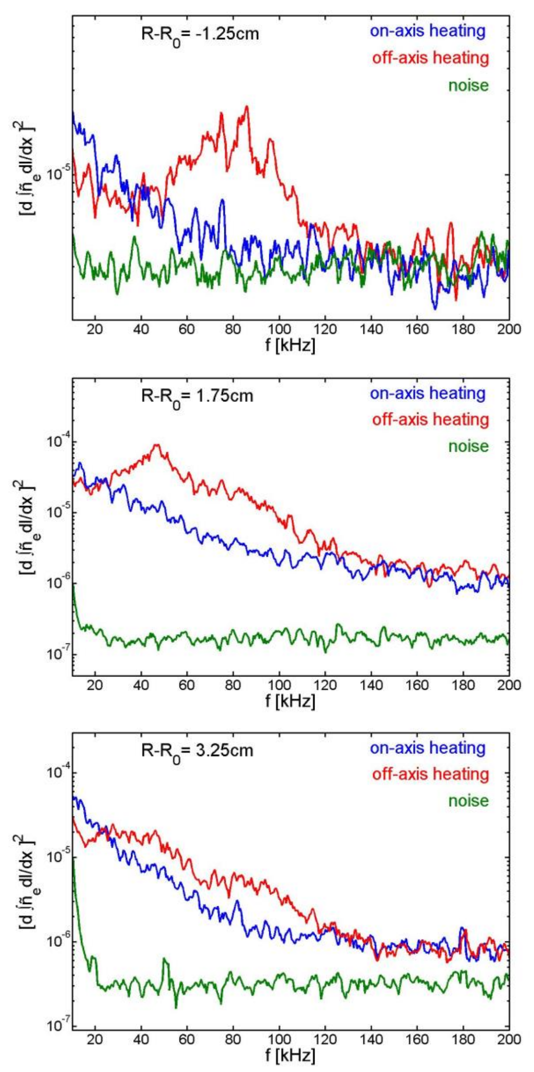

Input ECH power are similar, but significantly lower stored energy for off-axis heated plasma. Measured density fluctuations are of larger amplitude and at higher frequency for off-axis heating.

### Core localized measurement of Density gradient fluctuations shows large increase in amplitude for off-axis heating

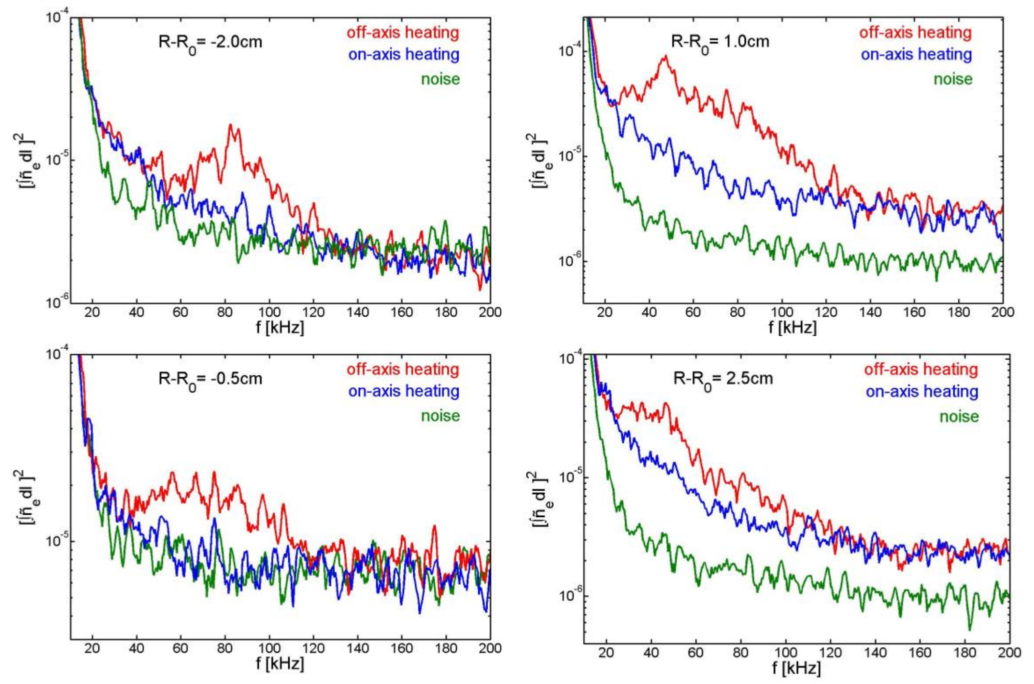
Coherence between two adjacent central chords



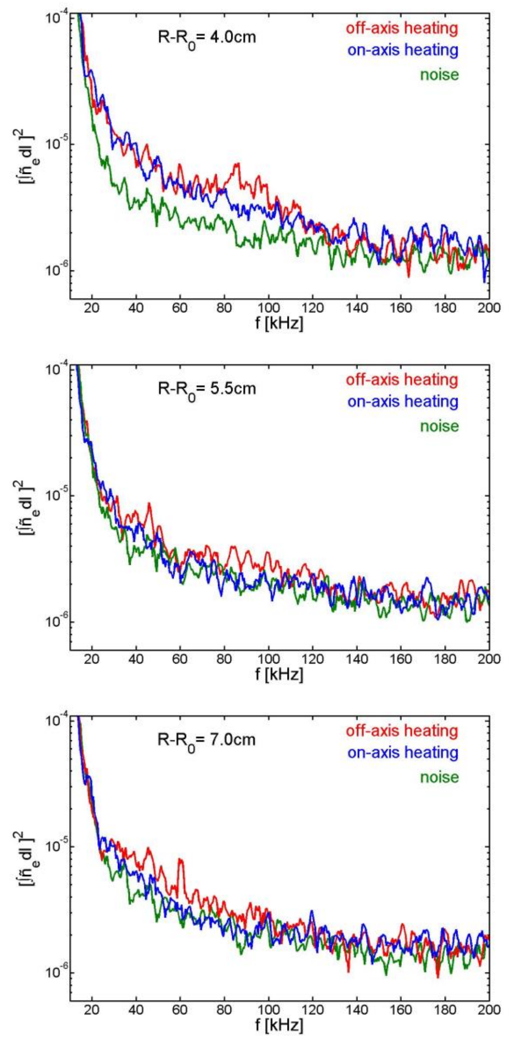




### Significant change in density fluctuations with heating location for central chords

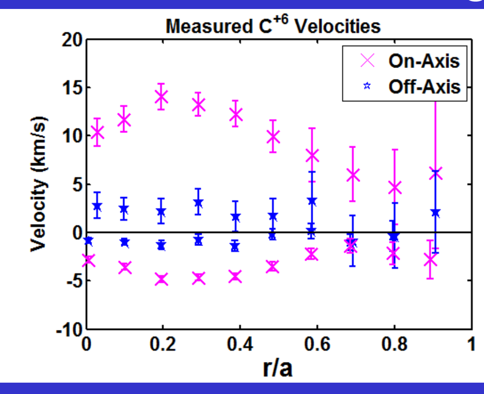



### No change in density fluctuations with heating location for edge chord chords




### Plasma flow reduced for Off-Axis Heating Case

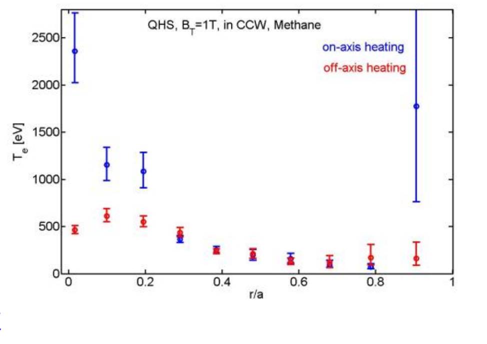
Doppler shift (reduced) cannot account for higher frequency density fluctuations with off-axis ECRH



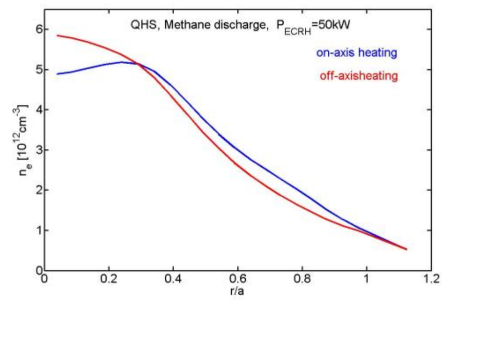

### Electron Temperature and Density Profiles

1) For equivalent ECRH power, off-axis heating results in lower stored energy and lower core temperature
2) Plasma flow is significantly reduced with off-axis heating. Doppler shift cannot account for change in frequency or amplitude of density fluctuations
3) Increased core density fluctuations with off-axis heating ; may act to degrade energy confinement

$T_e$ (Thomson Scattering)



$n_e$ (Interferometer)

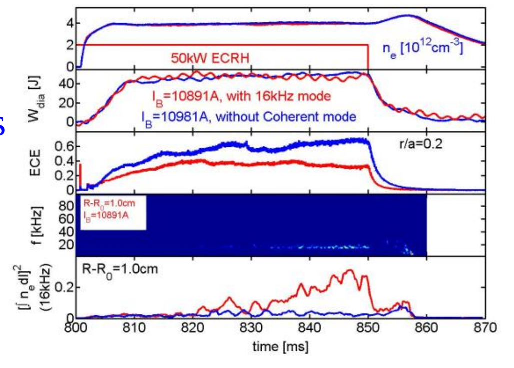


Very peaked Te profile ⟶ flat or slightly hollow density profile (dTe/dr driven diffusion)
⟶ negative density gradient ⟶ reduction of density fluctuations

## Coherent mode in QHS Plasma

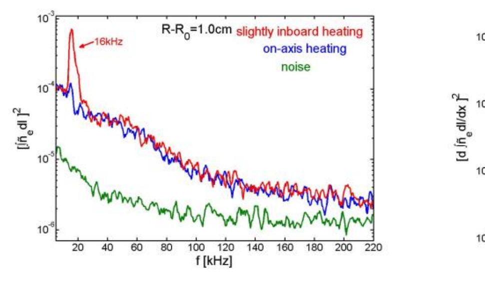
- Coherent mode (density fluctuation) is observed for slightly inboard heating
- Magnetic fluctuations observed on some Mirnov coils
- ECE signals reduced when coherent mode present
- No change in $n_e$(r)

$B_T$=1T in CCW direction

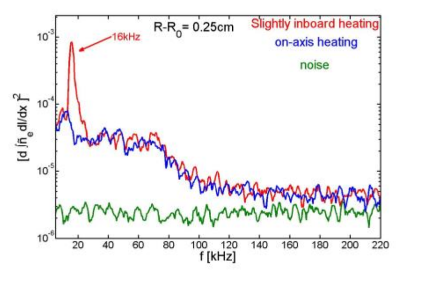



### Frequency Spectrum of Density Fluctuations

Density fluctuations



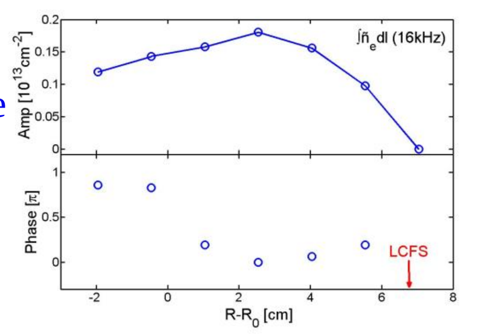
Density gradient fluctuations



- No changes for broad band fluctuations
- coherent mode was observed for slightly inboard heating

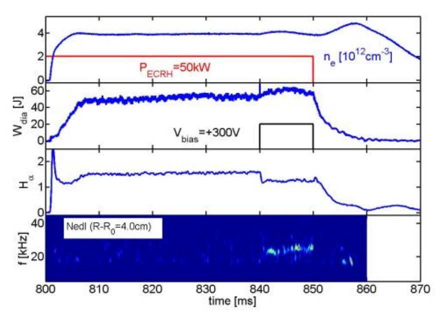
### Amplitude and Phase of the Coherent Mode

- Density mode amplitude peaked near plasma edge
- Density shows π phase shift across magnetic axis; m is odd
- Weak Magnetic fluctuations, external coils suggest m=1

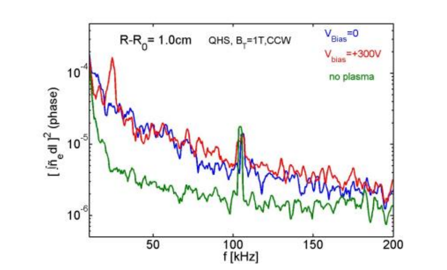



### Coherent mode in biased QHS plasma with $V_{bias}$=+300V

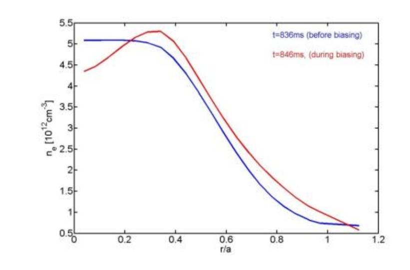
- Coherent mode observed in Biased QHS Plasma, and while broad band fluctuations did not change
- Mode observed in both density, and magnetic signals



#### Frequency Spectrum

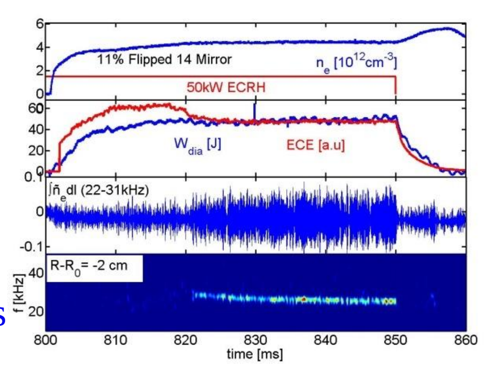


#### Density Profile



## Coherent mode in Mirror Plasma

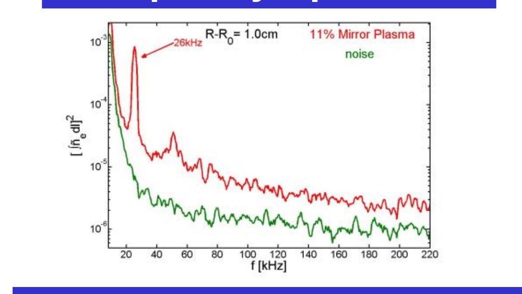
- Coherent mode observed in Mirror Plasma for $B_T$=1 T (ccw)
- Mode observed in density, not in magnetic signals
- Density window for mode is narrow: (3.8-4.5)* $10^{12}$ $cm^{-3}$
- Decrease in ECE emission suggests decrease in energetic electron confinement



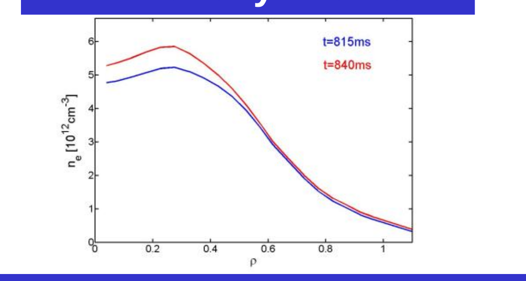

Differences in coherent mode for Mirror and QHS configurations:

1. Mirror: density fluctuation only; QHS: both density and magnetic fluctuation
2. Mirror: sensitive to equilibrium density; QHS is not
3. Mirror: sensitive to direction of B field [cw or ccw]; QHS is not
4. Mirror: not sensitive to $I_B$ (heating location); QHS case is very sensitive to $I_B$

### Frequency Spectrum

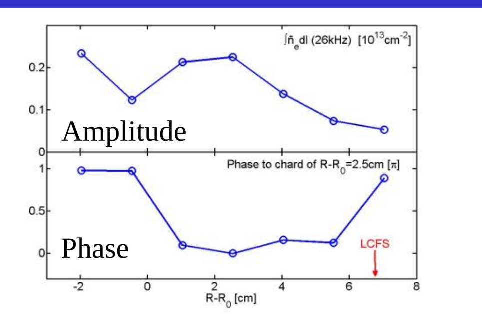



### No Significant Change in Density Profile



### Amplitude and Phase

- mode amplitude is higher on high field side
- π phase shift observed across magnetic axis (m is odd)
- mode not observed on external magnetic coils




## Summary and Future Plans

1. **Interferometry, Differential Interferometry and Far-forward Scattering are used to measure density fluctuations in HSX**
   - line-integrated measurements, some spatial information available by comparing chords
   - differential interferometry is used to obtain core localized measurements
2. **Both coherent modes and broadband fluctuations are observed**
3. **For QHS plasma**
   - Significant changes (amplitude and frequency) of fluctuations are observed when heating location changes from on-axis to HFS heating
   - Density fluctuation amplitude and frequency decrease with of electron temperature
   - core density fluctuations increase and confinement degrades with off-axis heating
   - coherent mode observed on density and magnetic when heating slightly off-axis
4. **Mirror plasma:**
   - Coherent mode observed on density fluctuation signal only,
   - mode not sensitive to ECRH location

**Future work will focus on identification of fluctuations**

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