Coherent Density Fluctuations in the HSX Stellarator

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Abstract

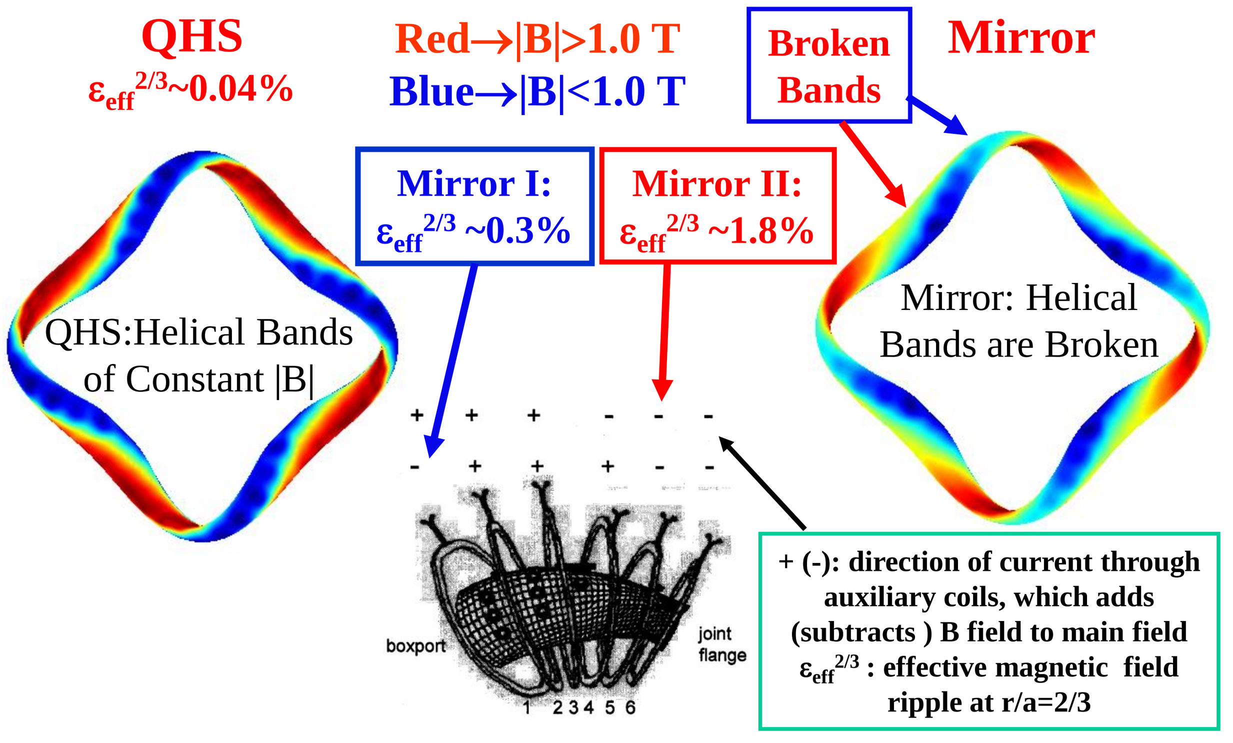
A multi-channel interferometer system is used to measure equilibrium density profile and its fluctuations in the HSX stellarator. Low-frequency, coherent density fluctuation modes are observed in certain quasi-helically symmetric (QHS) plasma conditions and have characteristic frequency of ~15kHz. The mode is observed for small displacement of the 1st harmonic O-mode ECRH location inward from the magnetic axis. This mode is also observed on magnetic fluctuation signals, using external coils, which shows n=1. When HSX is operated without quasi-helical symmetry (mirror configuration), a coherent electrostatic mode at ~28 kHz is observed. Mode radial structure can be obtained from inversion of interferometer measurement when the m number is known. Under certain Mirror conditions, the coherent modes display strong bi-coherence with Langmuir probe signals. Detailed characterization of the observed coherent modes will be reported and their identification will be explored. *Supported by USDOE grants DE-FG03-01ER54615 and DE-FG02-93ER54222.

Outline

1. HSX configurations: QHS, Mirror
2. Density fluctuation measurement techniques
3. Measurement Results:
   - I: Coherent mode in slightly inboard ECRH QHS plasmas
   - II: Coherent mode in Mirror configurations
   - III: Candidates for the coherent modes
4. 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.

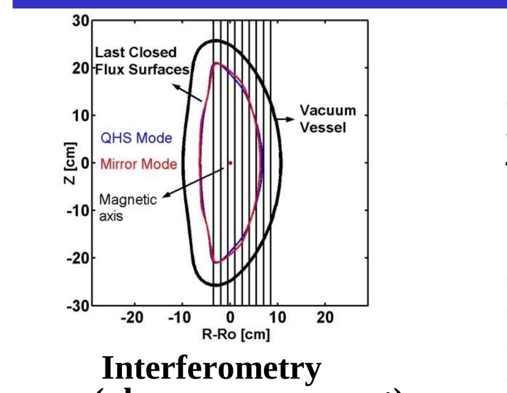


helical axis of symmetry, no toroidal curvature, no toroidal ripple

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

Interferometry System

Flux Surface and Chord Positions



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

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

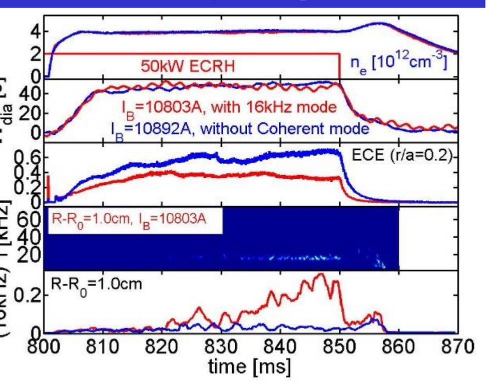
Far-forward Scattering- amplitude $P_{scatt}\sim P_{inc}\tilde{n}^2\sim(amplitude)^2$

Coherent Modes in QHS plasms

Coherent mode is observed in 50kW QHS plasma

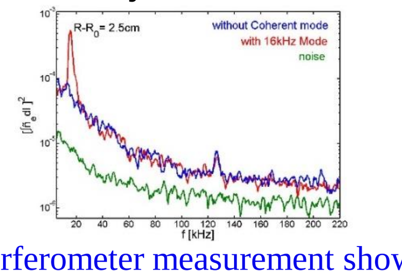
QHS: $\varepsilon_{eff}^{2/3}$ ~0.04%; ι(0)/ι(a)~1.05/1.10

- Coherent mode (density fluctuation) is observed with slight inboard offset of ECRH heating location at r/a~0.05
- Coherent magnetic fluctuations also observed on some Mirnov coils
- ECE signal reduced when coherent mode present
- No change in n_e(r)
- Mode unknown…. **Coherent mode is sensitive to ECRH location**

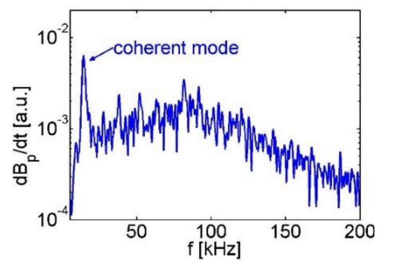


Coherent mode appears on both density and magnetic fluctuations

Density fluctuation



Magnetic fluctuation(Mirnov coils)



Interferometer measurement shows:
- There is sharp peak at f=16kHz on density fluctuations spectrum for slightly inboard heating [ECRH inboard at r/a~0.05]
- Coherent mode observed in both density and magnetic fluctuation signals
- Broadband fluctuations are similar for on-axis and (slightly) inboard heating locations

Inversion method used to get mode structure

assuming m is known, also including the ballooning effect, find the best fit to both the line-integrated mode amplitude and phase of Interferometer data by varying values of m and a.

$$\begin{bmatrix}N_1^{r,i}\\N_2^{r,i}\\\vdots\\N_k^{r,i}\\\vdots\\N_{81}^{r,i}\end{bmatrix}=\begin{bmatrix}L_{1,1}\cdot\cos(m\theta_{1,1})f(\theta_{1,1}) & \cdots & L_{1,j}\cdot\cos(m\theta_{1,j})f(\theta_{1,j}) & \cdots & L_{1,40}\cdot\cos(m\theta_{1,40})f(\theta_{1,40})\\ L_{2,1}\cdot\cos(m\theta_{2,1})f(\theta_{2,1}) & \cdots & L_{2,j}\cdot\cos(m\theta_{2,j})f(\theta_{2,j}) & \cdots & L_{2,40}\cdot\cos(m\theta_{2,40})f(\theta_{2,40})\\ \vdots & & \vdots & & \vdots\\ L_{k,1}\cdot\cos(m\theta_{k,1})f(\theta_{k,1}) & \cdots & L_{k,j}\cdot\cos(m\theta_{k,j})f(\theta_{k,j}) & \cdots & L_{k,40}\cdot\cos(m\theta_{k,40})f(\theta_{k,40})\\ \vdots & & \vdots & & \vdots\\ L_{81,1}\cdot\cos(m\theta_{81,1})f(\theta_{81,1}) & \cdots & L_{81,j}\cdot\cos(m\theta_{81,j})f(\theta_{81,j}) & \cdots & L_{81,40}\cdot\cos(m\theta_{81,40})f(\theta_{81,40})\end{bmatrix}\cdot\begin{bmatrix}n_1^{r,i}\\n_2^{r,i}\\\vdots\\n_j^{r,i}\\\vdots\\n_{40}^{r,i}\end{bmatrix}$$

Where $N_k^{r,i}$ is line-integrated real (r) and imaginary (i) part of mode amplitude at k-th chord, obtained by spline fitting of data measured by interferometer; $n_j^{r,i}$ is the inverted real and imaginary mode amplitude at j-th ring. $L_{k,j}$ is path length at k-th chord, j-th flux ring . 40 flux surface rings, 81 Chord positions are used.

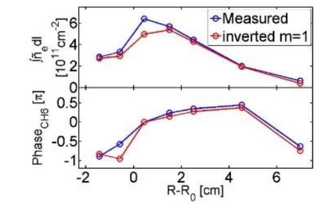
Ballooning effect has the form: $f(\theta_{k,j})=10^{g(\theta_{k,j})}$; $g(\theta_{k,j})=\frac{-a\sin^2\frac{\theta_{k,j}}{2}}{1-a\sin^2\frac{\theta_{k,j}}{2}}$

When a>0, ballooning effects, when a<0, anti-ballooning effects

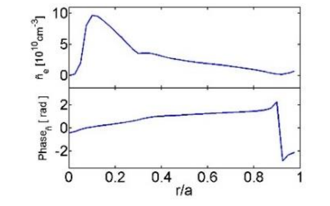
Mode phase can be obtained: $phase_j=\tan^{-1}\frac{n_j^i}{n_j^r}$

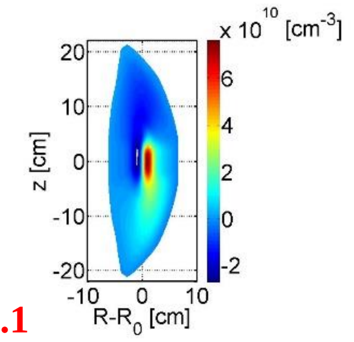
Coherent mode in 50kW ECRH plasma is likely an m=1 mode

Line-integrated Amplitude and Phase



Inverted Amplitude and Phase

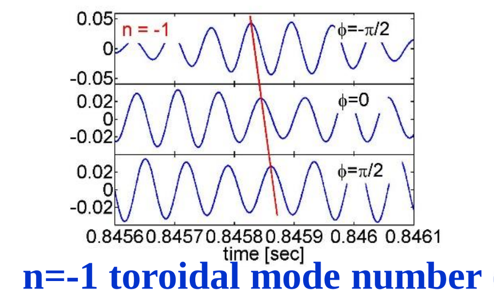




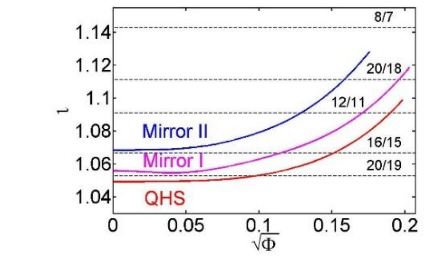
m=1 mode located in the plasma core: r/a~0.1

Coherent toroidal mode number is n=-1

Magnetic fluctuation(Mirnov coils)



ι and rational surfaces

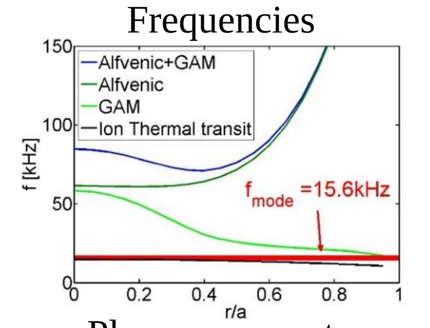


n=-1 toroidal mode number (measured by magnetic), no low m/n rational surfaces in HSX:

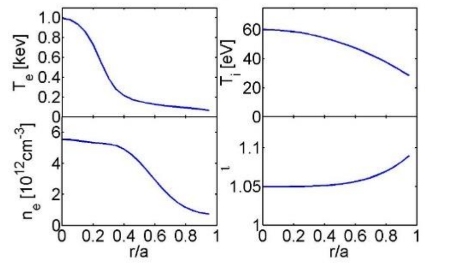
indicating the mode may be driven by energetic particles, or non-linear turbulence

Mode frequency is close to ion thermal transit frequency (50kW ECRH Plasma)

Frequencies



Plasma parameters



$$\omega=(\omega_A^2+\omega_{GAM}^2)^{1/2}=\left[(m\iota-n)^2\frac{V_A^2}{R^2}+\frac{2T_e}{m_iR^2}\left(1+\frac{7}{4}\frac{T_i}{T_e}\right)\right]^{1/2}$$

$$\omega_{Alfven}=(m\iota-n)\frac{V_A}{R}\qquad m/n=1/1$$

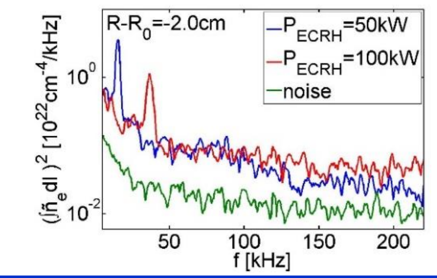
$$\omega_{GAM}=\left[\frac{2T_e}{m_iR^2}\left(1+\frac{7}{4}\frac{T_i}{T_e}\right)\right]^{1/2}$$

$$\omega_{Ti}=\sqrt{2T_i/m_i}/qR_0$$

Mode frequency close to ion transit frequency, indicating the mode may be : (1) BAE (2) BAAE (3) KBM

Mode frequency increases with ECRH Power

Spectrum of density fluctuations



Mode frequency:

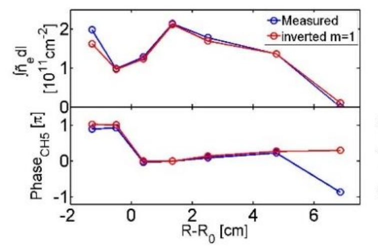
16 kHz: 50 kW ECRH (ion transit frequency)

37 kHz: 100 kW ECRH (GAM frequency)

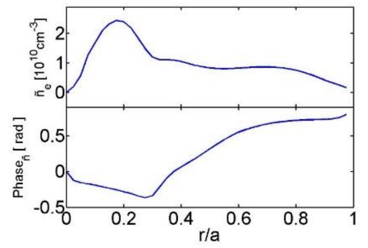
mode resonates to different particle energies

Coherent mode in 100kW ECRH plasma is likely an m=1 mode

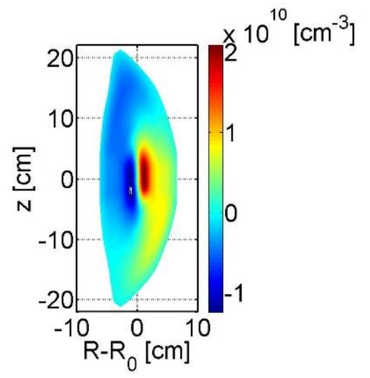
Line-integrated



Inverted



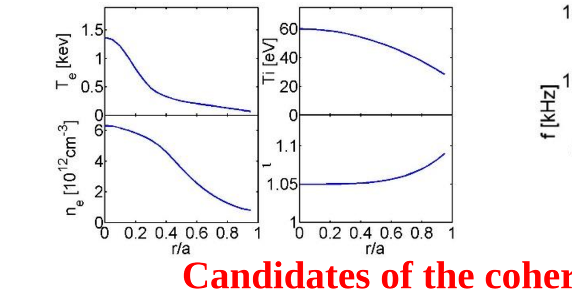
2D image of the mode



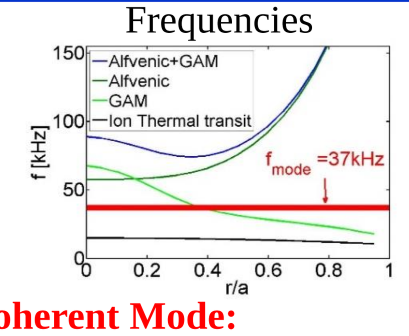
Best fit to Inversion of Interferometer data shows: mode is most likely m=1 mode, and located at r/a~0.2

Mode Frequency is close to GAM frequency for 100kW ECRH plasma

Plasma parameters



Frequencies



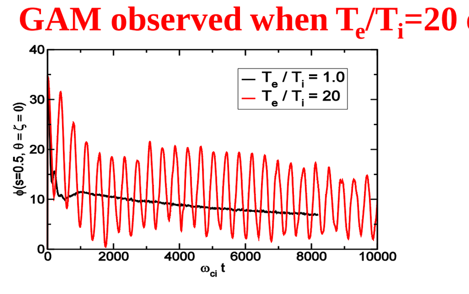
Candidates of the coherent Mode: (1) GAM (2) Ion sound wave

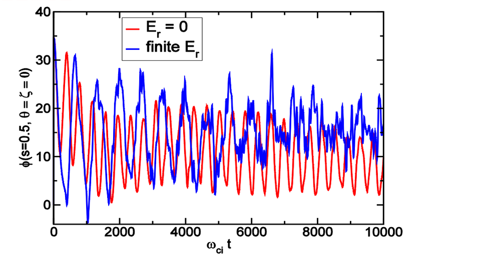
Simulations show GAM could exist on HSX when Te>>Ti (Alexey Mishchenko)

HSX for 50kW ECRH QHS plasma Te(0)/Ti(0)=1000eV/55eV=18, no Landau damping to sound wave

GAM damping rate: $\gamma\propto-\exp\left(-\left(\tau^{-1}+\frac{3}{4}\right)q^2-\xi\right)\exp(-q^2)$; $\tau=\frac{T_i}{T_e}$; $q=\frac{1}{\iota}$

GAM observed when T_e/T_i=20 on HSX



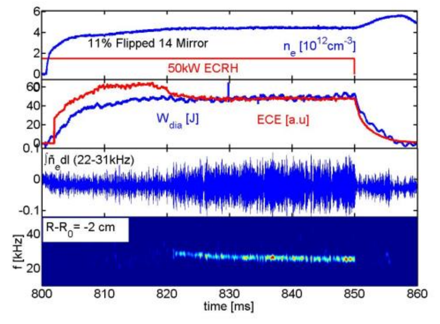


The linear HSX simulations (using adiabatic-electron approximation) at large flat Te/Ti ~ 20 show:
- **a) GAM exists**
- **b) Ambient Er affects GAM**

Coherent modes in Mirror I plasma

Mirror I: $\varepsilon_{eff}^{2/3}$ ~0.3%; ι(0)/ι (a)~1.055/1.125

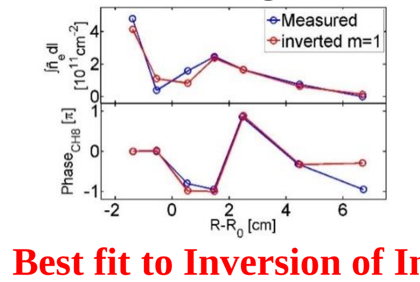
- Coherent mode observed in Mirror I Plasma for B_T=1 T
- Mode observed in density, not in magnetic signals
- Density window for mode is narrow: (3.5-4.5)*10^{12}cm^{-3}
- Decrease in ECE emission suggests decrease in energetic electron confinement.



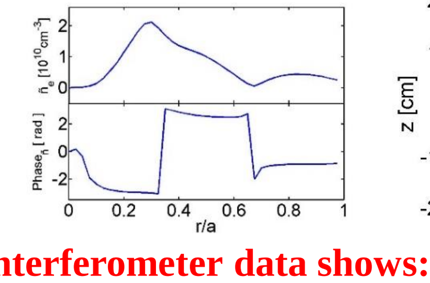
Coherent mode is sensitive to electron density

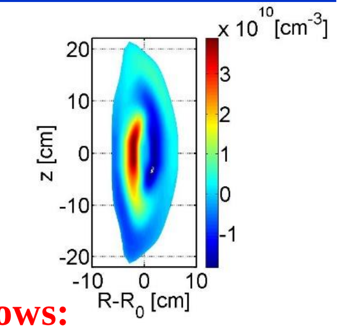
Coherent mode is likely an m=1 and shows anti-ballooning effect

Line-integrated



Inverted

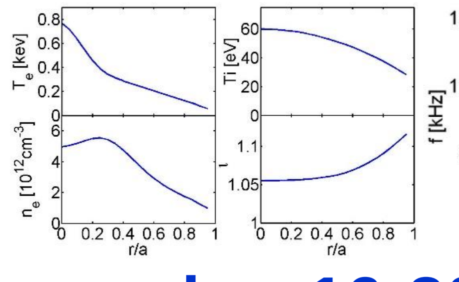




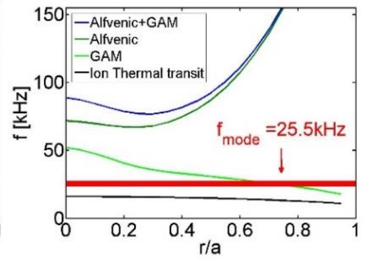
Best fit to Inversion of Interferometer data shows: the mode is most likely m=1 mode and located at r/a~0.3

Mode frequency is close to GAM frequency

Plasma parameters



Frequencies

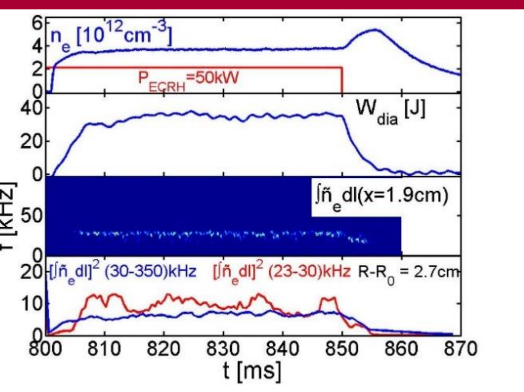


Candidates of the coherent mode: (1) GAM (2) EPM

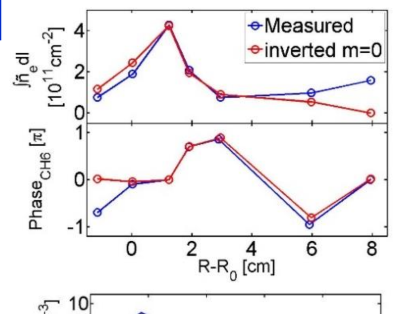
Coherent Density Fluctuation mode observed in Mirror II Plasma

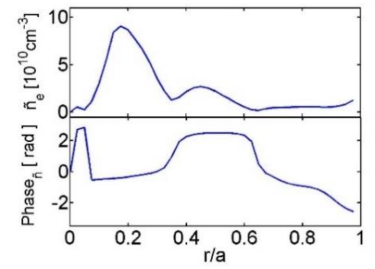
Mirror II: $\varepsilon_{eff}^{2/3}$ ~1.8%;ι(0)/ι (a)~1.067/1.13

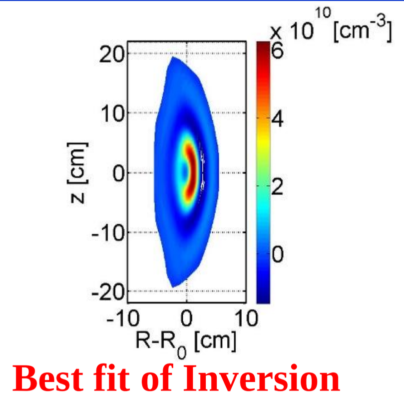
- mode at f=20kHz is observed on interferometer, magnetic pick-up coils and Langmuir probes
- mode is intermittent, coherent
- Mode not driven by energetic electrons (mode exists for 5ms after ECRH)
- Bi-coherency observed on Langmuir probe signals: zonal flows may be active



Coherent mode in Mirror II plasma is likely an m=0 mode



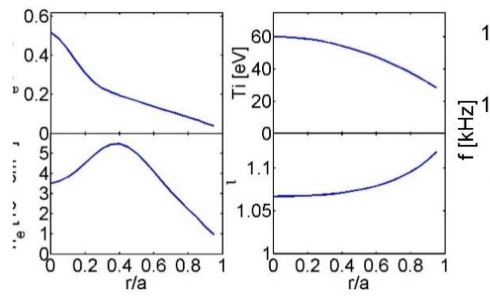




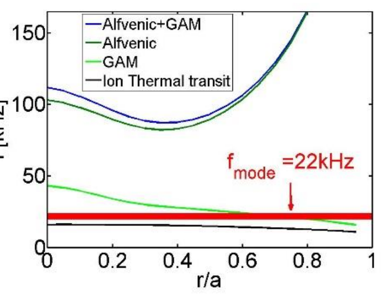
Best fit of Inversion shows: the mode is most likely m=0 mode, peaked at r/a~0.2

Mode frequency is close to GAM wave frequency

Plasma parameters

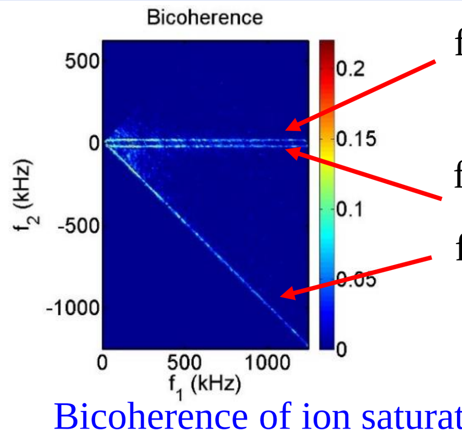


Frequencies



Candidate of the coherent mode: GAM

Strong Bicoherence of ion saturation currents is observed



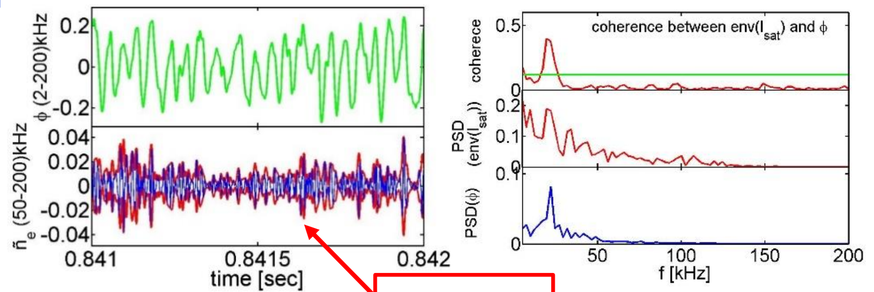
Bicoherence of ion saturation current :

Zonal flow-like oscillations

Coherent mode modulates density fluctuations

Floating potential and envelop of ion saturation current

Floating potential and envelop of ion saturation current fluctuations are correlated



Strong correlation between floating potential and envelop of ion saturation current fluctuations at mode frequency in Mirror II

Summary and Future Plans

1. **Interferometry and Differential Interferometry are used to measure density fluctuations in HSX**
   Non-perturbing measurement, both broad-band (Nucl. Fusion **55** (2015)123003) and coherent fluctuations are measured.
   Coherent mode radial structure could be obtained by Abel Inversion
2. **QHS: coherent mode observed on density and magnetic signals, f=(15-40) kHz, when ECH at slightly inboard (r/a=0.05); m=1, f_{mode} increases with ECRH power.**
3. **Mirror I: coherent mode with f=(20-30)kHz observed only on density signals in certain density window ne~(3-5)x10^{12}cm^{-3} , m=1 mode frequency is close to GAM frequency.**
4. **Mirror II: coherent mode with f=(20-30)kHz, observed on density and magnetic signals with likely m=0; Langmuir probe measurements show strong bicoherence and density turbulence modulated by the coherent mode: indicating zonal flow may be active**

Future works

1. **Identification of coherent modes and relation to transport**
2. **Upgrade of FIR interferometer and collective scattering system is proposed to increase wavenumber sensitivity from an upper bound of 2 cm^{-1} to 10-15 cm^{-1}.**

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