



Energetic-Electron-Driven Alfvénic Modes in HSX



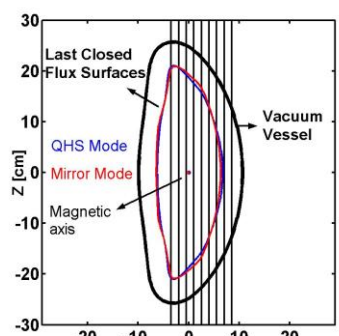
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Overview

1. Density Profiles for 0.5 and 1 Tesla Operation
2. Characteristics of observed fluctuations
 - Quasi-Helically Symmetric (QHS) configuration
 - Mirror (MM) configuration (conventional stellarator)
3. Impact of the GAE mode on Plasma Stored Energy
4. Mode amplitude and frequency variation with ECRH power.
5. Temperature effects on mode frequency

Density Profile Measurement

Flux Surfaces and Interferometer Chords

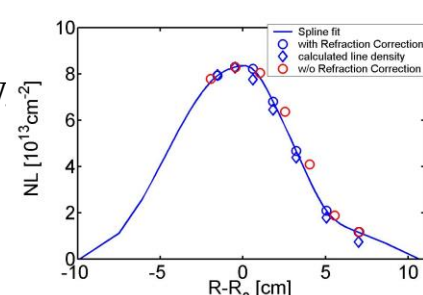


Interferometer System:

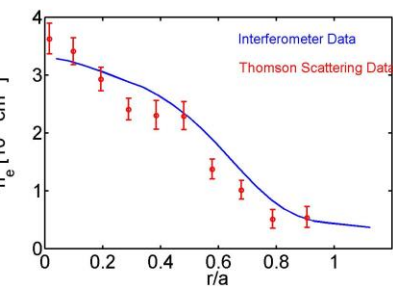
1. 9 chords
2. 200 kHz B.W
3. 1.5 cm chord spacing

HSX Density Profile in 0.5 T QHS Plasma

Measured Line-Integrated Density Profile and fitting

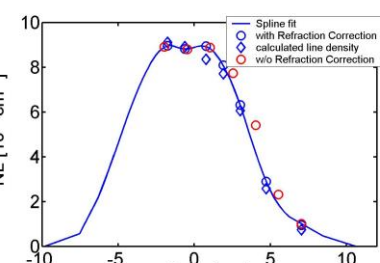


Inverted Density Profile

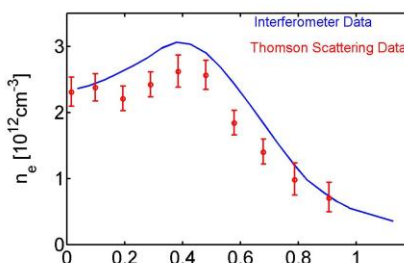


HSX Density Profile in 0.5 T Mirror Plasma

Measured Line-Integrated Density Profile and fitting

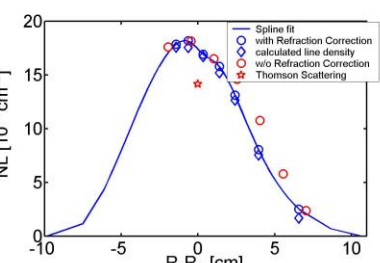


Inverted Density Profile

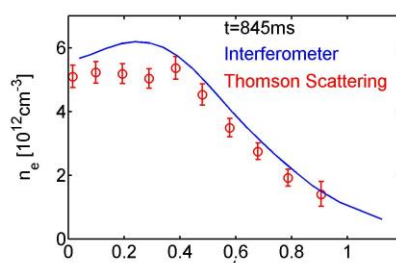


HSX Density Profile in 1 T QHS Plasma

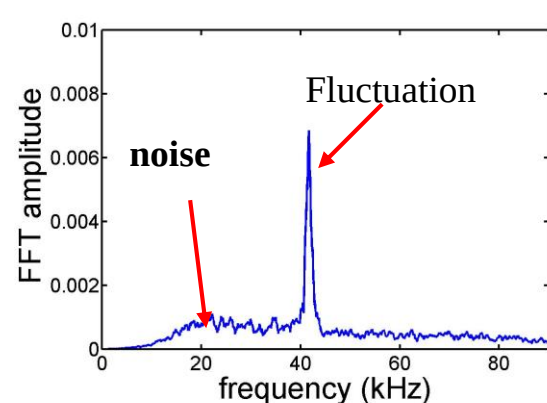
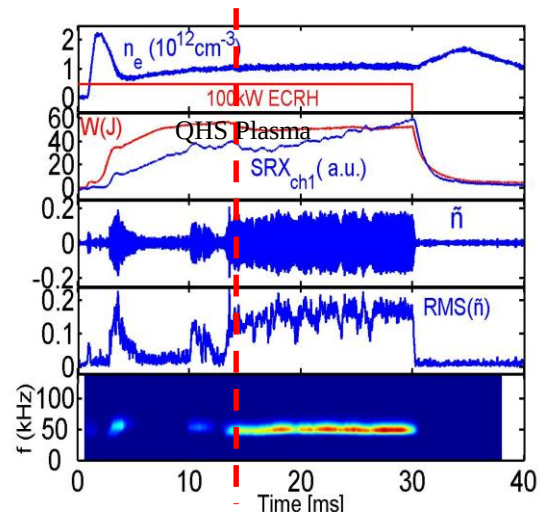
Measured Line-Integrated Density Profile and fitting



Inverted Density Profile



Coherent Density Fluctuations in 0.5T QHS Plasma

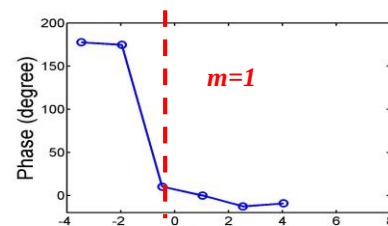


- 28 GHz ECRH
- 2nd Harmonic X-mode
- Generates fast electrons with $T_{e\perp} \gg T_{e\parallel}$

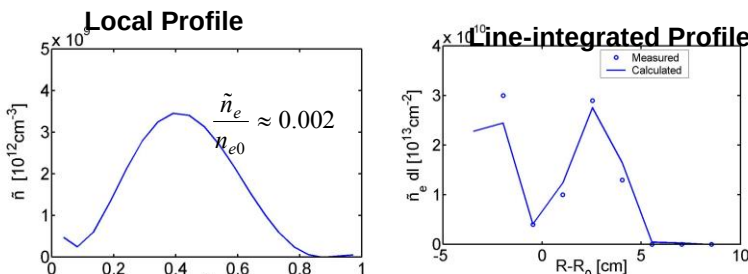
For $P_{ECRH} > 100$ kW, mode degrades confinement,
- perturbs particle orbits leading to enhanced loss

Fluctuation features

1. only observed in QHS plasmas
2. coherent, $m=1$ / $n=1$
3. localized to steep gradient region
5. Satellite mode appears at low densities, $\Delta f \sim 20$ kHz
6. Electromagnetic component



Density Fluctuation Spatial Distribution

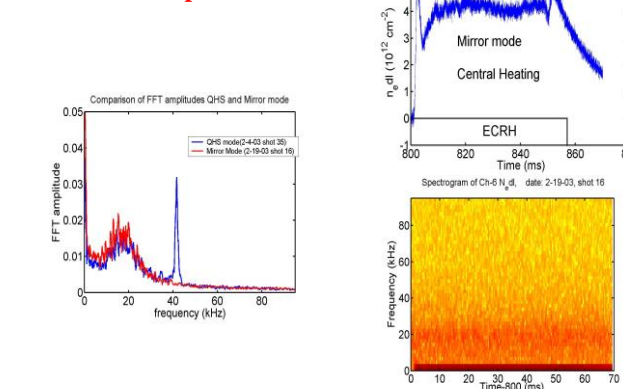


Since helicity (m,n) is known, density perturbation can be inverted to obtain local density distribution
- local density perturbation shape is guessed using 5th order polynomial
- line-integrals are calculated and compared to measured line-integrals
- free parameters are changed to optimize fit
- best fit obtained when m=1 was selected, in agreement with measurements

- Mode is core localized,
- Mode peaks in region of steepest density gradient

No Mode In Mirror Configuration

10% Mirror perturbation

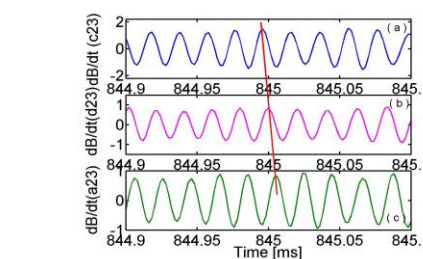
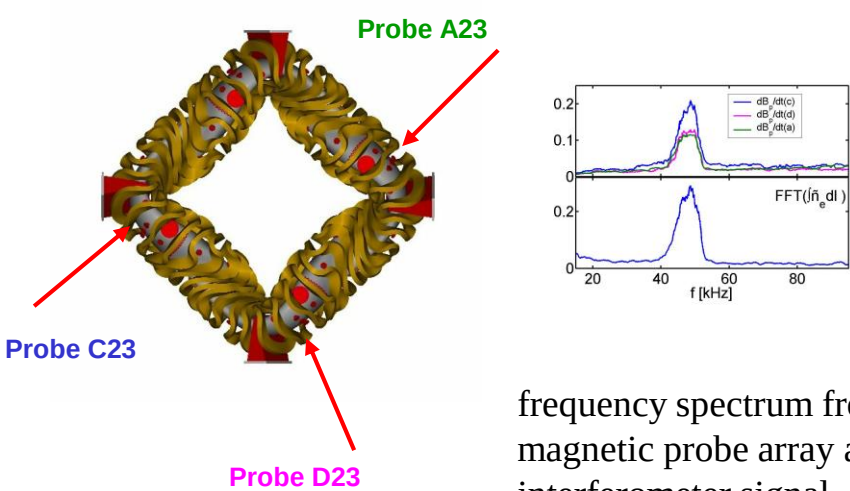


Observed Fluctuations Associated with ECRH

- Mode disappears ~ 0.2 msec after ECRH turn-off, - faster timescale than W_E and soft x-rays
- 2nd Harmonic X-mode generates nonthermal electrons (ECE) (no source for fast ions: $T_e \sim 20$ eV)

Modes are driven by energetic electrons

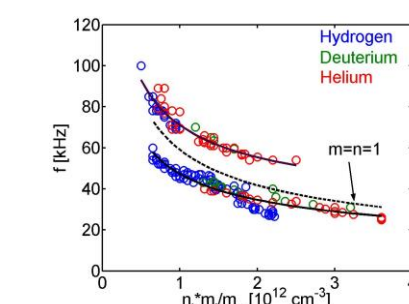
Fluctuation data from Magnetic Toroidal Coil Array, mode number: n=1



Signals (a), (b), (c) are from probes at Port c23,d23 and a23. The magnetic probe arrays measurement shows the $n=1$.

Mode Frequency Scaling

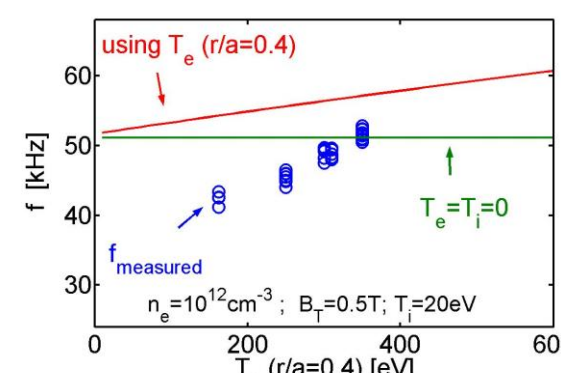
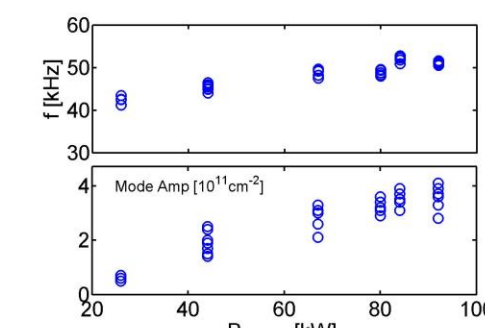
Mode Frequency Scaling with Ion Mass Density



$$\omega_{GAE} \leq k_{\parallel} V_A = \frac{(m-1)n}{R} \frac{B}{\sqrt{4\pi m_i m_e}}$$

- frequency and mass density scaling consistent with Alfvénic mode
- If iota is lowered < 1 , mode not observed

Mode Frequency and Amplitude Dependence on P_{ECRH}



- Mode amplitude and frequency increase with P_{ECRH} .
- Frequency increase with P_{ECRH} largely explained by finite temperature effects.
- Finite E_r may also be important:

$$f_{\text{measured}} = f_{\text{mode}} + kE_r/B$$

$$\omega_{AC}(t) = \left[(m-1)n^2 \frac{V_A^2}{R^2} + \frac{2T_e}{M_e R^2} \left(1 + \frac{7}{4} \frac{T_e}{T_i} \right) \right]^{1/2}$$

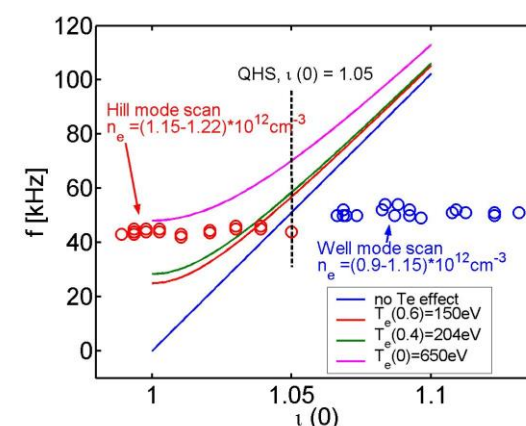
Breizman, PoP 12,112506(2005)

Mode Frequency Scaling with iota

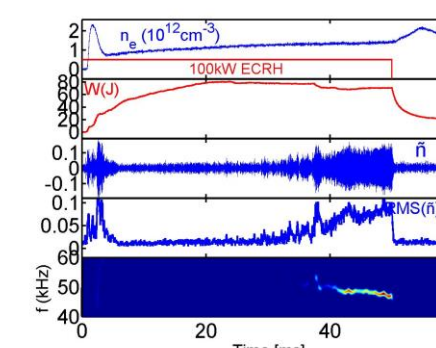
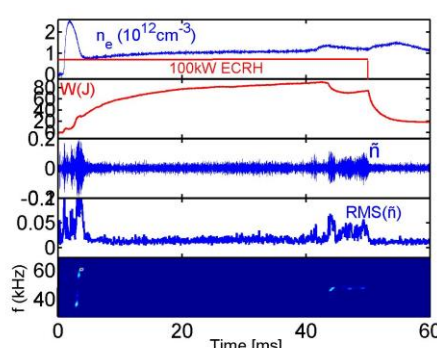
Iota scanned by changing the current through auxiliary coils.

Expected iota scaling was not observed

Observed mode may possibly be an Energetic Particle Mode (EPM)



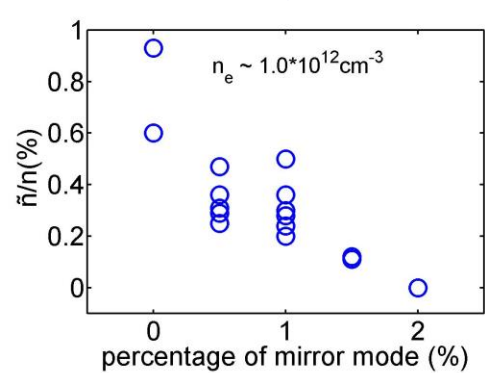
GAE Mode and Plasma Stored Energy



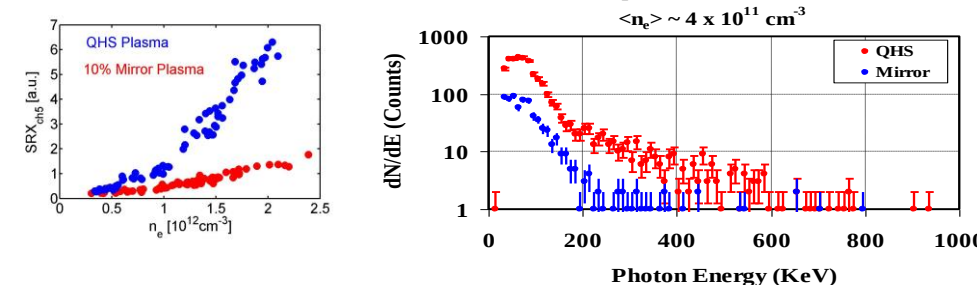
When $P_{ECRH} > 100$ kW, onset of GAE mode triggers reduction of plasma stored energy by up to 20%.

Fluctuations with Symmetry Breaking

Density fluctuations decrease with introduction of symmetry breaking (toroidal mirror) term



Soft X-ray, Hard X-ray Emission for QHS and

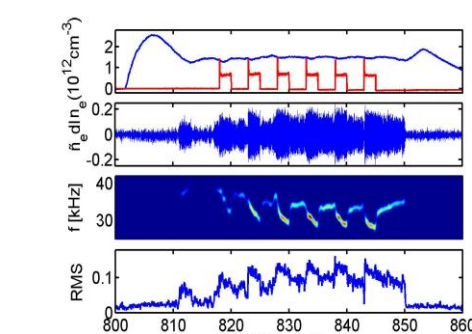


- Soft X-ray (600 eV-6 keV) emission, QHS >> Mirror
- Hard X-ray flux: QHS >> Mirror; decay time longer
- Indicates fast particles are better confined in QHS
- $\omega_{dh} = \omega_{GAE}$: 15-30 keV particles

- fast particles (trapped electrons) are better confined for QHS
- provide drive for Alfvénic modes

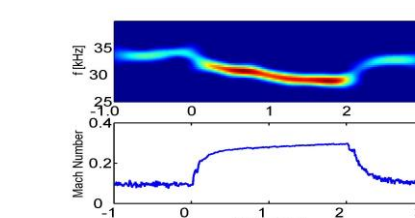
Effects of Biasing on GAE mode

QHS: + biasing increases amplitude and decreases frequency



- amplitude increases 50-100%
- frequency decreases 10-20%

Alfvénic mode frequency shift can be used to measure core flow dynamics



$$f_{\text{obs}} = f_{\text{GAE}} + f_{\text{Doppler}} = f_{\text{GAE}} + \frac{1}{2\pi} k \cdot v_{\text{flow}} = f_{\text{GAE}} + \frac{m}{r} \frac{E_r}{2\pi B_e}$$
$$\Delta f_{\text{obs}} = f_{\text{obs}}|_{v_{\text{flow}}=0} - f_{\text{obs}}|_{v_{\text{flow}}=v_{\text{flow}}} = \Delta f_{\text{Doppler}} = \frac{m}{r} \frac{\Delta E_r}{2\pi B_e}$$

for plasma core with bias

During biasing: n_e and B do not change so V_A is constant

Ambient plasma potential is (+)

$E \times B$ flow (edge) in ion drift direction

Alfvénic mode propagates in electron diamagnetic drift direction (lab frame, without bias)

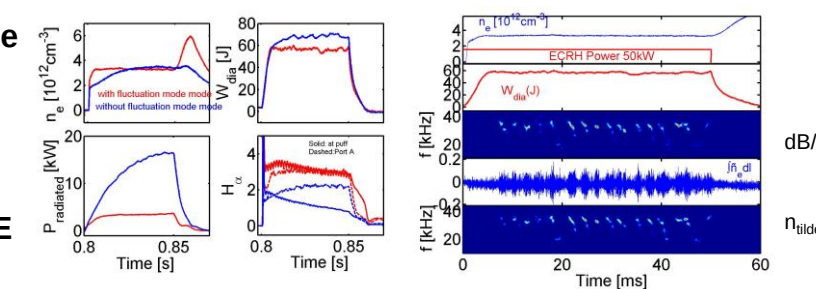
Mode in 1 T Plasma

Mode rarely observed (<5%) for $B_r = 1$ T plasmas. Likely due to fewer trapped particle for O-mode heating at the fundamental frequency, 28 GHz

When observed:

- (1) Mode chirps down in frequency.
- (2) $f_{\text{measured}} < 40$ kHz ($m=n=1$) does not match expected GAE scaling (80kHz)
- (3) effect of E_r unknown.

Experiments just beginning to investigate mode at 1 Tesla



Conclusions and Discussions

1. The equilibrium density distribution for $B_r = 0.5$ and 1 T was obtained by the multi-channel Interferometer on HSX
2. The plasma stored energy could be reduced up to 20% by onset of GAE mode.
3. The coherent fluctuation is global with mode number $m/n=1/1$, with frequency and ion mass density scaling is consistent with Alfvénic mode.
 - poloidally: propagates in the electron diamagnetic drift direction
4. The plasma temperature effect on Alfvénic mode was observed. GAE mode frequency increases with T_e as expected.
5. Alfvénic Mode is only observed for QHS configuration, not for Mirror Configuration (2%)
6. Mode propagates poloidally in the electron drift direction, as expected for fast electron drive. Toroidal propagation??
7. Mode helicity [$m=1, n=1$] and spatial structure are measured.
8. Mode scaling with ion mass density consistent with Alfvénic mode
9. Satellite frequency: likely due to different n , measurements are required to verify
10. Electric field measurement is necessary to determine the actual mode frequency in plasma frame.