Evidence for Alfvénic Fluctuations in Quasi-Helically Symmetric HSX Plasmas

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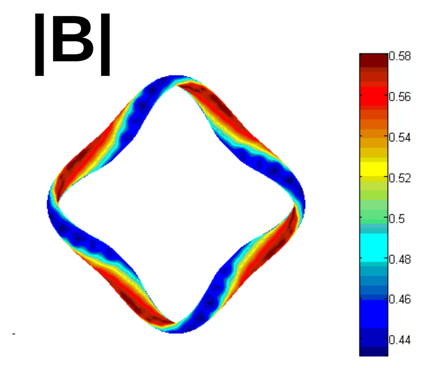
Key Results

1. Alfvén Continua for QHS and Mirror Mode Plasmas (conventional stellarator) on HSX
2. Characteristics of observed fluctuations in Quasi-Helically Symmetric plasma
3. Evidence for fast-electron driven GAE mode

Helically Symmetry Configuration

|B|



- Conventional stellarators exhibit poor neoclassical transport in low-collisionality regime due to magnetic field ripple
- HSX: helical axis of symmetry, no toroidal curvature, no toroidal ripple

Symmetry in |B| : $B = B_0\left[1-\varepsilon_h \cos(N - m\iota)\phi\right]$, $\varepsilon_t \approx 0$

- Symmetry in |B| leads to small deviation of trapped particles orbits from a flux surface and, as a result, to improved neoclassical confinement in low collisionality regime

reduction in '1/ν' transport

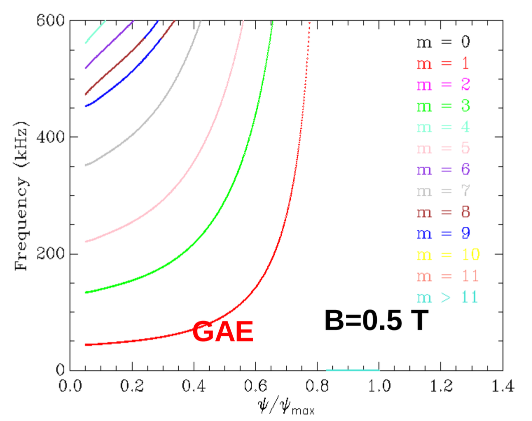
Alfvén continua: n = 1 mode family

Quasi-Helically Symmetric (QHS) configuration

Quasi-Helical Symmetry: Helical axis of symmetry, no toroidal curvature

GAE Gap: 0 - 40kHz, for m=1, n=1

B=0.5 T, $n_e(0)=1.8\times10^{12}$ cm^{-3}



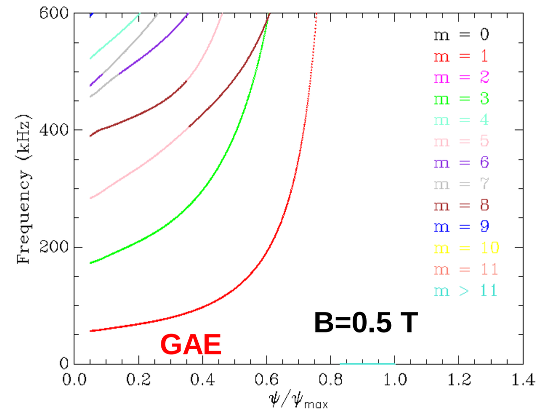
STELLGAP code (D. Spong)

Mirror Mode (MM) configuration

Mirror Mode: toroidal mirror term introduced to magnetic configuration, equivalent to conventional stellarator operation

GAE Gap: 0 - 60kHz, for m=1, n=1

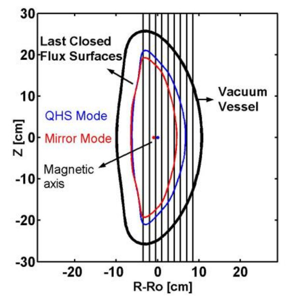
B=0.5 T, $n_e(0)=1.8\times10^{12}$ cm^{-3}



10% mirror perturbation (STELLGAP code)

HSX Interferometer Channels

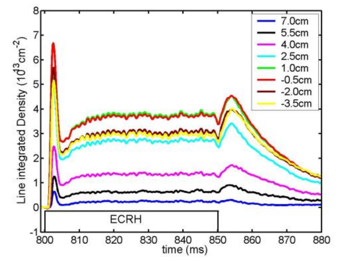
Flux Surfaces and Interferometer Chords



Interferometer System:

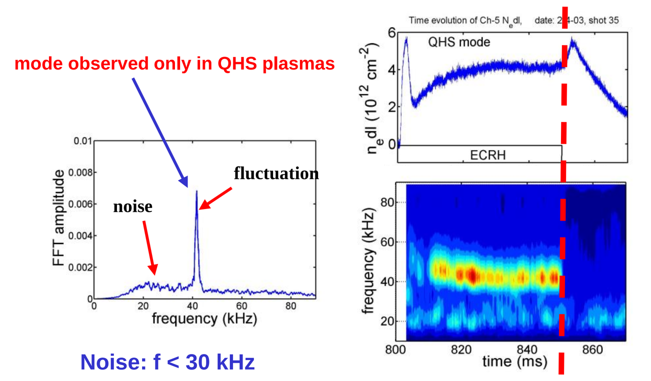
1. 9 chords
2. 200 kHz B.W.
3. 1.5 cm chord spacing

Density Evolution for QHS Plasma



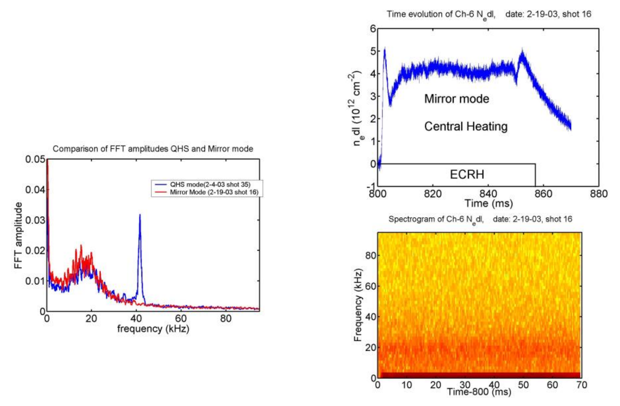
Density Fluctuations

Density Fluctuations in QHS



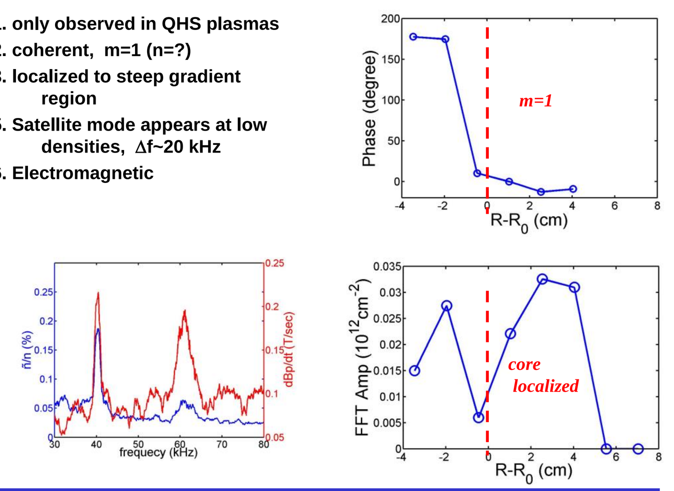
Noise: f < 30 kHz

No Mode In Mirror Configuration

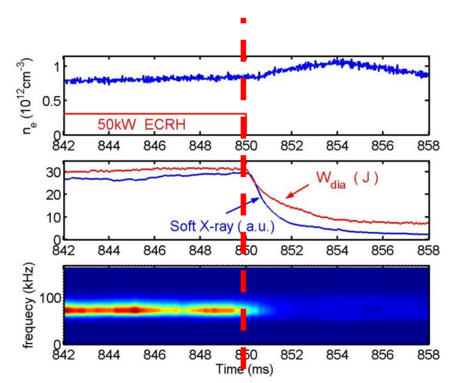


Fluctuation Features

1. only observed in QHS plasmas
2. coherent, m=1 (n=?)
3. localized to steep gradient region
5. Satellite mode appears at low densities, Δf~20 kHz
6. Electromagnetic

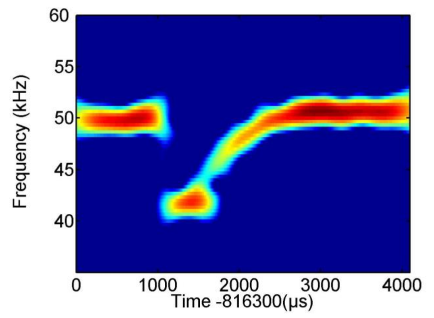


Observed Fluctuations Associated with ECRH



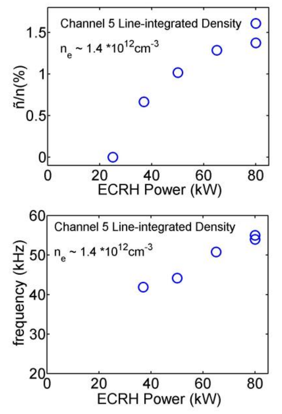
Mode disappears ~1 msec after ECRH turn-off, same timescale as W_E and soft x-rays

Frequency chirping sometimes observed

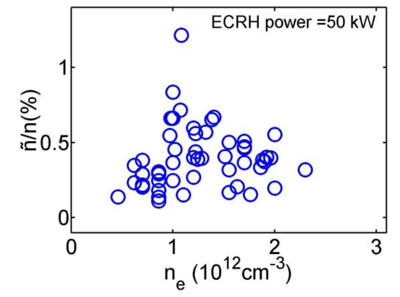


Fluctuations with ECRH Power

- Fluctuation amplitude increases with P_{ECRH}
- Fluctuation frequency increases slightly with P_{ECRH}
- No fluctuations observed when P_{ECRH} < 27kW

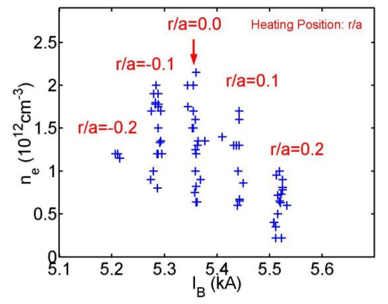


Coherent Fluctuation observed over broad range of density



•When heating location at the magnetic axis, and when n_e < 0.5x10^{12}cm^{-3} or n_e > 3.0x10^{12}cm^{-3} , no density fluctuation is observed

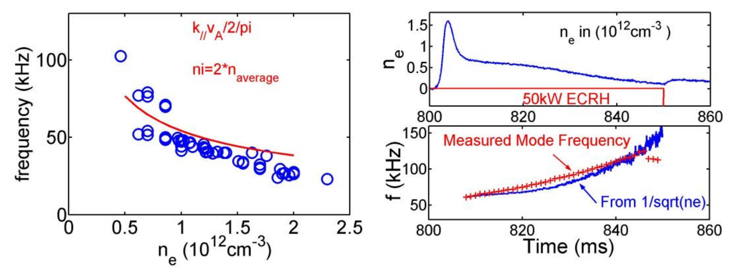
Fluctuation Observed in Different Heating Locations



fluctuation observed when ECRH resonance near plasma center

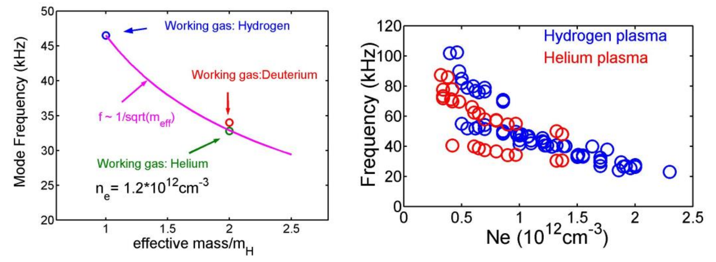
Mode Frequency Scaling

Mode Frequency Scaling with Electron Density



$$\omega_{GAE} \le k_{//}v_A = \frac{(m\iota - n)}{R}\frac{B}{\sqrt{4\pi n_i m_i}}$$

Mode Frequency Scaling with Ion Mass

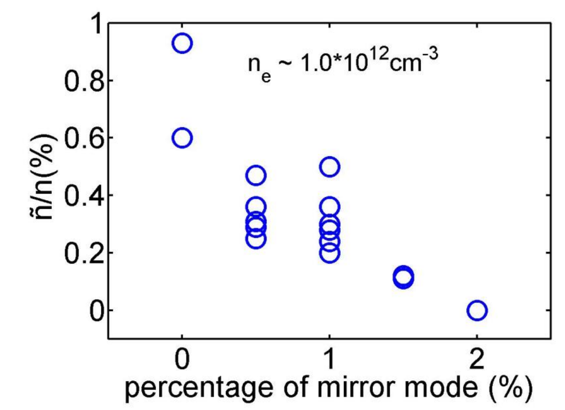


- mode frequency decreases with ion mass

Dispersion and Density and mass scalings consistent with Alfvénic mode

Fluctuations with symmetry Breaking

Fluctuation decreased with introduction of Symmetry Breaking (toroidal mirror) term

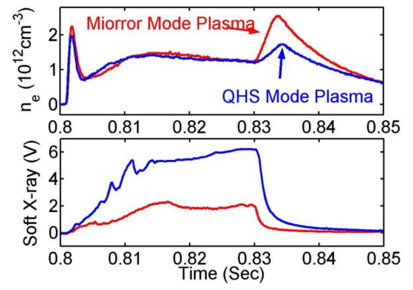


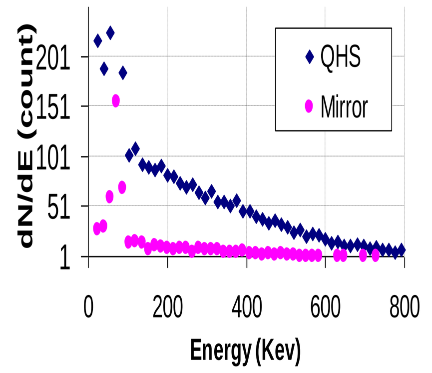
Fluctuation no longer observed for Mirror perturbation >2%

(conventional stellarator configuration: ~10% mirror perturbation)

Soft, Hard X-rays Emission for QHS and Mirror

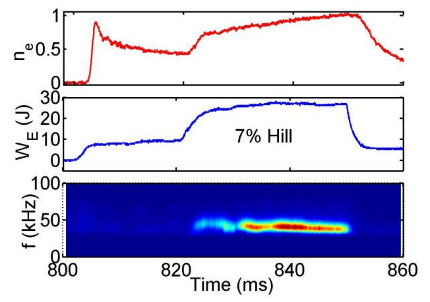
- Soft X-ray (0.6-6 keV) Emission is 3x higher for QHS over Mirror mode
- Hard X-ray emission in QHS plasma is much higher than in Mirror Mode
- Implies fast particles are better confined in QHS

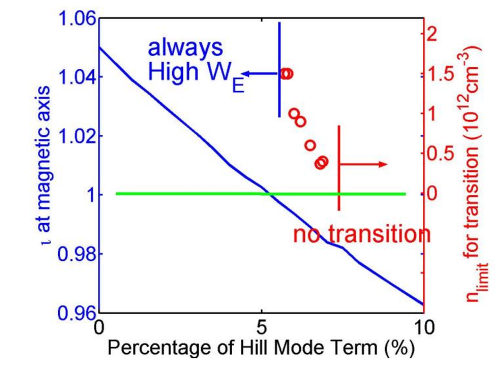




Fluctuations in Hill Configurations

- For certain percentage of Hill term, when $n_e < n_{crit}$, plasma transits to improved confinement; W_E and n_e increased greatly.
- During improved status, the fluctuation mode appears.
- n_{crit} decreases with Hill mode percentage and the transition becomes less frequent. When Hill percentage greater than 7.5%, no transition
- Explanation: ι ~ 1
  - ι>1: see fluctuation
  - ι<1: no fluctuation (mode stable)





The GAE Mode Growth Rates

Growth Rate Formula (Cylindrical Plasma)

$$\frac{\gamma}{\omega_A} = -\frac{\beta_{e\_nonth}}{4k_{//}^2R^2}\left(1-\frac{\omega^*_{e\_nonth}}{\omega}\right)\left(R_{m+1}+R_{m-1}\right)-\left(k_r^2+k_\perp^2\right)\rho_s^2\pi^{1/2}\frac{v_A}{v_e} \quad (1)$$

$$R_{m\pm1} = \frac{\pi\omega}{v^4_{e\_nonth}}\int d^3v\left(\frac{v_\perp^2}{2}+v_{//}^2\right)^2 f_{e\_nonth0}\,\delta(\omega - k_{//}v_{//}) \quad (2)$$

where $\beta_{e\_nonth} = 8\pi n_{e\_nonth}T_{e\_nonth}/B^2$ and $v^2_{e\_nonth} = 2T_{e\_nonth}/$

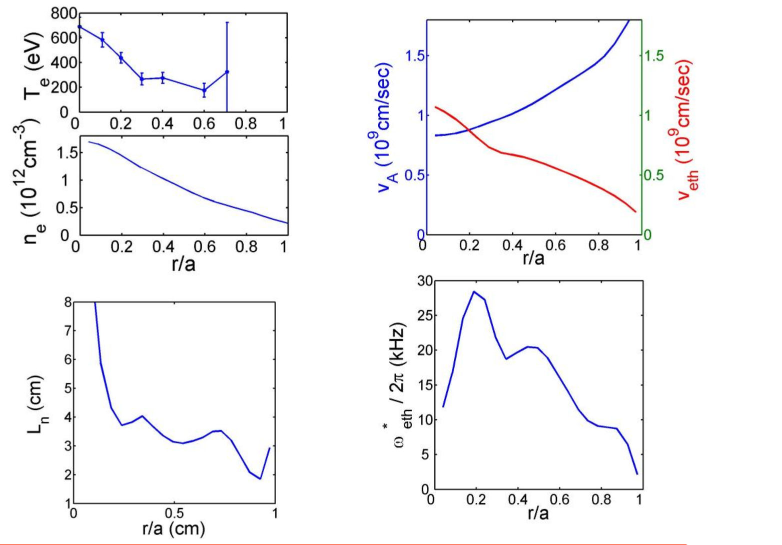
With T_{e_nonth} , n_{e_nonth} being the temperature, density, beta value and thermal velocity of the non thermal electrons. f_{e_nonth0} is the non-thermal electron distribution function. $\omega^*_{e\_nonth}$ is diamagnetic drift frequency of the non-thermal electrons

-large β_{e_non-th} and $\omega^*_{e\_non-th}$ increase growth rate

- low shear (1.05< ι<1.12) and cold ions (no ion Landau damping) may also play a role

HSX Plasma

HSX plasma produced/heated by 2nd Harmonic X-mode ECRH; can produce non-thermal electrons with $T_\perp > T_{//}$



The GAE Mode Driving

Case I. Passing Particles

mode unstable when

1. $\omega^*_e/\omega_{mode} > 1$ [first term Eq.(1)], and
2. $V_A \sim V_e \sim 10^9$ cm/s; occurs at r/a=0.2 for thermal population. To drive mode unstable at larger radii, non-thermal electrons must provide the drive

For L_n= 3 cm, non-thermal electron population 30%, $k_r = 0$ and $k_\perp = 1/a$

From, Eq. (1), perpendicular temperature needed to drive the mode unstable is $T_\perp > 4.4\,keV$

Energetic electrons are able to drive fast particle instabilities

Case II: Trapped Particles

mode unstable when

$\omega_{GAE}=\omega_{De\_nonth}$, where ω_{De_nonth} is the precession drift frequency

$$\omega_{De\_nonth}/2\pi = v^2_{\perp e\_nonth}/(\pm 4\pi\,\omega_{ce\_nonth}\,rR) \quad (3)$$

If GAE mode frequency is ~50kHz,

- for r_{eff}=0.1*a= 1.3cm, R=120cm, perpendicular energy required $\varepsilon_{\perp e\_nonth} = m_e v^2_{\perp e\_nonth}/2 = 2.4\ keV$
- for r_{eff}=0.5*a=6.5cm, $\varepsilon_{\perp e\_nonth} = 12\ keV$

ECRH produces non-thermal electrons with $T_\perp > T_{//}$

Instability depends on energy of fast particles, not mass

Experimental Evidence for non-thermal Electrons

1. ECE measurement: shows the perpendicular energy of the non-thermal electrons ~4-16 keV at n_e=0.5-2*10^{12}cm^{-3}, at 50kW ECRH power [see K.M. Likin's Poster]
2. Soft X-ray measurement: (0.6-6kV)
3. Hard X-ray measurement: shows non-thermal electrons have energy up to 200keV

Summary

1. Calculations of Alfven Wave Continuum by 3-D gyro-fluid code shows the possibility of GAE mode in HSX
2. Density fluctuation characterized as m=1 global mode
3. Electromagnetic component: Fluctuation observed on Magnetic probe is coherent with the density fluctuation
4. frequency ~ density scaling and frequency- mass scaling of the fluctuations show the mode is Alfvénic
5. The growth rate calculations and experiment show that the fluctuations is most likely driven by non-thermal electrons,
6. Mode is only observed for QHS configuration in HSX, not for Mirror Configuration
   (i) non-thermal electrons are better confined
   (ii) the damping of the mode in Mirror Configuration is likely greater than in QHS case
7. Experimental evidence suggests the observed fluctuation is a GAE mode