Energetic-Electron-Driven Alfvénic Mode in the HSX

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Outline

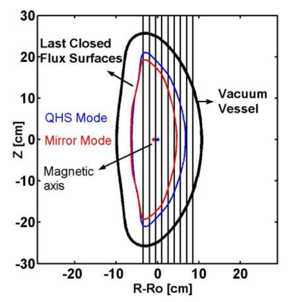
1. Characteristics of observed fluctuations in Quasi-Helically Symmetric plasma
2. Alfvén Continua for QHS and Mirror Mode Plasmas (conventional stellarator) on HSX
3. Evidence for Fast-Electron-Driven GAE mode
4. Effect of Biasing on Alfvenic mode

GOAL

1. Observe Alfvénic modes driven by fast electrons
2. Quasi-Helical Symmetry makes a difference

HSX Interferometer

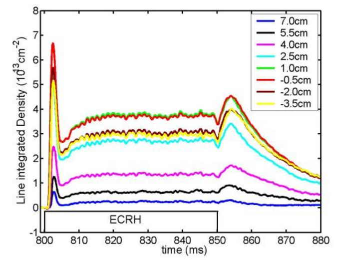
Flux Surfaces and Interferometer Chords



Interferometer System:

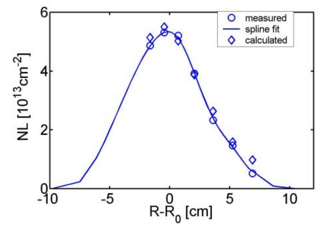
1. 9 chords
2. 200 kHz B.W.
3. 1.5 cm chord spacing

Density Evolution QHS Plasma

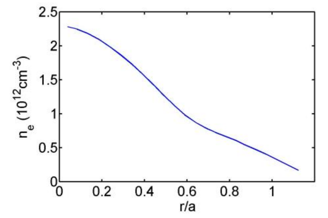


Density Profile for QHS Plasma

Measured Line-Integrated Density Profile and fitting



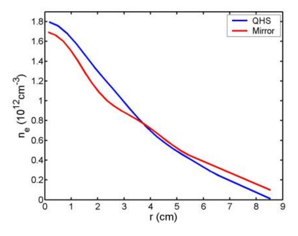
Inverted Density Profile



QHS and Mirror Density Profile

$W_{QHS}=W_{Mirror}$~20J

Profile shapes are
(1) centrally peaked
(2) similar shape



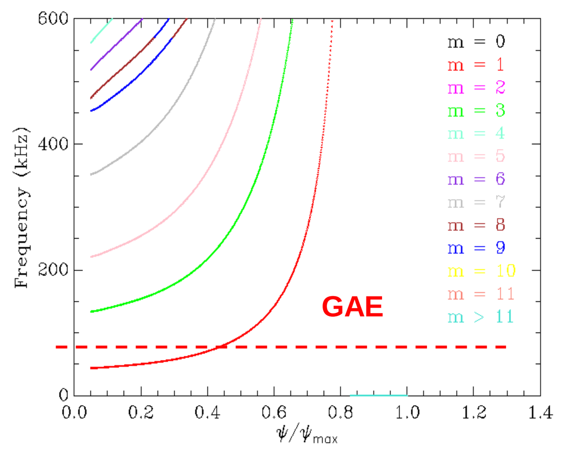
Alfvén Mode

HSX : Quasi-Helically Symmetric (QHS) configuration
Normal mode Alfvén continua: n = 1 mode family

GAE Gap: B=0.5 T
0 - 50 kHz for m=1,n=1 $n_e(0)=1.8\times10^{12}\ cm^{-3}$

Only minor changes for mirror configuration

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



STELLGAP code (D. Spong)

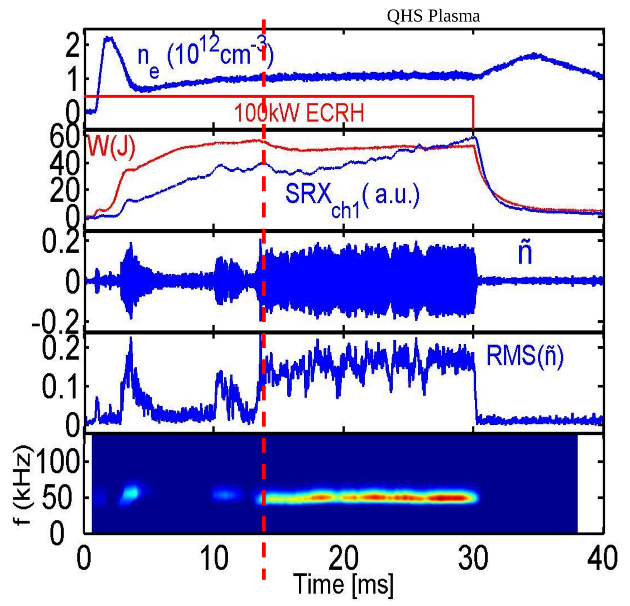
Resonant and distablizing conditions

Historically, Alfvénic modes have been observed on tokamaks or stellarators with NBI or ICRF to generate fast particles.

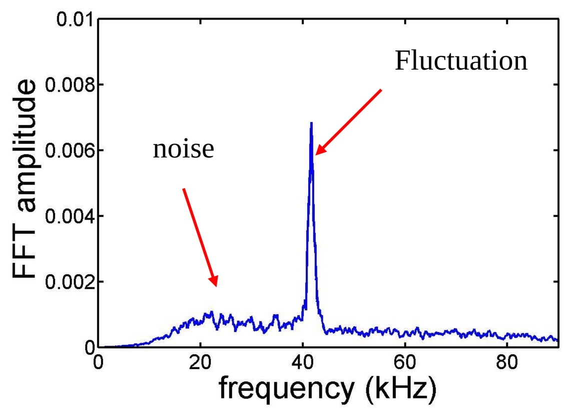
Alfvénic modes are generated if

1. resonance condition:
   a. for passing particles $V_p \geq V_A$
   (V_p: particle velocity)
   b. for trapped particles, $\omega_{Dh} = \omega_{Alfven}$
   where ω_{Dh} is the trapped-particle precessional drift frequency,
   depends on particle energy, not mass
2. unstable when: $\omega^*_{dia} > \omega_{Alfv}$
   where ω^*_{dia} is the diamagnetic drift frequency of energetic particles
   energetic ions or electrons can drive instability

Coherent Density Fluctuations



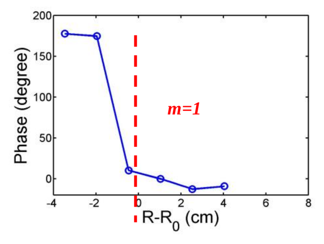
For P_{ECRH} > 100 kW, confinement degrades
Mode perturbs particle orbits leading to enhanced loss

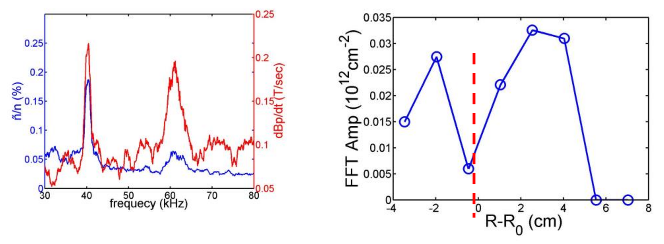


- 28 GHz ECRH
- 2nd Harmonic X-mode
- Generates fast electrons with $T_{e\perp} >> T_{e//}$

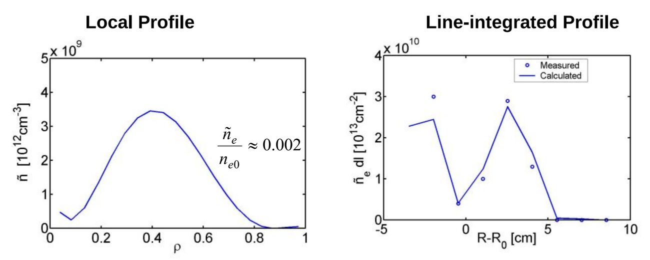
Fluctuation Features

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, Δf~20 kHz
6. Electromagnetic component





Density Fluctuation Spatial Distribution

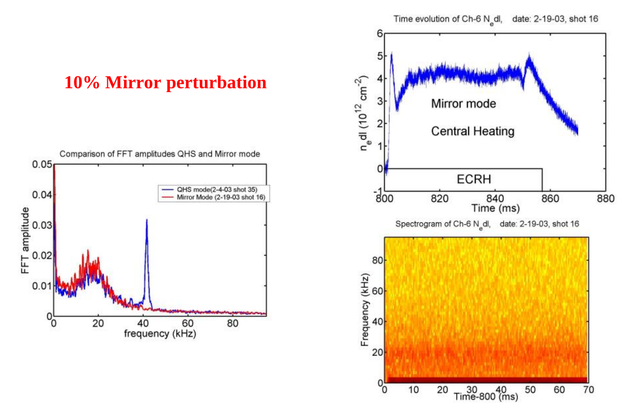


mode can be inverted to obtain local density distribution
- local density perturbation shape is guessed using 5th order polynomial
- line-integrals are calculated and compared to measured line-integrals
- free parameters are changed to optimize fit
- best fit obtained when m=1 was selected, in agreement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

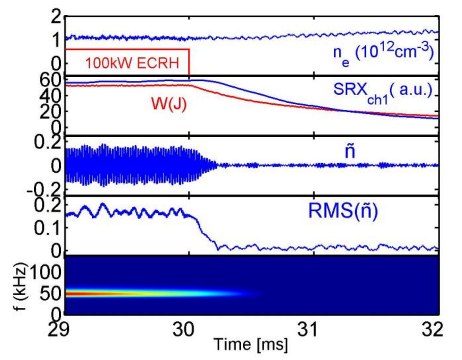
- **Mode is core localized,**
- **Mode peaks in region of steepest density gradient**

No Mode In Mirror Configuration

10% Mirror perturbation



Observed Fluctuations Associated with ECRH

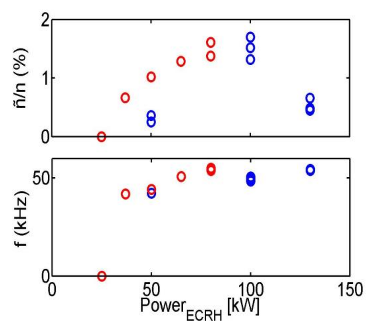


- Mode disappears ~0.2 msec after ECRH turn-off,
- faster timescale than W_E and soft x-rays
- 2nd Harmonic X-mode generates nonthermal electrons (ECE) $T_{e\perp} >> T_{e//}$
(no source for fast ions: T_i~20 eV)

Modes are driven by energetic electrons

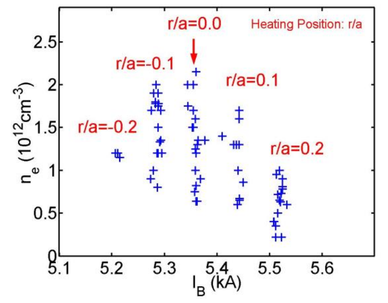
Fluctuations with ECRH Power

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



Blue and Red points are for different run days

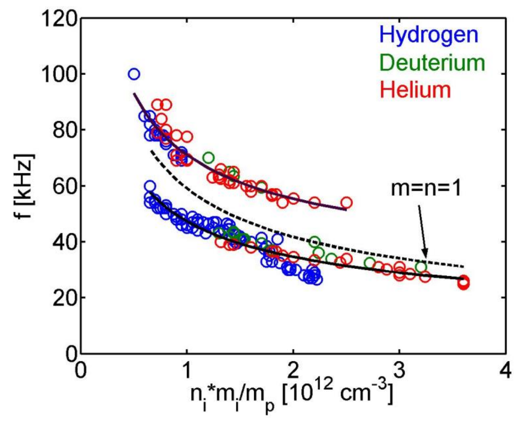
Fluctuation Observed in Different Heating Locations



Alfvenic mode stronger on LFS - trapped particles?

Mode Frequency Scaling

Mode Frequency Scaling with Ion Mass Density



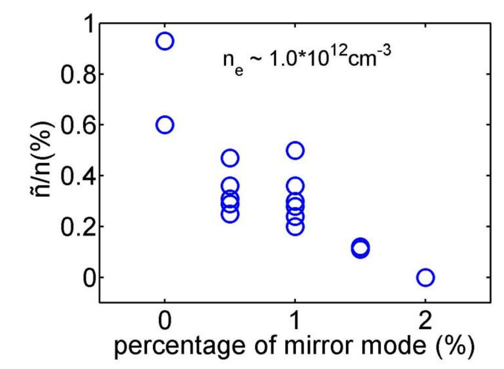
$$\omega_{GAE} \leq k_{//} v_A = \frac{(m\iota - n)}{R} \frac{B}{\sqrt{4\pi n_i m_i}}$$

- Frequency and mass density scaling consistent with Alfvenic mode
- If iota is lowered < 1, GAE gap disappears and mode not observed

Fluctuations with symmetry Breaking

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

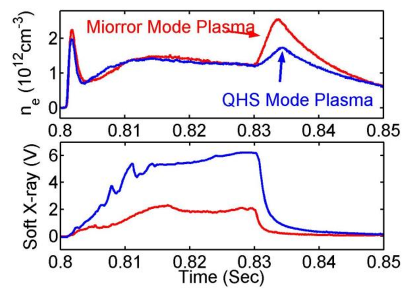
$\omega_{Dh} = \omega_{Alfven}$



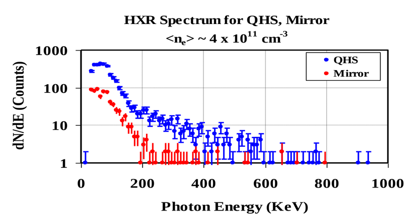
Fluctuation no longer observed for Mirror perturbation >2%
(conventional stellarator configuration: ~10% mirror perturbation)

Soft, Hard X-rays Emission for QHS and Mirror

- **Soft X-ray (0.6-6 keV) Emission QHS>>Mirror**
- **Hard X-ray emission: QHS >> Mirror, decay time longer**



- **fast particles are better confined in QHS,**
- **$\omega_{Dh}=\omega_{GAE}$: 5-10 keV particles**



Bias Probe (V_B=0) Perturbs HSX Plasma Equilibrium

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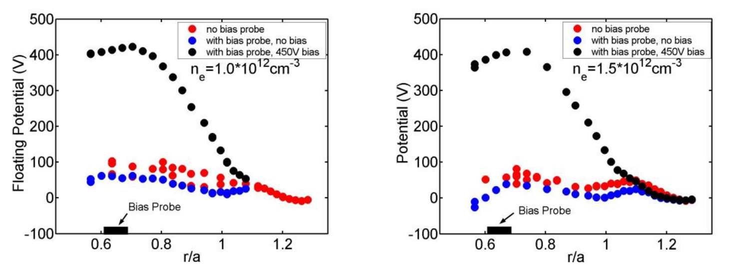
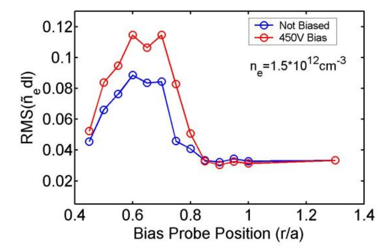


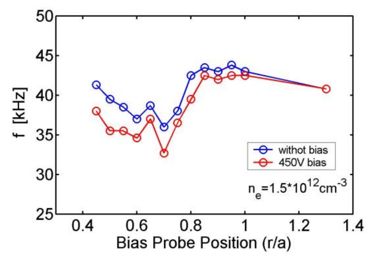
Plasma potential is modified by insertion of bias probe, even if V_B=0.

Bias Probe (V_B=0) Perturbs Alfvenic Mode in HSX

Mode Amplitude



Mode Frequency

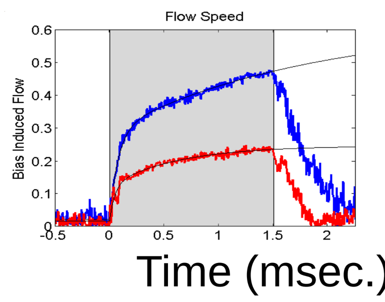


Mode properties measured by chord at $R-R_o$~2.7 cm

Both the Alfvenic mode amplitude and frequency are modified by the presence of the probe (with NO bias)

Effects of Biasing on GAE mode

Viscous Damping measurement Result



QHS Flows Damp More Slowly, and, Go Faster For Less Drive
Viscous Damping is Reduced for QHS

$$M = \frac{V_f}{\sqrt{T_e/m_i}} \leq 0.5$$

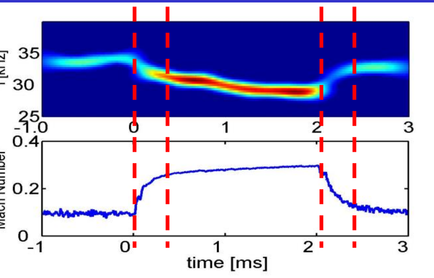
QHS: 8 A of electrode current
Mirror: 10 A of electrode current

Bias spins QHS plasma

other parameters ($n_e=1\times10^{12}cm^{-3}$, $n_n \approx 1\times10^{10}cm^{-3}$ $T_i\approx25eV$, B=0.5T, P_{ECH}=50 kW) held constant.

S.P. Gerhardt et al., PRL 94,015002(2005)

Alfvenic mode frequency shift can be used to measure *core* flow dynamics



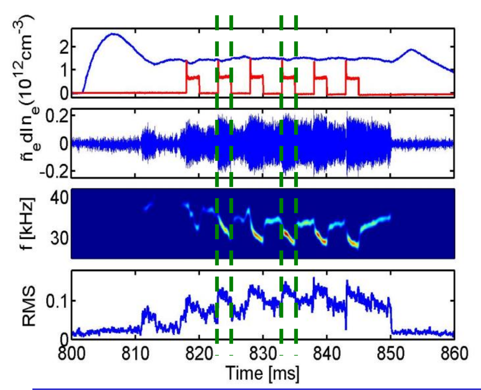
$$f_{lab} = f_{GAE} + f_{Doppler} = f_{GAE} + \frac{1}{2\pi} k \bullet v_{flow} = f_{GAE} + \frac{m}{r}\frac{E_r}{2\pi B_o}$$

$$\Delta f_{lab} = f_{lab}|_{w/bias} - f_{lab}|_{w/o-bias} = \Delta f_{Doppler} = \frac{m}{r} \bullet \frac{\Delta E_r}{2\pi B_o}$$

$\Delta f_{lab} \approx 5-10kHz; \Rightarrow \Delta E_r \approx 5-10V/cm$ *for plasma core with bias*

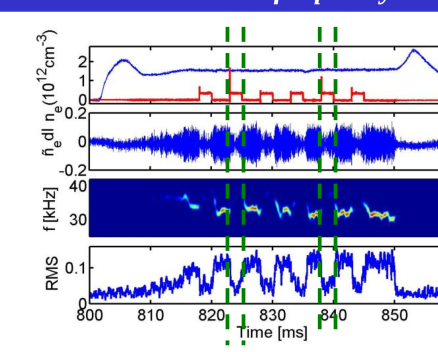
- **During biasing: n_e and B do not change so V_A is constant**
- **Ambient plasma potential is (+)**
- **ExB flow (edge) in ion drift direction**
- **Alfvenic mode propagates in electron diamagnetic drift direction (lab frame, without bias)**

QHS: + biasing increases *amplitude* and decreases *frequency*



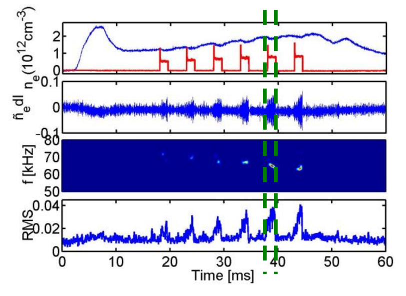
- amplitude increases 50-100%
- frequency decreases 10-20%

QHS: - biasing decreases mode *amplitude* and increases *frequency*



- Biasing against direction of ambient flow

Mirror Mode: Alfvenic Mode observed with + biasing



No Alfvenic mode observed between bias pulses

Mirror Mode: mode observed w/bias in direction of ambient flows; no mode observed for opposite bias

Evidence for Alfvenic mode in HSX

1. Calculations of Alfven Wave Continuum by 3-D STELLGAP code shows the possibility of GAE mode in HSX
2. Measure a coherent fluctuation global mode [m=1,n=1] with frequency and ion mass density scaling consistent with Alfvénic mode (B scaling unknown).
3. Measurements suggest that the fluctuation is most likely driven by non-thermal electrons
4. Alfvenic Mode is only observed for QHS configuration, not for Mirror Configuration (> 2%)
5. Biasing: Df_{lab} may provide information on core E_r and flow dynamics!
   - How do flows affect Alfvenic mode growth rate?
   Mode amplitude can be controlled by (1) flows and (2) configuration

Open Issues

1. Mode propagation direction: Langmuir probes measure edd in lab. frame. Expect mode to propagate in diamagnetic drift direction of driving species
2. Mode structure [m=odd (1?), n=1]: External magnetics suggest m=0? Langmuir probes measurement indicate n=1. Differences between magnetic and density measurements
3. B-scaling?: need to know E_r profile. Can mode frequency be explained by plasma rotation?
4. Source of satellite frequencies: (1) different m,n, or (2) different roots of the same MHD equations (different radial structure with same m,n)?
5. Sensitivity of Alfvenic mode to mirror perturbation (2%). Which particles are resonant with mode? How are they affected by mirror perturbation? Energy component of energetic electrons should be measured.
6. Biasing: Δf_{lab} may provide information on core E_r and flow dynamics!
   - How do flows affect Alfvenic mode growth/damping rate and frequency?
   - E_r measurements in plasma core…… How is potential profile modified by biasing? What is potential profile for non-biased plasmas?