Evidence for Fast-Electron-Driven Alfvénic Modes in the HSX Stellarator

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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.

QHS: Helical Bands of Constant |B|

Mirror: Helical Bands are Broken

Conventional stellarators exhibit poor neoclassical transport in low-collisionality regime due to magnetic field ripple
HSX
major radius: 1.2 m
minor radius: 0.15 m
magnetic field: 0.5 T
28 GHz ECRH: <150 kW
pulse length: < 50 ms
Outline

1. Characteristics of observed fluctuations
   - Quasi-Helically Symmetric (QHS) configuration
   - Mirror (MM) configuration (conventional stellarator)

2. Alfvén Continua for QHS and Mirror Mode Plasmas (conventional stellarator) in HSX

3. Evidence for fast-electron driven GAE mode

4. Effect of biasing on Alfvénic mode

GOAL

1. Observe Alfvénic modes driven by fast electrons
2. Quasi-Helical Symmetry makes a difference
Flux Surfaces and Interferometer Chords

Interferometer System:

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

For $P_{ECRH} > 100$ kW, confinement degrades
Mode perturbs particle orbits leading to enhanced loss
No mode observed in Mirror Configuration Plasma

10% Mirror perturbation
Fluctuation Features

- only observed in QHS plasmas
- coherent, $m=1$ ($n=\ ?$)
- localized to steep gradient region
- satellite mode appears at low densities, $f \sim 20 \ kHz$
- propagates electron drift direction
- **Electromagnetic component**

![Plot 1](image1)

- $m=\text{odd} \ [1]$
- ![Plot 2](image2)

![Plot 3](image3)
Observed Fluctuations Associated with ECRH

- Mode disappears \( \sim 0.2 \) 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: \( T_i \sim 20 \) eV) \( T_{e\perp} >> T_{e//} \)

**Modes are driven by energetic electrons**
Alfvénic Modes

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: \( V_p \geq V_A \) (\( V_p \): particle velocity) for trapped particles, \( \bigcup_{Dh} = \bigcup_{Alfven} \)
   where \( \bigcup_{Dh} \) is the trapped-particle precessional drift frequency, 
   \[ \text{depends on particle energy, not mass} \]

2. unstable when: \( \bigcup_{dia}^* > \bigcup_{Alfven} \)
   where \( \bigcup_{dia}^* \) is the diamagnetic drift frequency
   \[ \text{energetic ions or electrons can drive instability} \]
HSX: Quasi-Helically Symmetric (QHS) configuration
Normal mode Alfvén continua: \( n = 1 \) mode family

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

- GAE Gap: \( B=0.5 \) T
  0 - 50 kHz for \( m=1, n=1 \)
  \( n_e(0)=1.8 \times 10^{12} \) cm\(^{-3} \)

- Only minor changes for mirror configuration
Mode frequency scaling with ion mass density

\[ \Box_{\text{GAE}} \Box_{k/} v_A = \frac{(m/i \nabla n)}{R} \frac{B}{\sqrt{4 \Box n_i m_i}} \]

- frequency and mass density scaling consistent with Alfvénic mode
- If iota is lowered < 1, GAE gap disappears and **mode not observed**
Density fluctuations *decrease* with introduction of symmetry breaking (toroidal mirror) term.

Fluctuation no longer observed for Mirror perturbation $>2\%$
(conventional stellarator configuration: $\sim10\%$ mirror perturbation)
Soft X-ray, Hard X-ray Emission for QHS and Mirror

- Soft X-ray (600 eV-6 keV) emission
  QHS>>Mirror

- Hard X-ray flux:
  QHS>>Mirror
decay time longer

- fast particles are better confined in QHS

- \( D_{Dh} = D_{GAE} \):
  5-10 keV particles

- fast particles (trapped electrons) are better confined for QHS
- provide drive for Alfvénic modes
Result: QHS Flows Damp More Slowly, and, Go Faster For Less Drive

**Viscous Damping is Reduced for QHS**

Other parameters ($n_e = 1 \times 10^{12} \text{cm}^{-3}$, $n_n \leq 1 \times 10^{10} \text{cm}^{-3}$ $T_i \leq 25 \text{eV}$, $B = 0.5 \text{T}$, $P_{ECH} = 50 \text{kW}$) held constant.

S.P. Gerhardt et al., PRL 94,015002(2005)
QHS: + biasing increases *amplitude* and decreases *frequency*

- amplitude increases 50-100%
- frequency decreases 10-20%
Alfvenic mode frequency shift can be used to measure core flow dynamics

\[
\begin{align*}
    f_{\text{lab}} &= f_{\text{GAE}} + f_{\text{Doppler}} = f_{\text{GAE}} + \frac{1}{2} k \cdot v_{\text{Doppler}} = f_{\text{GAE}} + \frac{m}{r} \frac{E_r}{2 B_o} \\
    \square f_{\text{lab}} &= f_{\text{lab}} \bigg|_{w/\text{bias}} \quad \square f_{\text{lab}} \bigg|_{w/o\text{bias}} = \square f_{\text{Doppler}} = \frac{m}{r} \cdot \frac{\square E_r}{2 \square B_o} \\
    \square f_{\text{lab}} &\square 5 \square 10 \text{ kHz;} \quad \square E_r \square 5 \square 10 \text{ V/cm} \quad \text{for plasma core with bias}
\end{align*}
\]

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

Ambient plasma potential is (+)

ExB flow in ion drift direction

Alfvenic mode propagates in electron diamagnetic drift direction?
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 \([m=\text{odd } (1?)]\) with frequency and ion mass density scaling is consistent with Alfvenic mode \((B \text{ scaling unknown})\).

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: \(\mathcal{D}f_{\text{lab}}\) may provide information on core \(E_r\) and flow dynamics!
   - How do flows affect to Alfvenic mode growth rate?

Mode amplitude can be controlled by (1) flows and (2) configuration