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

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HSX

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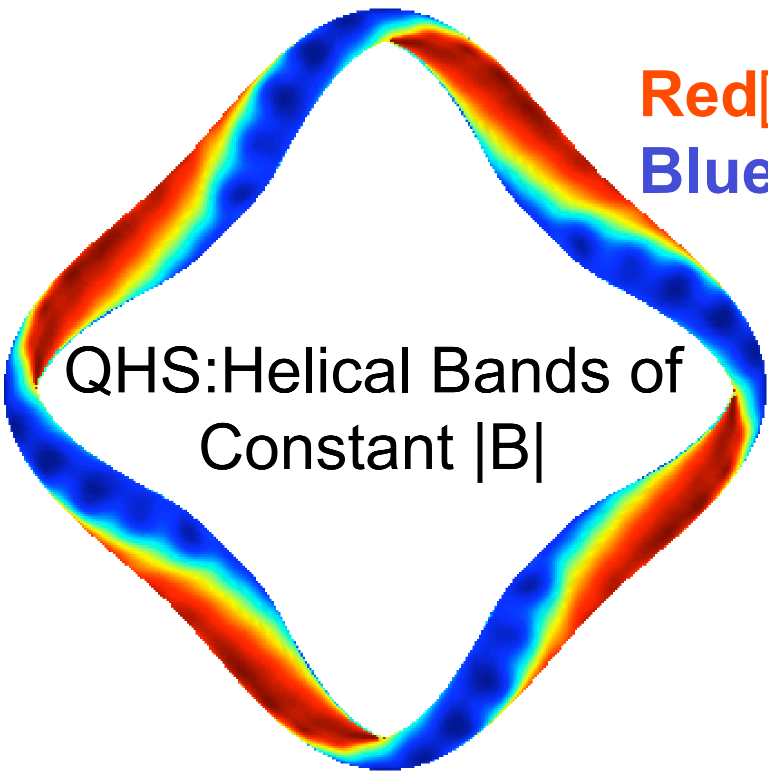
HSX Provides Access to Configurations With and Without Symmetry

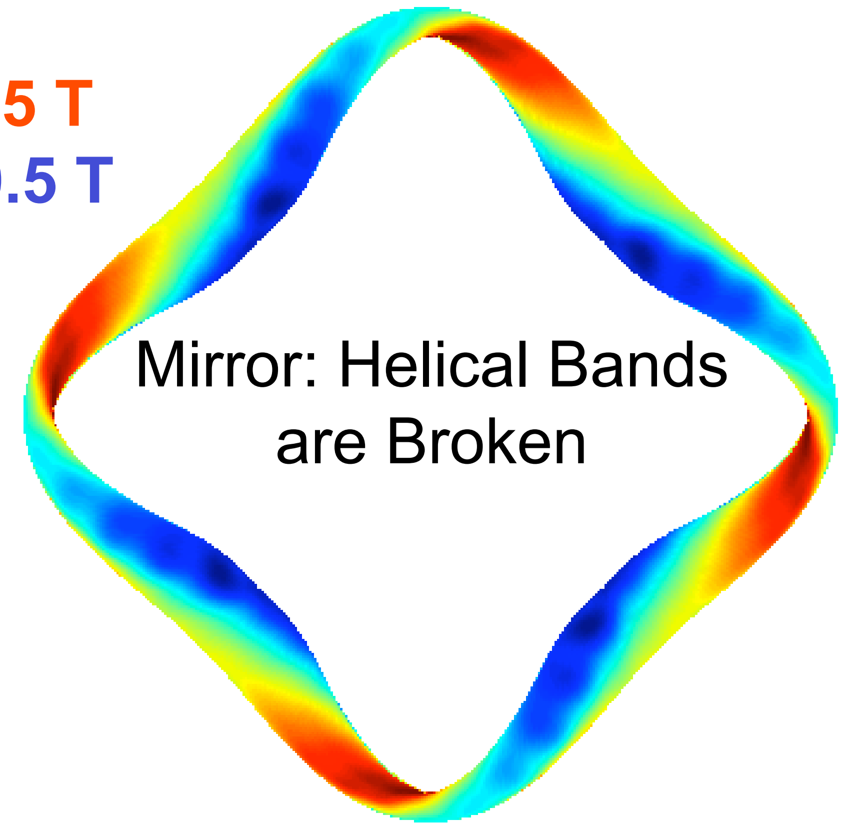
QHS: helical axis of symmetry in |B|; predicted very low neoclassical transport
Mirror: quasi-helical symmetry broken by adding a mirror field.

QHS



Red□ |B|>0.5 T
Blue□ |B|<0.5 T

Mirror



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

HSX

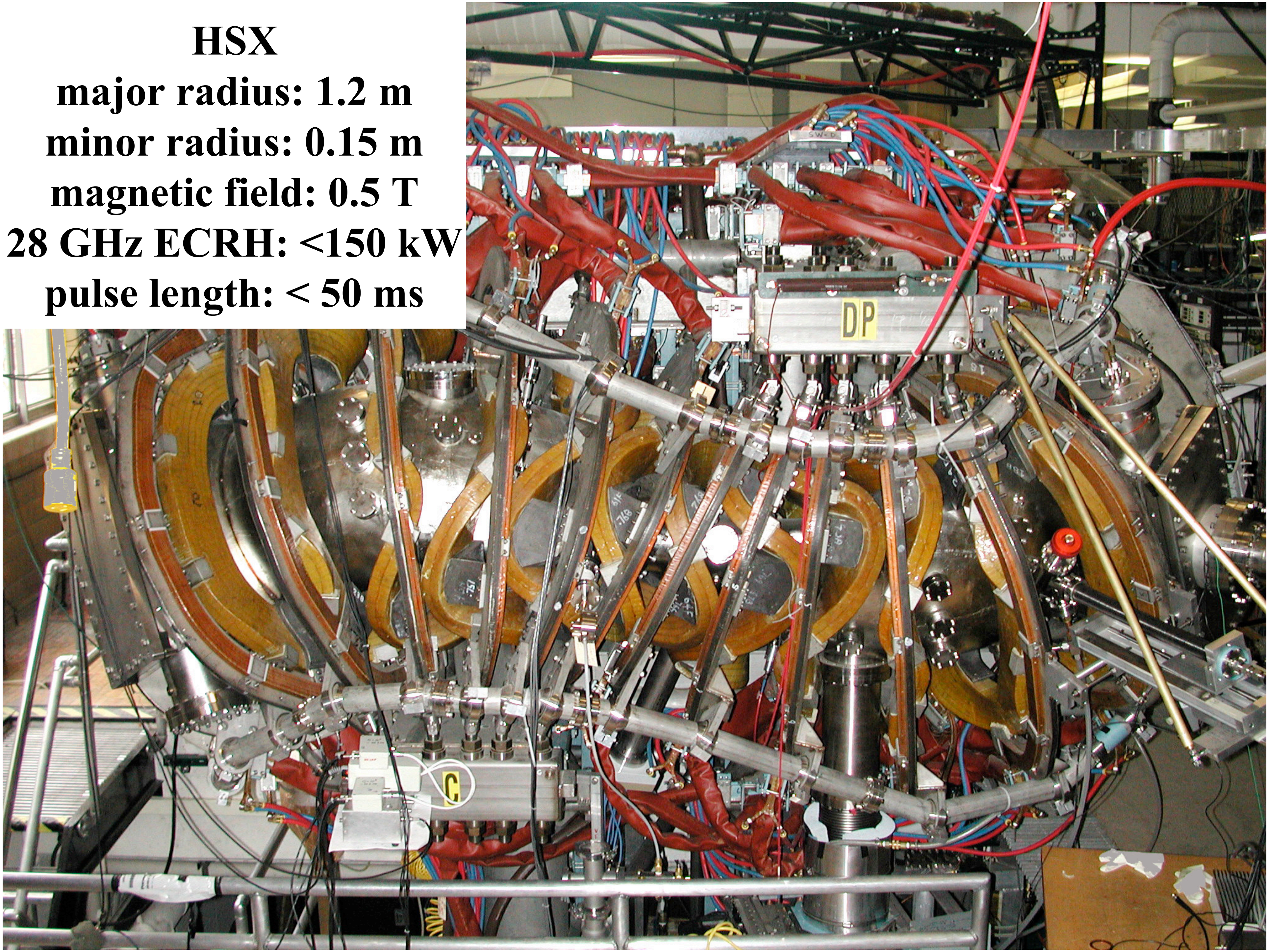
major radius: 1.2 m

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**

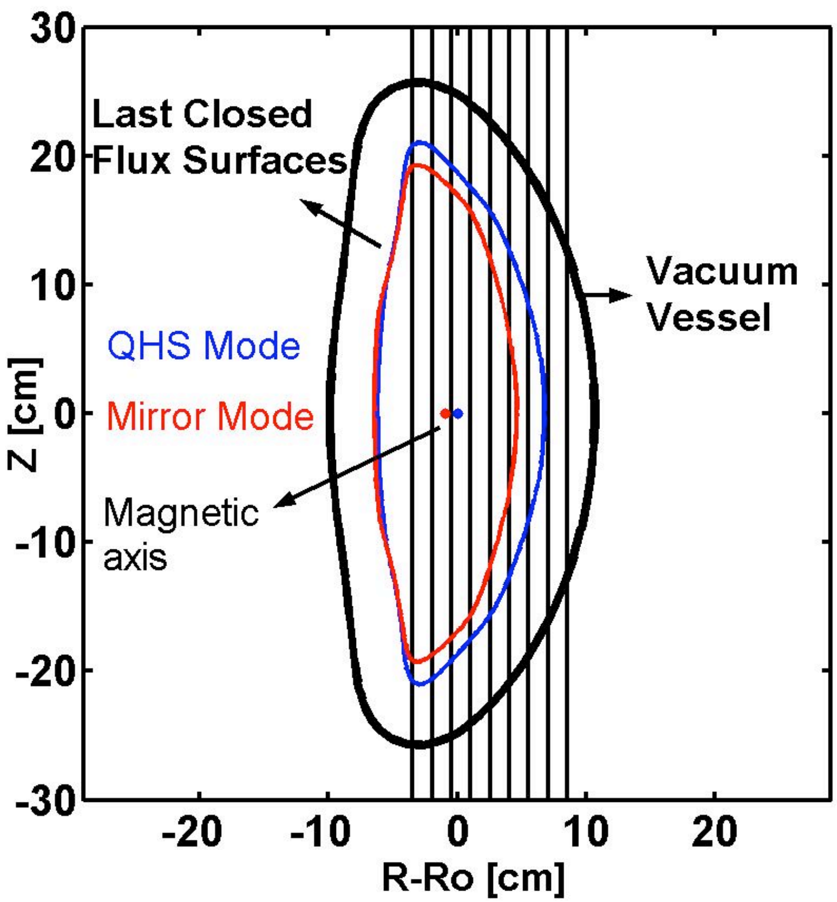
3. **Evidence for fast-electron driven GAE mode**

4. **Effect of biasing on Alfvenic mode**

GOAL

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

Flux Surfaces and Interferometer Chords

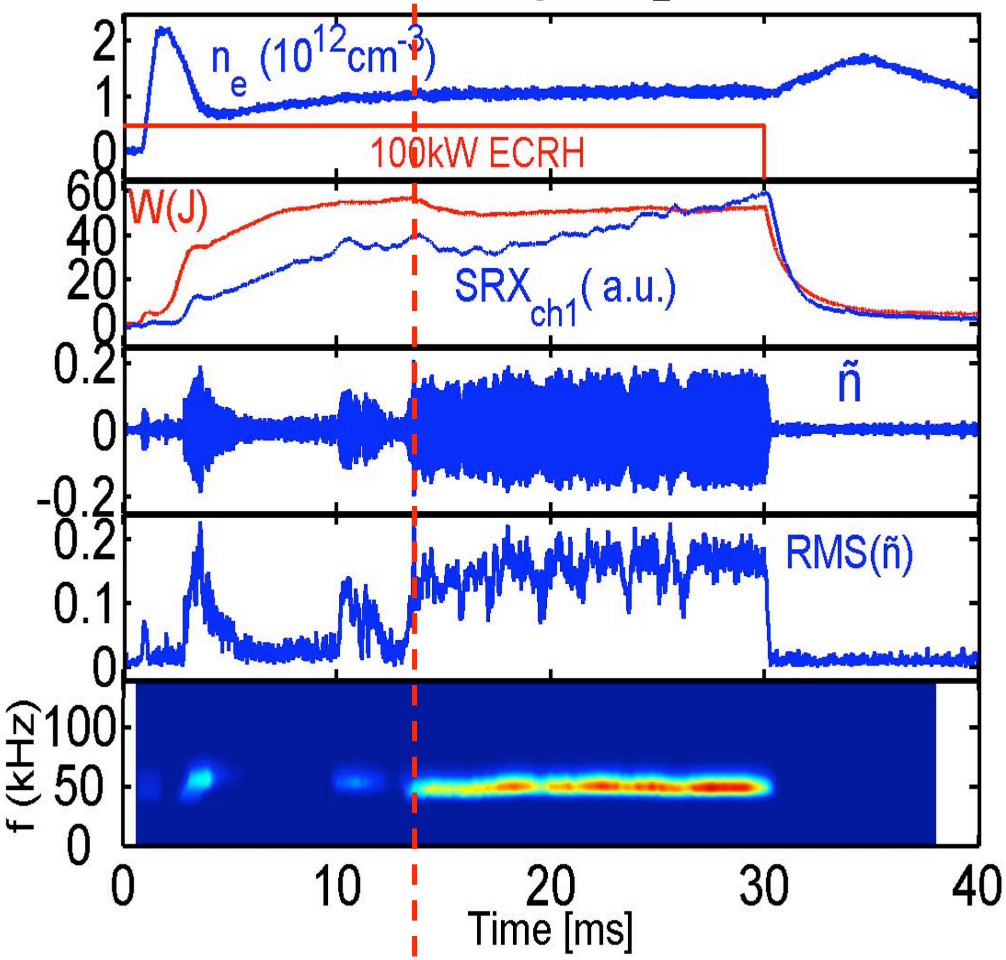


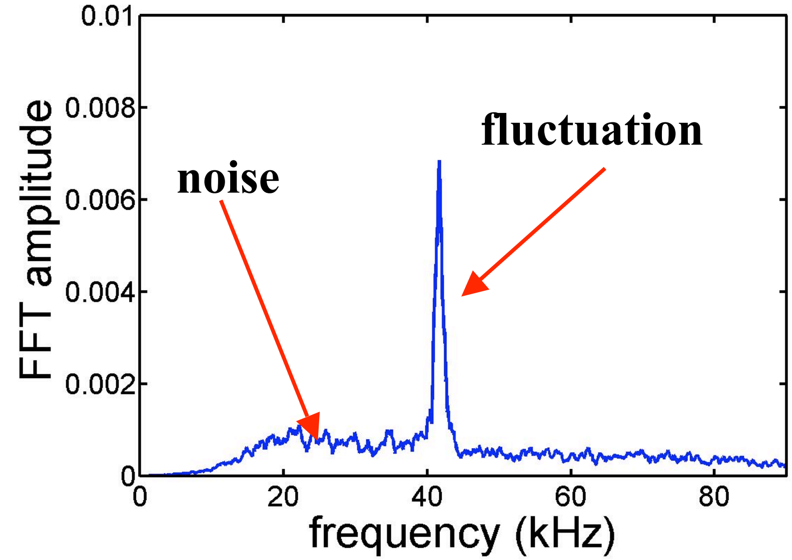
Interferometer System:

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

Coherent Density Fluctuations

QHS plasma

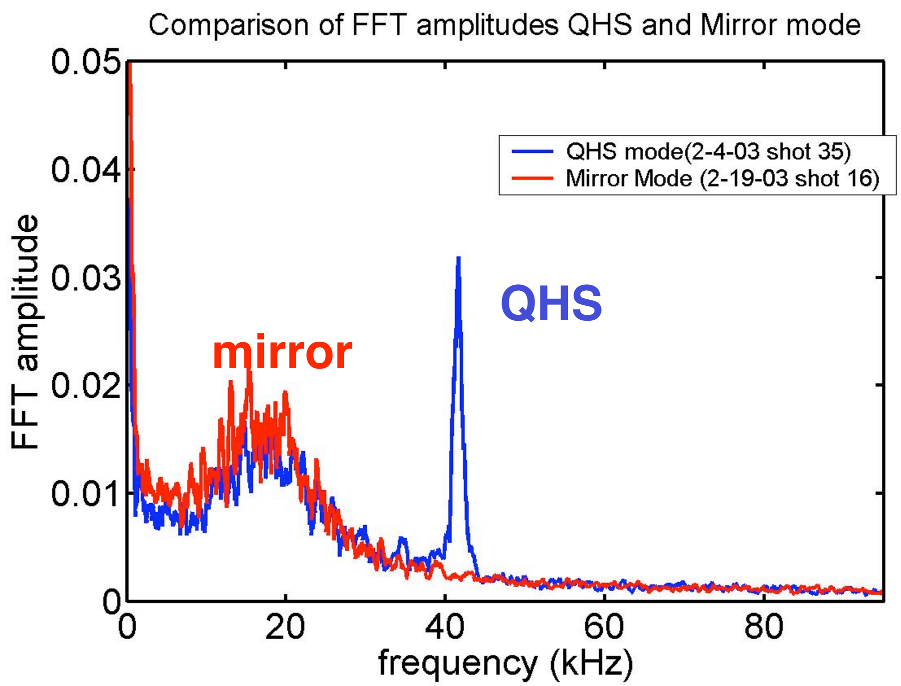




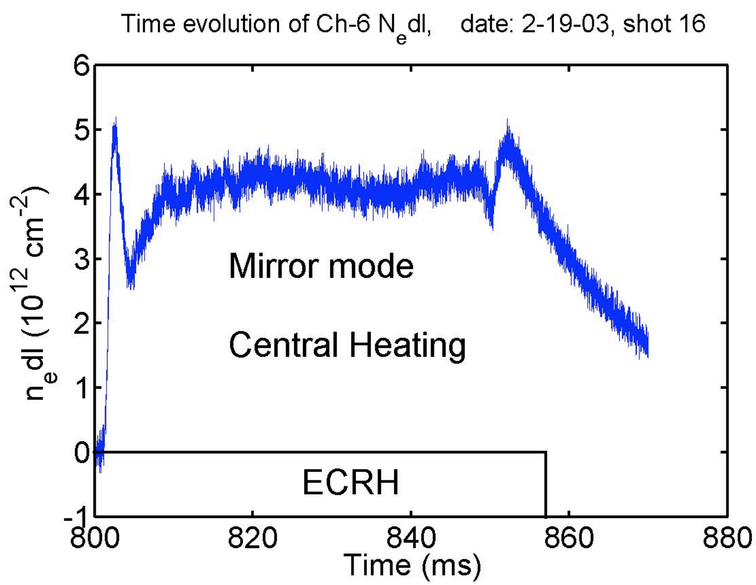
- **28 GHz ECRH**
- **2nd Harmonic X-mode**
- **Generates fast electrons with** $T_{e\perp} >> T_{e//}$

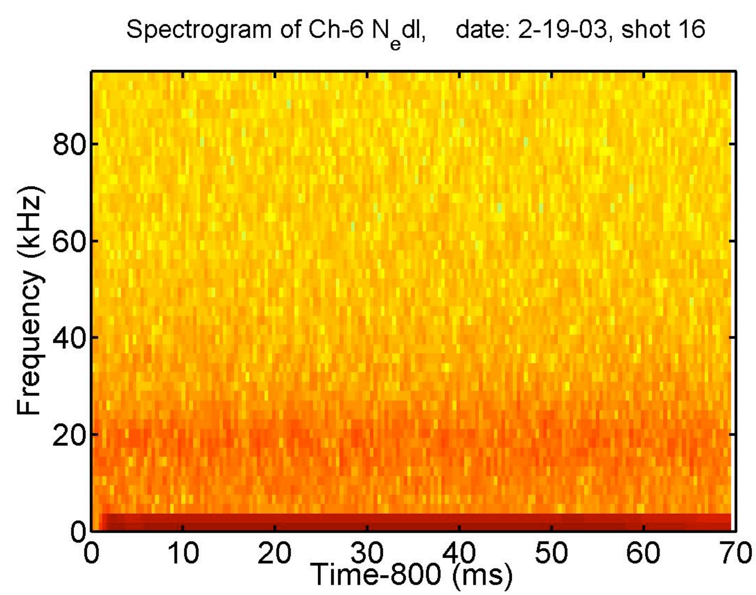
For P_{ECRH} > 100 kW, confinement degrades
Mode perturbs particle orbits leading to enhanced loss

No mode observed in Mirror Configuration Plasma



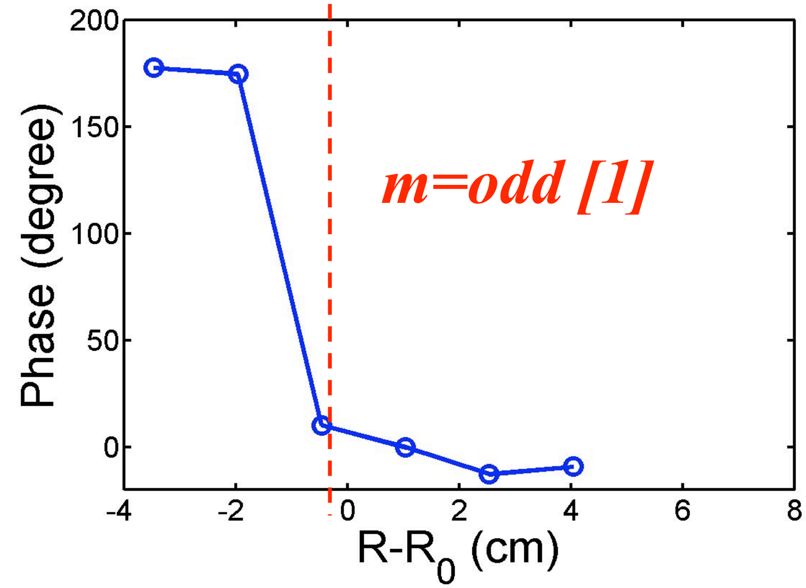
10% Mirror perturbation

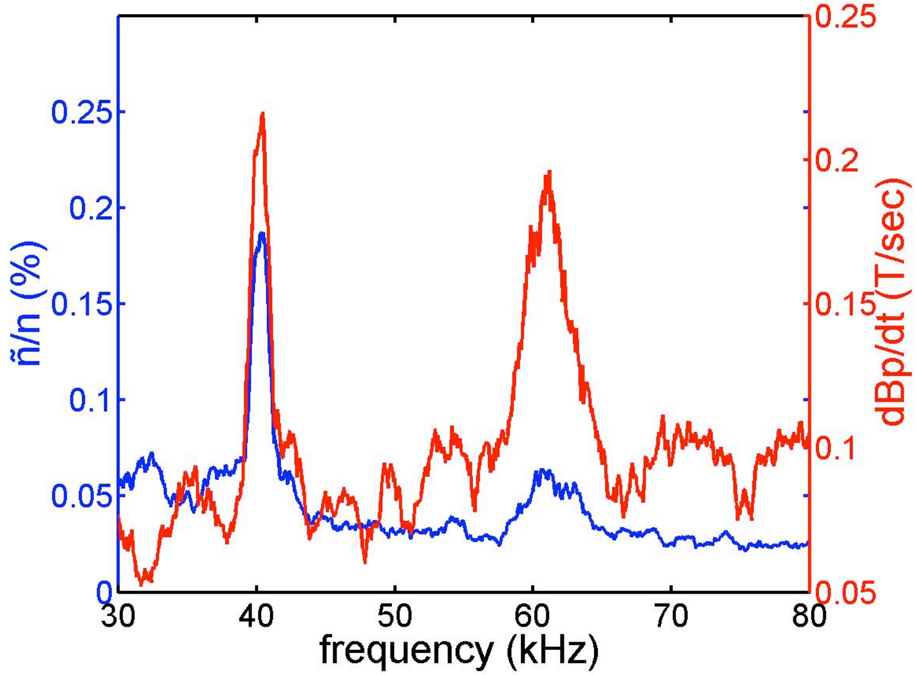


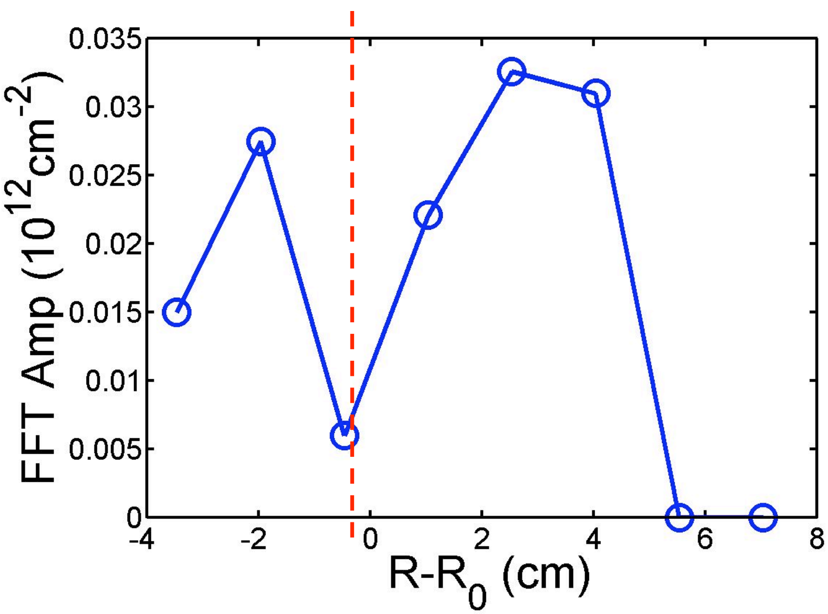


Fluctuation Features

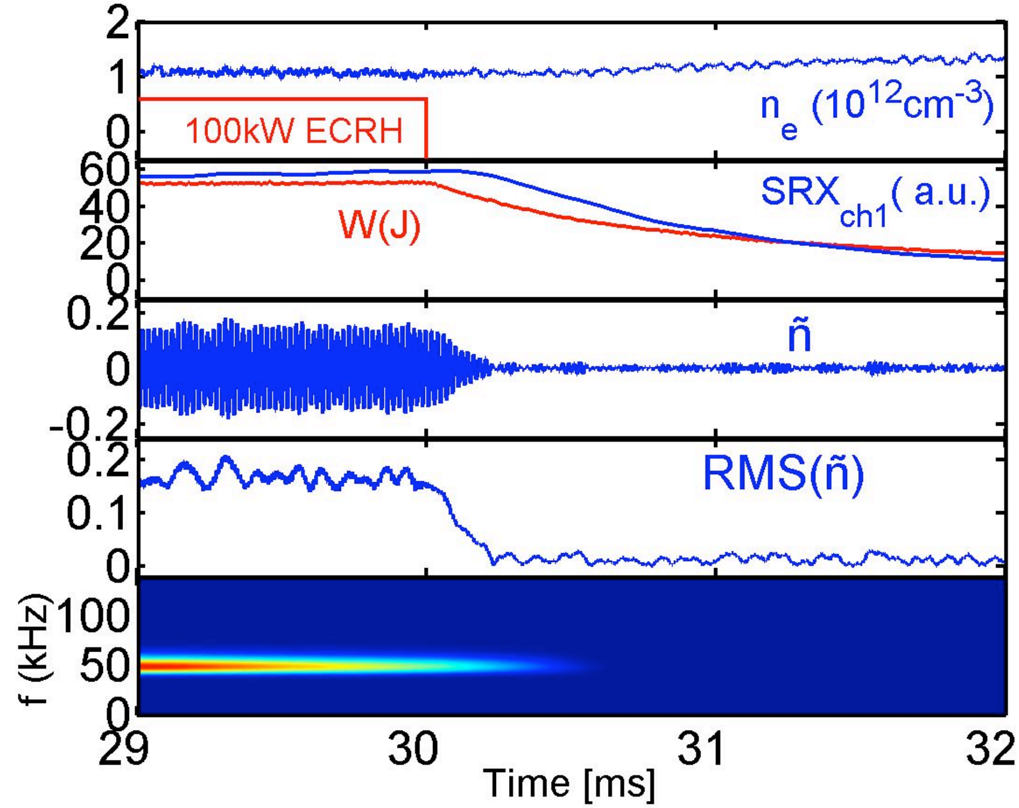
- only observed in QHS plasmas
- coherent, m=1 (n=?)
- localized to steep gradient region
- satellite mode appears at low densities, □f~20 kHz
- propagates electron drift direction
- **Electromagnetic component**







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_i~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, $\omega_{Dh} = \omega_{Alfven}$

   where ω_{Dh} is the trapped-particle precessional drift frequency,

   depends on particle energy, not mass

2. unstable when: $\omega^*_{dia} > \omega_{Alfven}$
   where ω^*_{dia} is the diamagnetic drift frequency

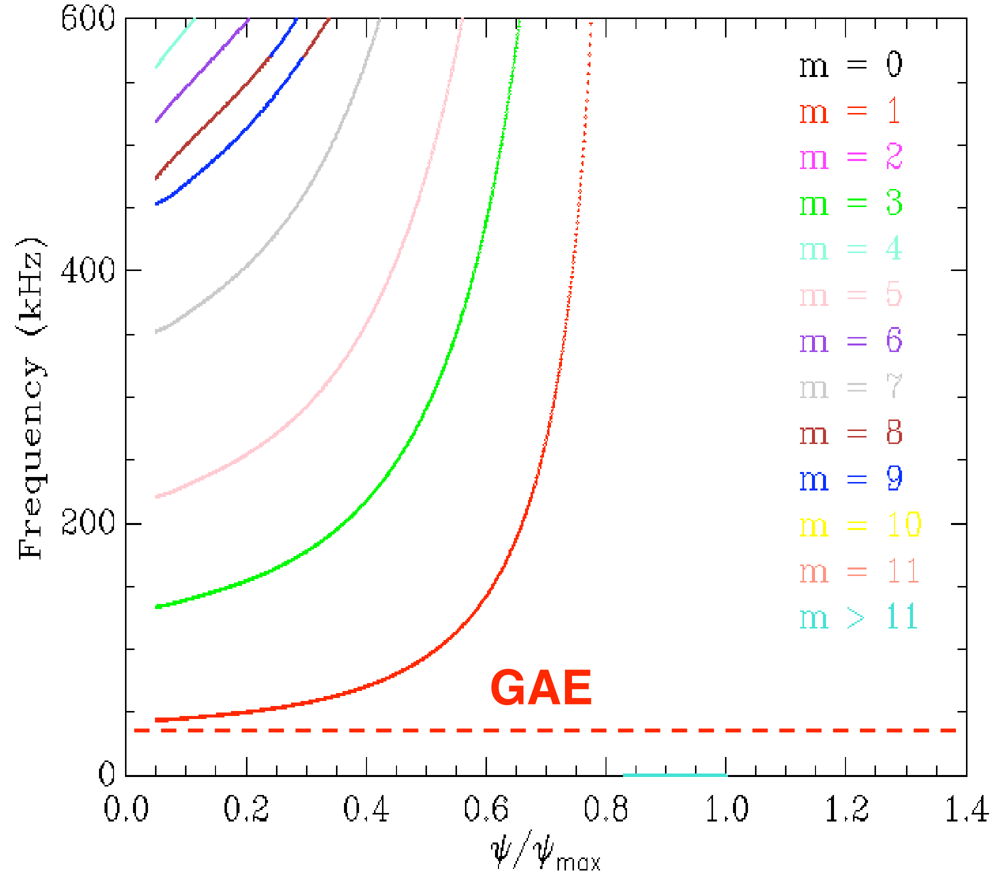
   energetic ions or electrons can drive instability

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
  $n_e(0)=1.8x10^{12}$ cm^{-3}

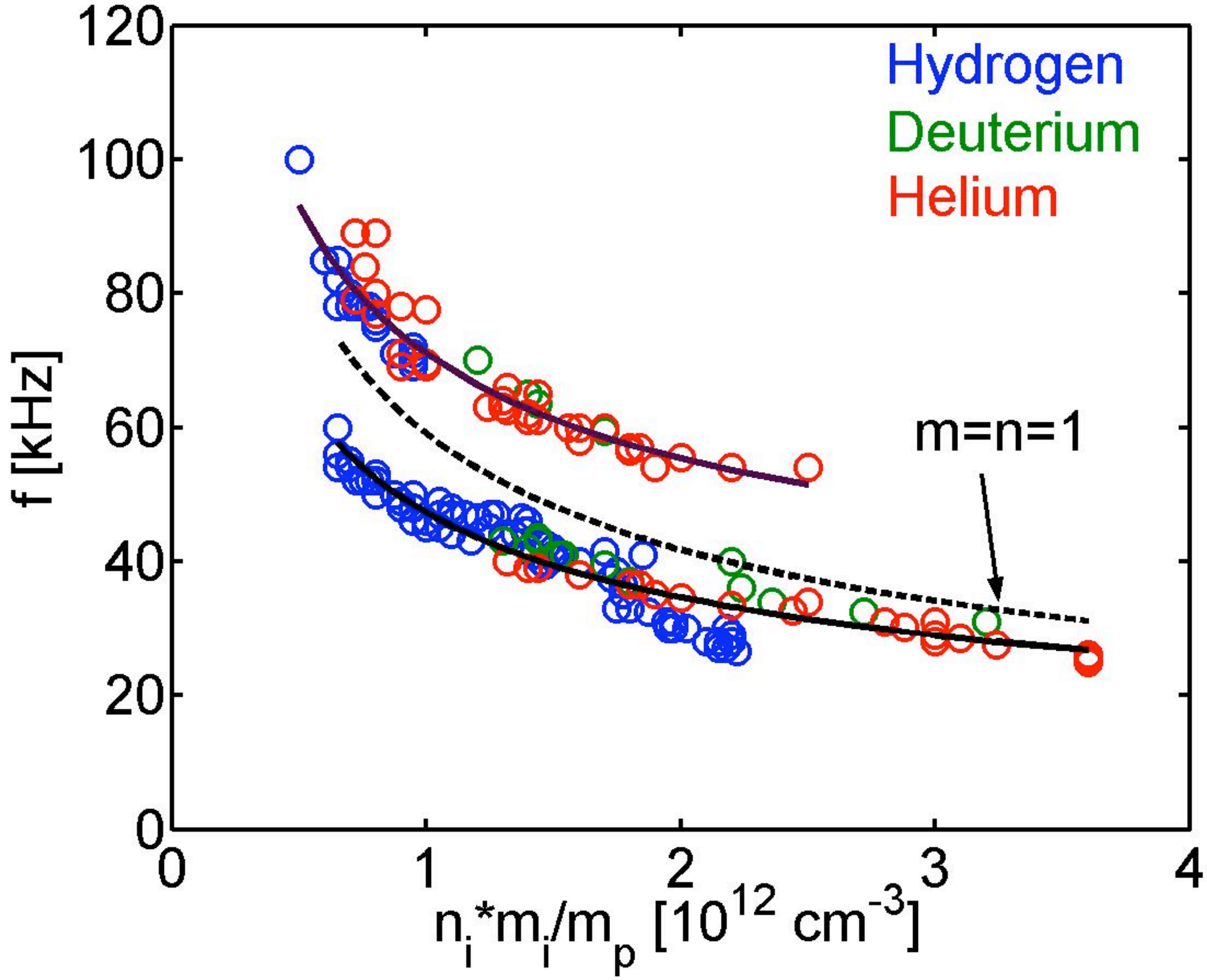
- Only minor changes for mirror configuration



B=0.5 T

STELLGAP code (D. Spong)

Mode frequency scaling with ion mass density

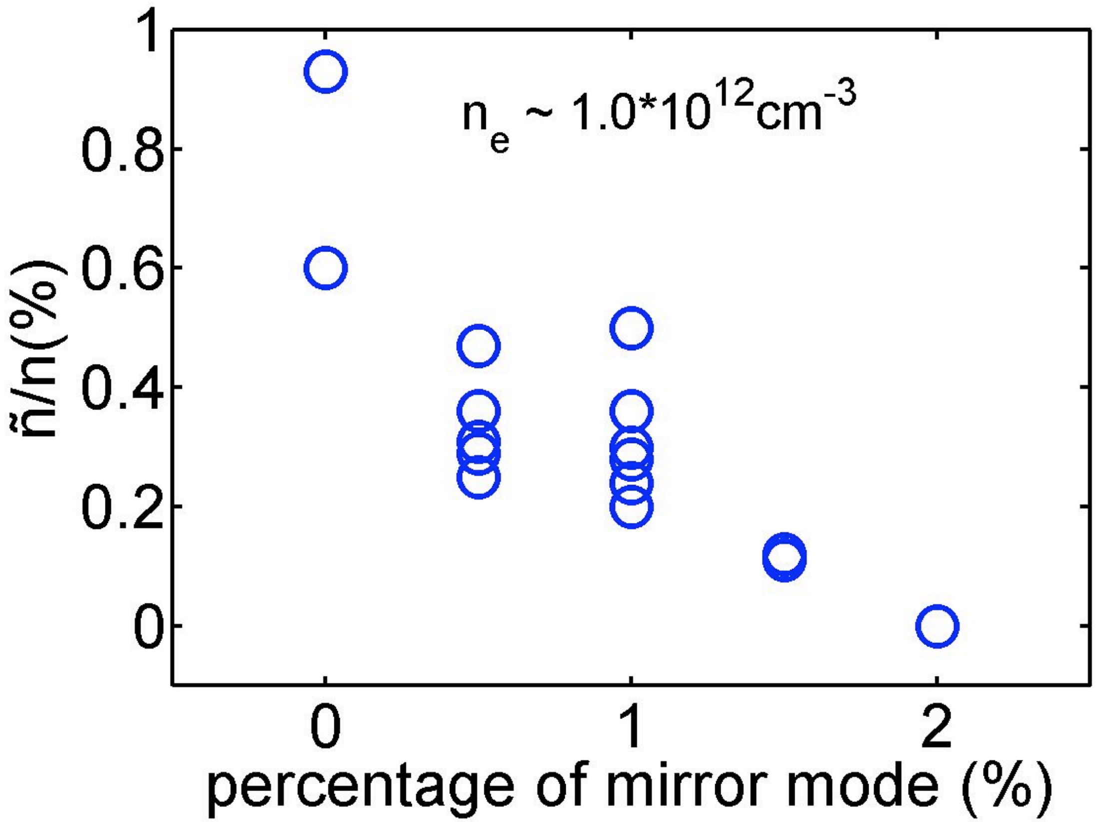


$$\omega_{GAE} \approx k_{//} v_A = \frac{(m - \iota n)}{R} \frac{B}{\sqrt{4\pi n_i m_i}}$$

- frequency and mass density scaling consistent with Alfvenic mode

- If iota is lowered < 1, GAE gap disappears and *<u>mode not observed</u>*

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



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

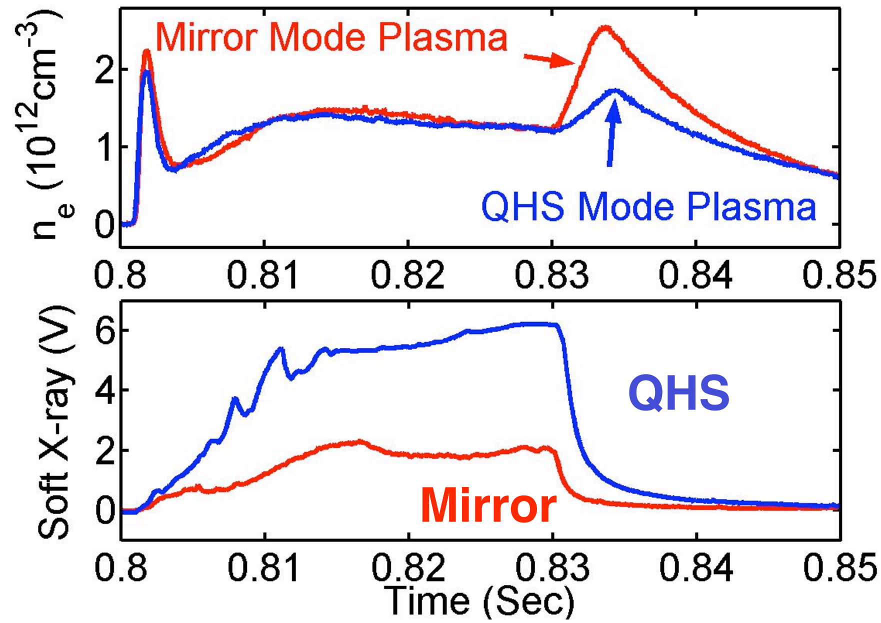
Soft X-ray, Hard X-ray Emission for QHS and Mirror

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

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

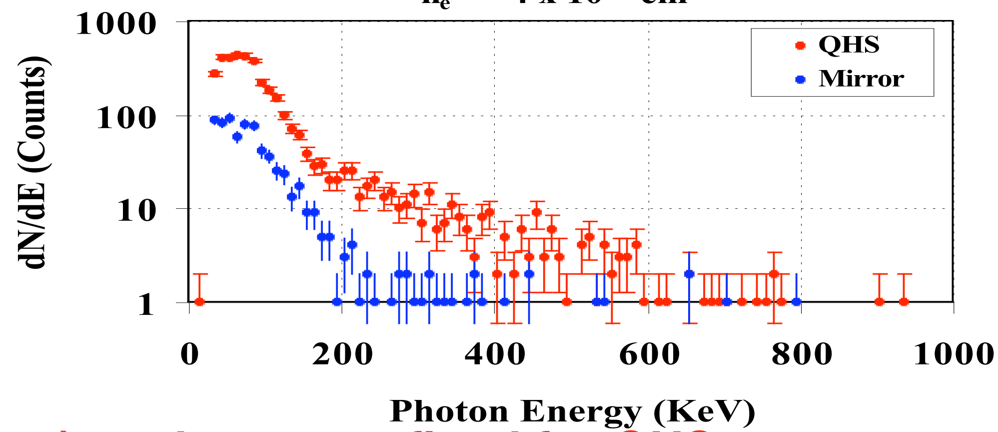
- fast particles are better confined in QHS

- ·$\square_{Dh}$=$\square_{GAE}$:
  5-10 keV particles



HXR Spectrum for QHS, Mirror

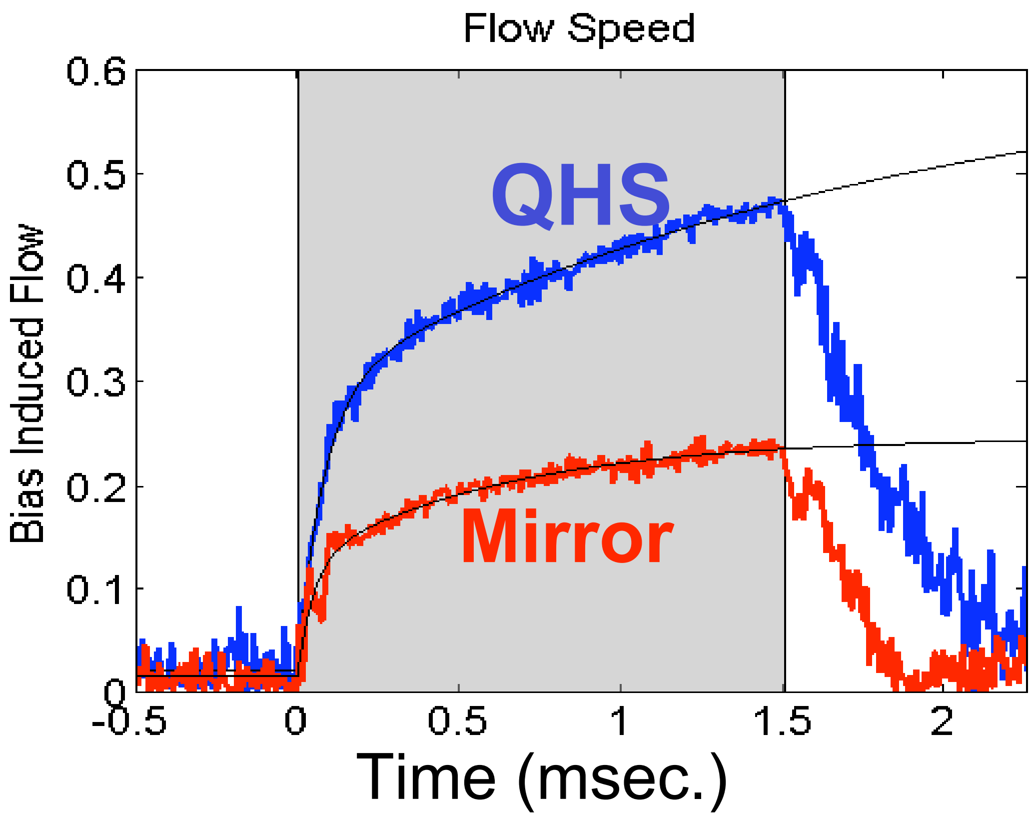
$<n_e> \sim 4 \times 10^{11}$ cm^{-3}



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

Result: QHS Flows Damp More Slowly, and, Go Faster For Less Drive

Viscous Damping is Reduced for QHS



QHS: 8 A of electrode current

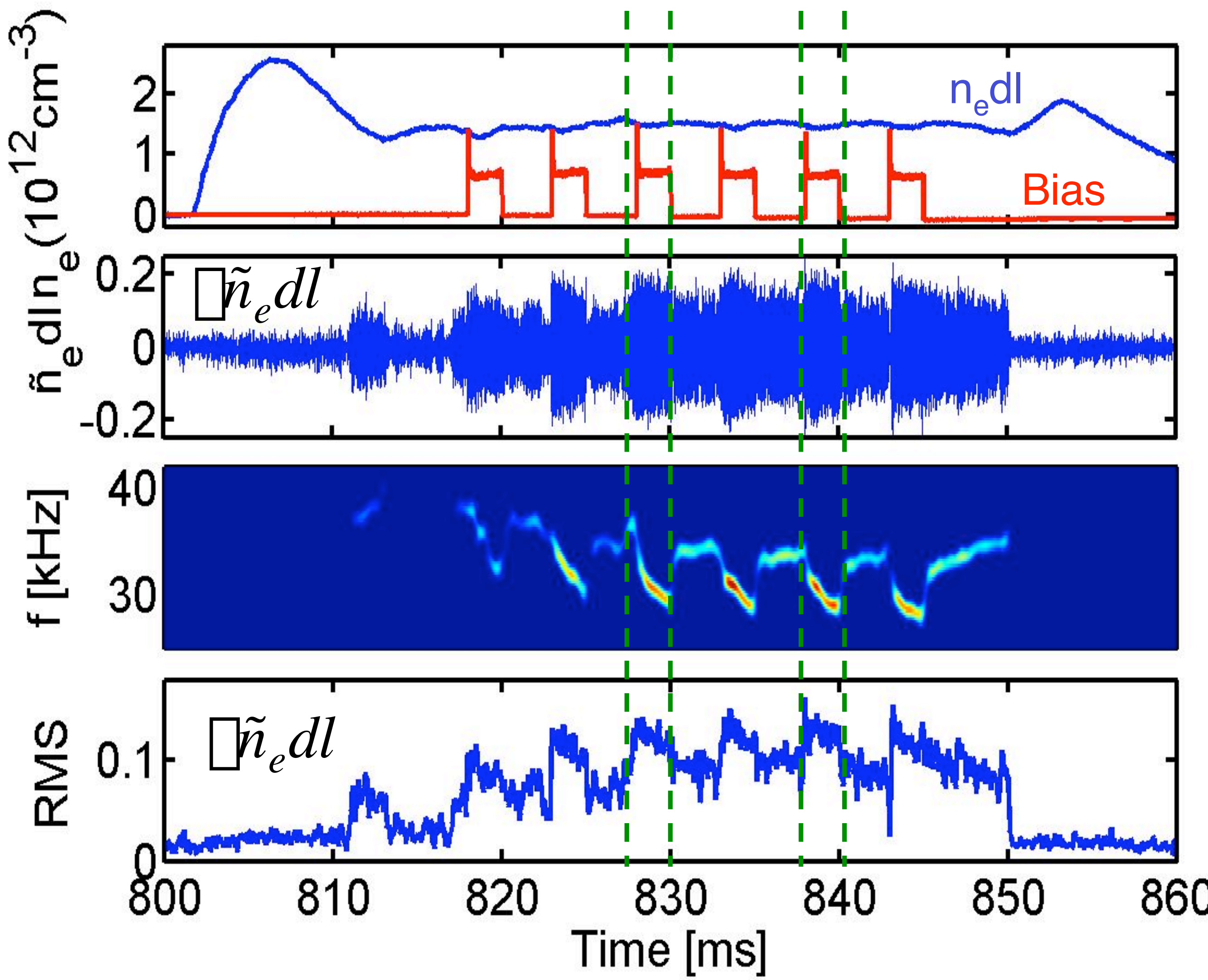
$$M = \frac{V_f}{\sqrt{T_e/m_i}} \; □ \; 0.5$$

Mirror: 10 A of electrode current

other parameters (n_e=1x10^{12}cm^{-3}, n_n □ 1x10^{10}cm^{-3} T_i□25eV, B=0.5T, P_{ECH}=50 kW) held constant.

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

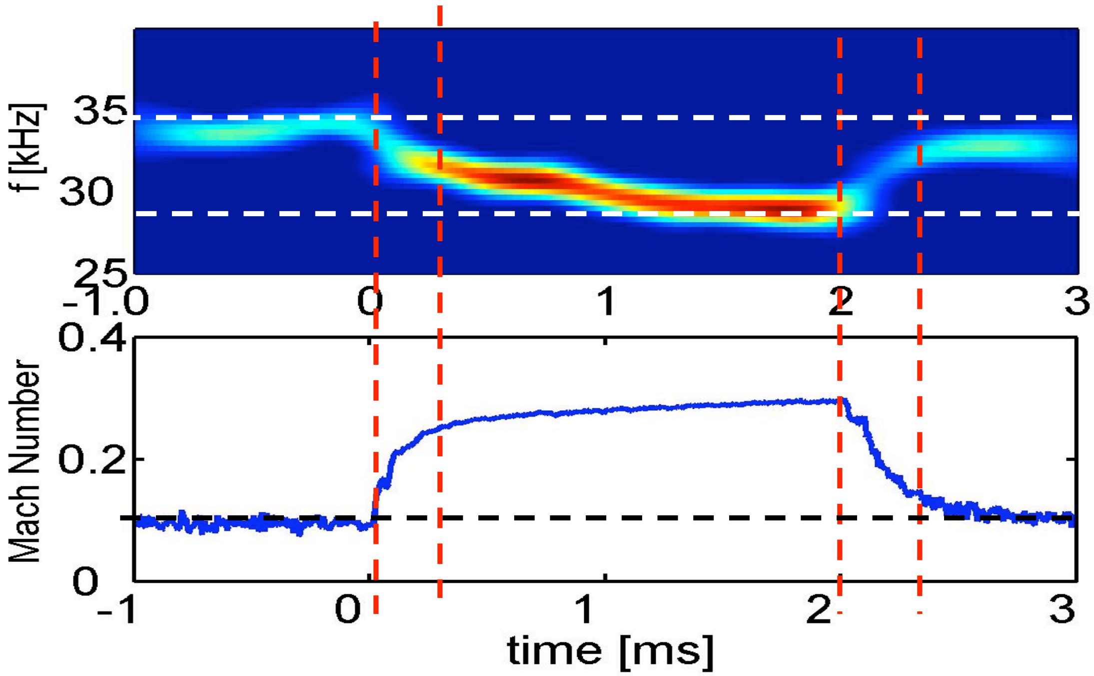
QHS: + biasing increases *amplitude* and decreases *frequency*



- amplitude increases 50-100%

-frequency decreases 10-20%

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



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

Ambient plasma potential is (+)

ExB flow in ion drift direction

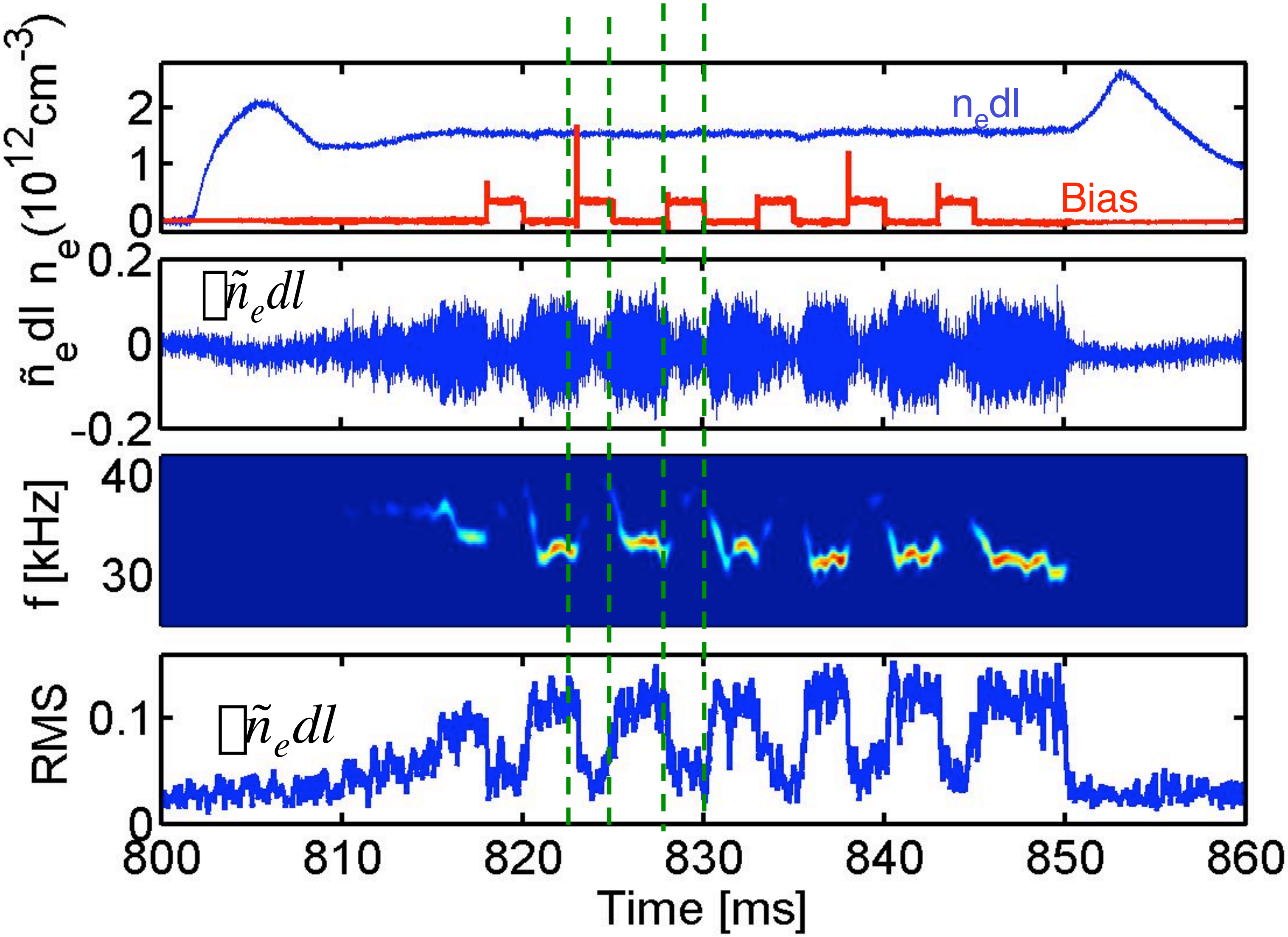
Alfvenic mode propagates in electron diamagnetic drift direction?

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

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

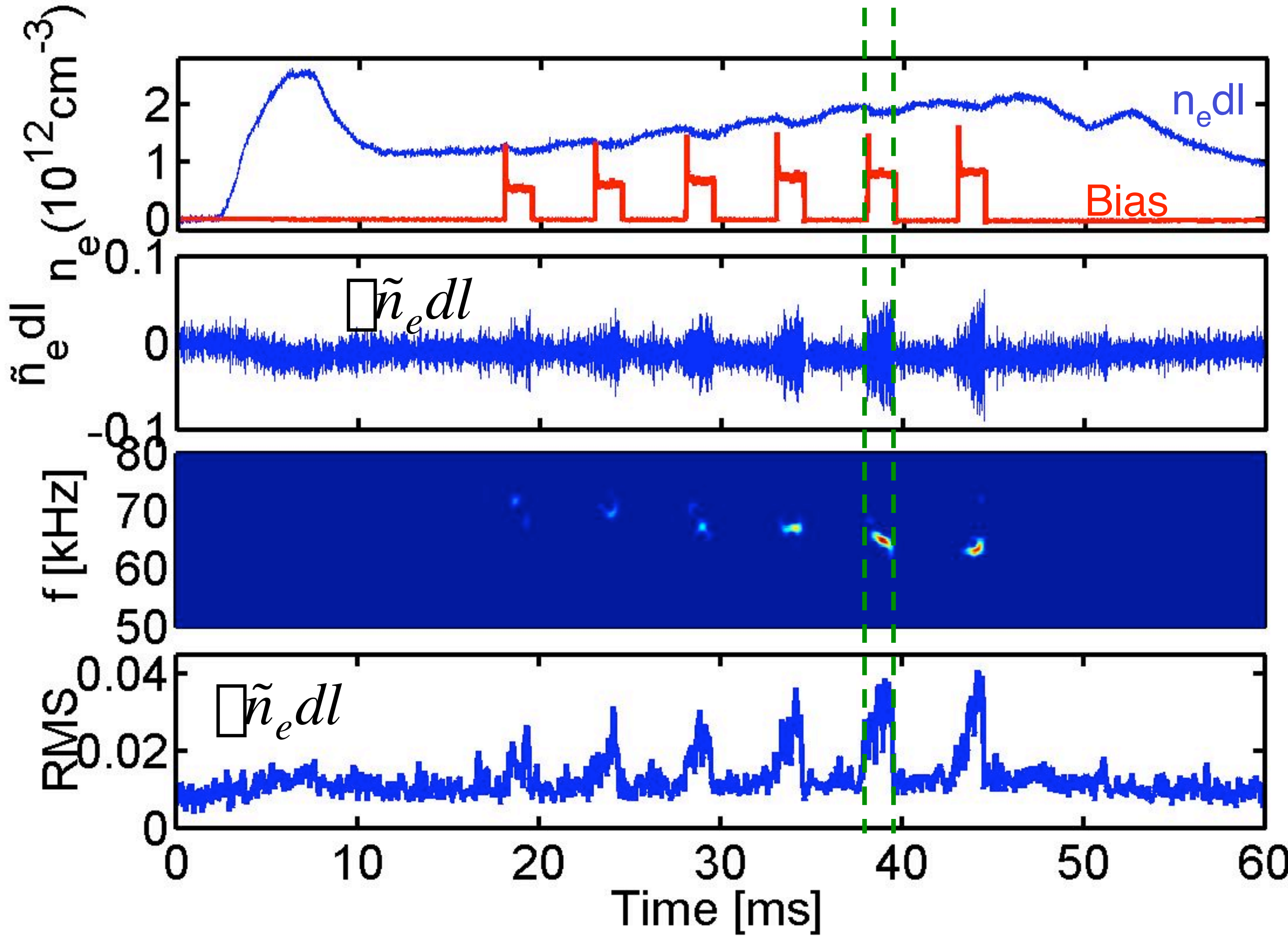
$$\Delta f_{lab} \approx 5-10\ kHz; \Rightarrow \Delta E_r \approx 5-10\ V/cm \quad for\ plasma\ core\ with\ bias$$

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=odd (1?)] with frequency and ion mass density scaling is 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: Δf_{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