

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

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June 28, 2005 EPS-Tarragona

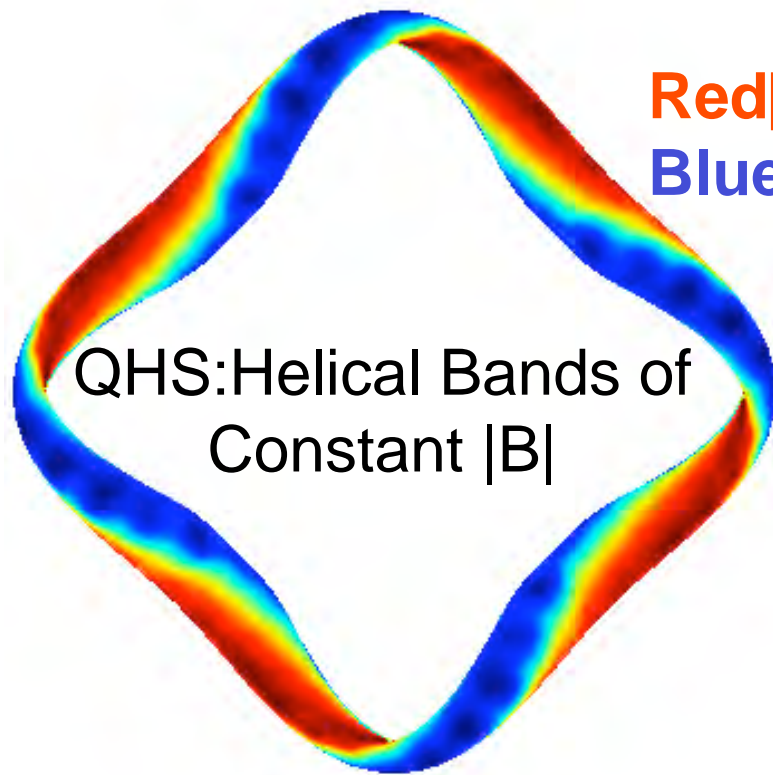
HSX Provides Access to Configurations With and Without Symmetry

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

QHS

Mirror

Red \square $|B| > 0.5$ T
Blue \square $|B| < 0.5$ T



QHS: Helical Bands of Constant $|B|$



Mirror: Helical Bands are Broken

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

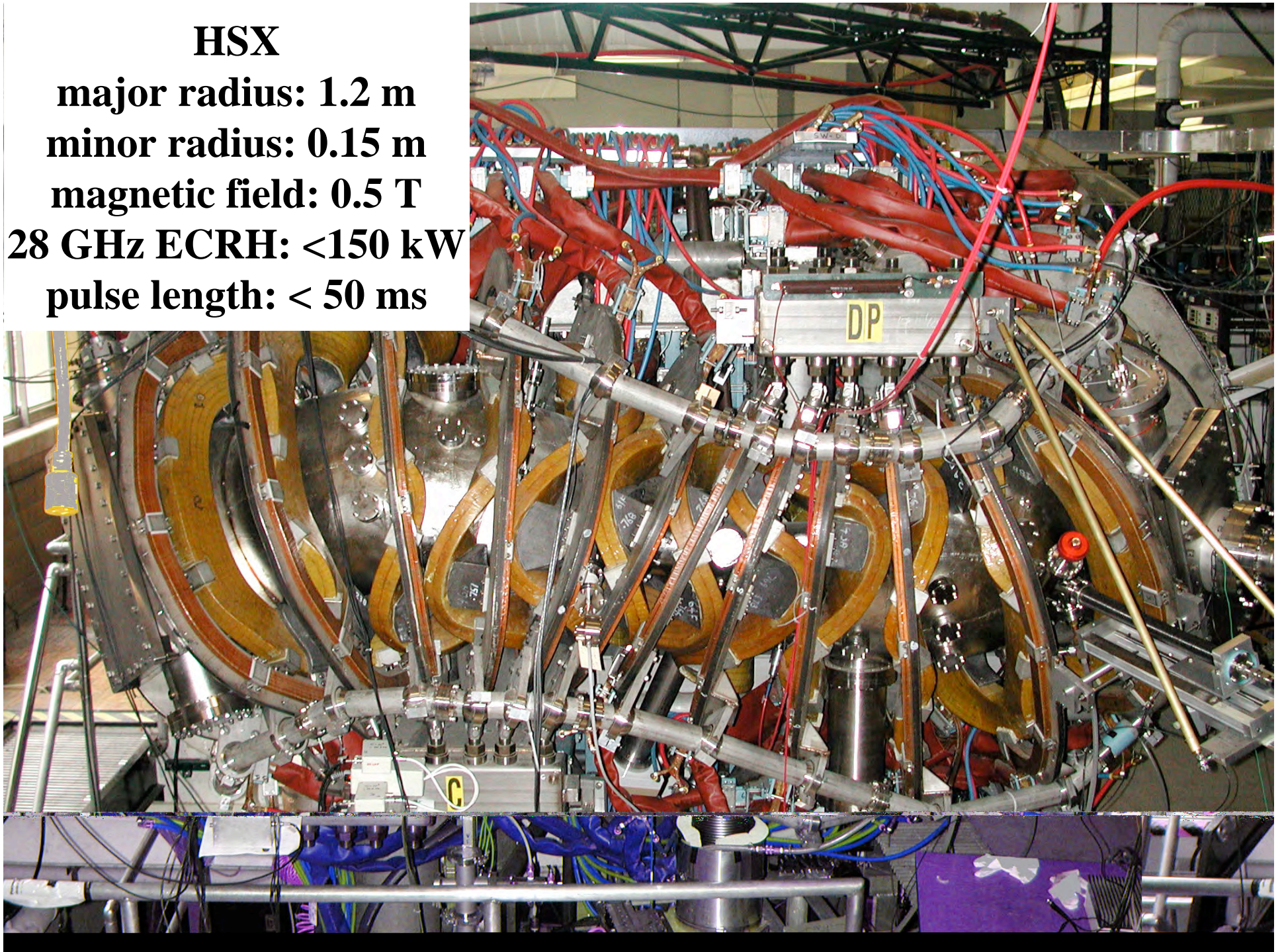
major radius: 1.2 m

minor radius: 0.15 m

magnetic field: 0.5 T

28 GHz ECRH: <150 kW

pulse length: < 50 ms



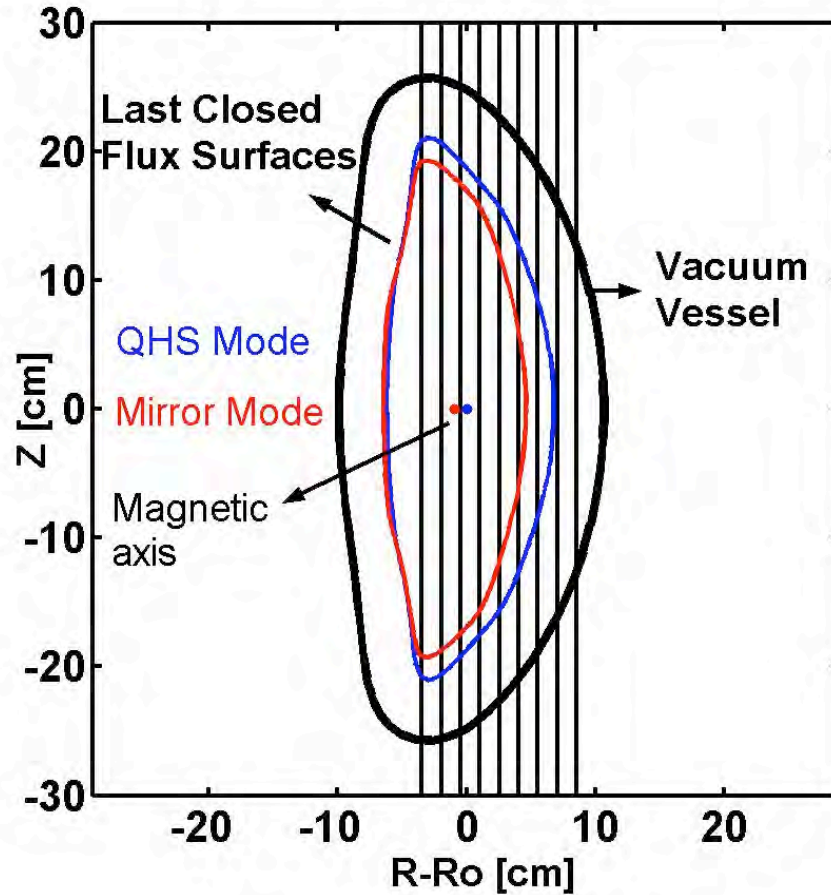
Outline

- 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 Alfvénic mode**

GOAL

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

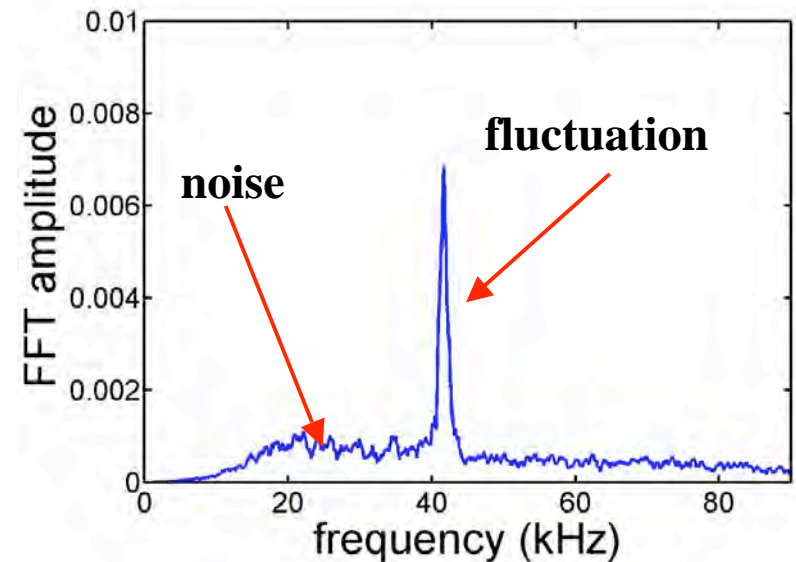
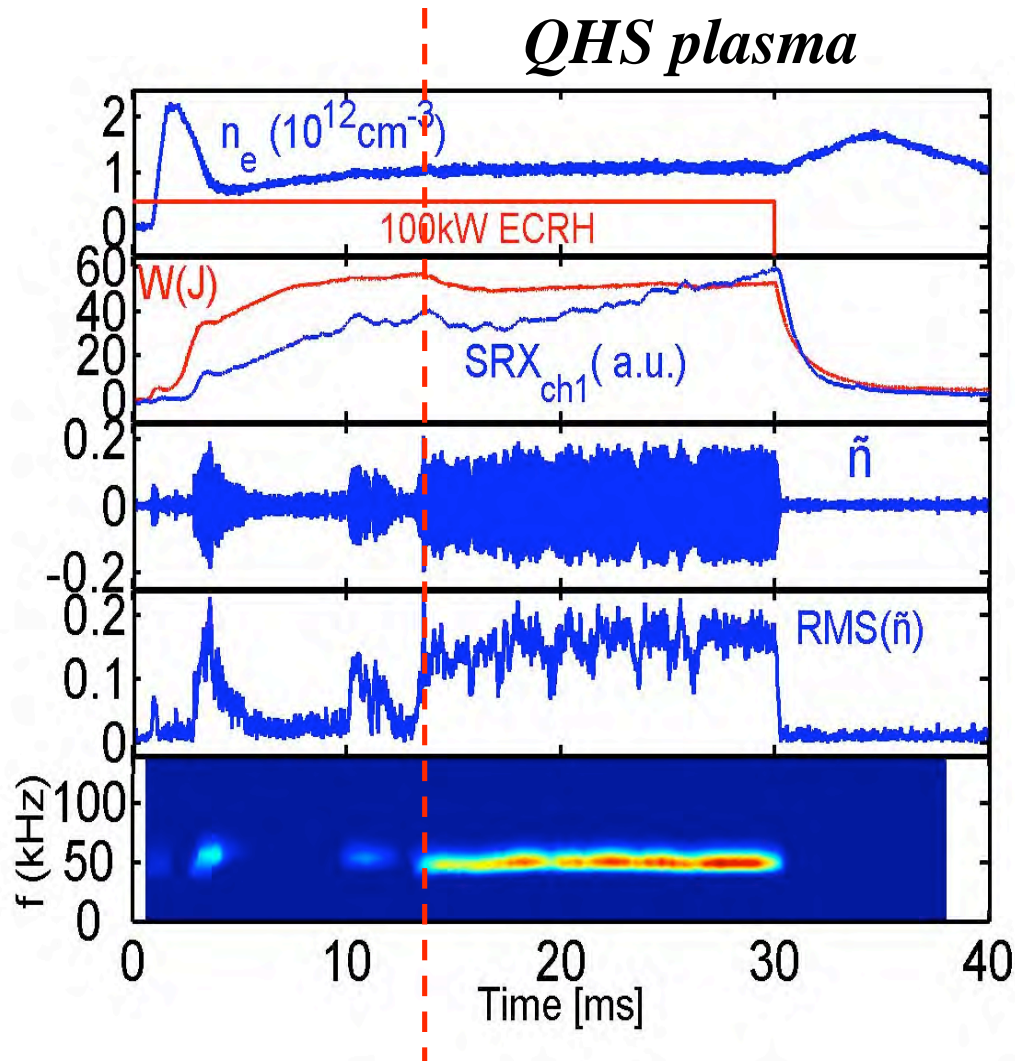
Flux Surfaces and Interferometer Chords



Interferometer System:

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

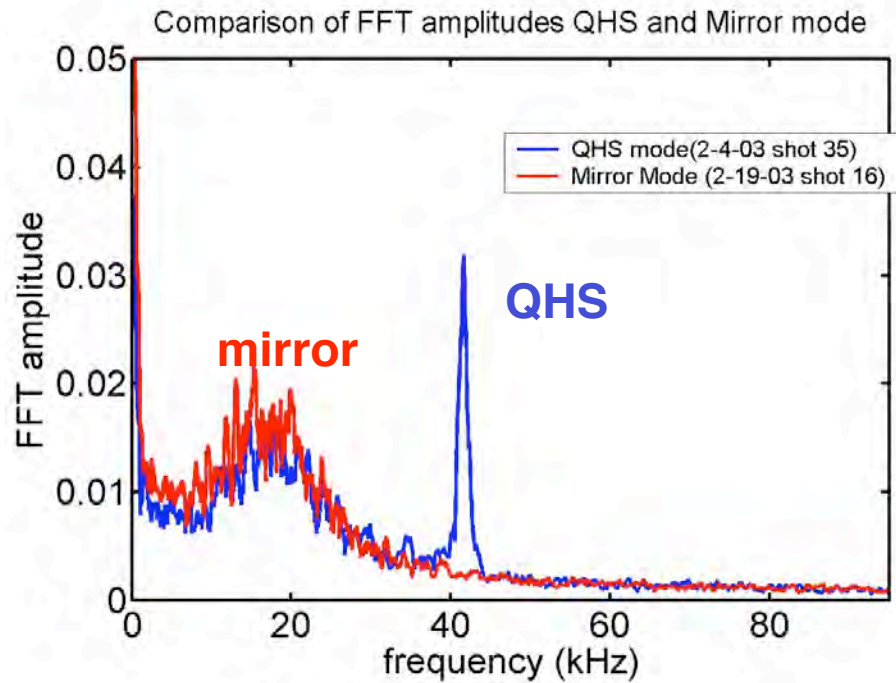
Coherent Density Fluctuations



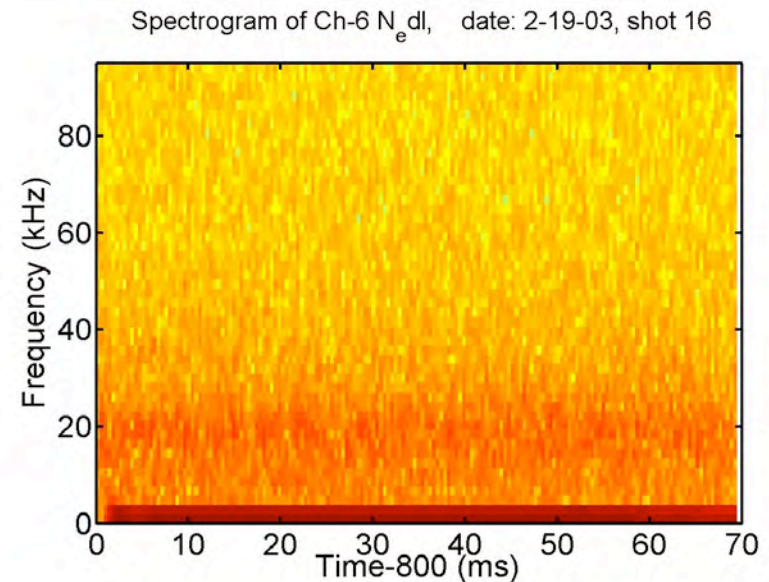
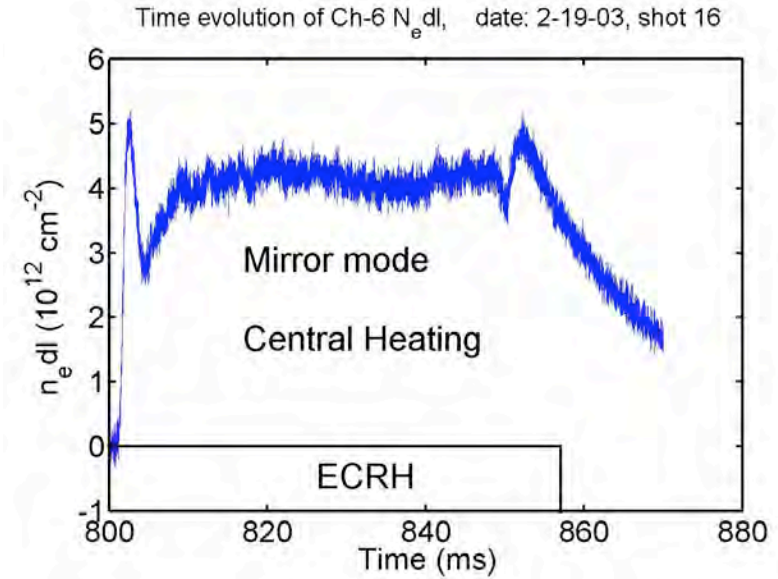
- 28 GHz ECRH
- 2nd Harmonic X-mode
- Generates fast electrons with $T_{e\perp} \gg T_{e\parallel}$

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

No mode observed in Mirror Configuration Plasma

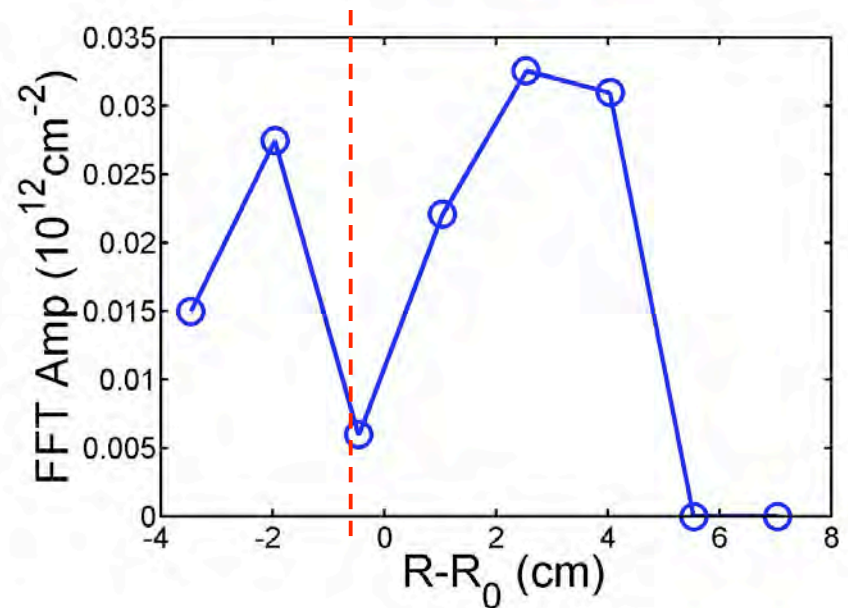
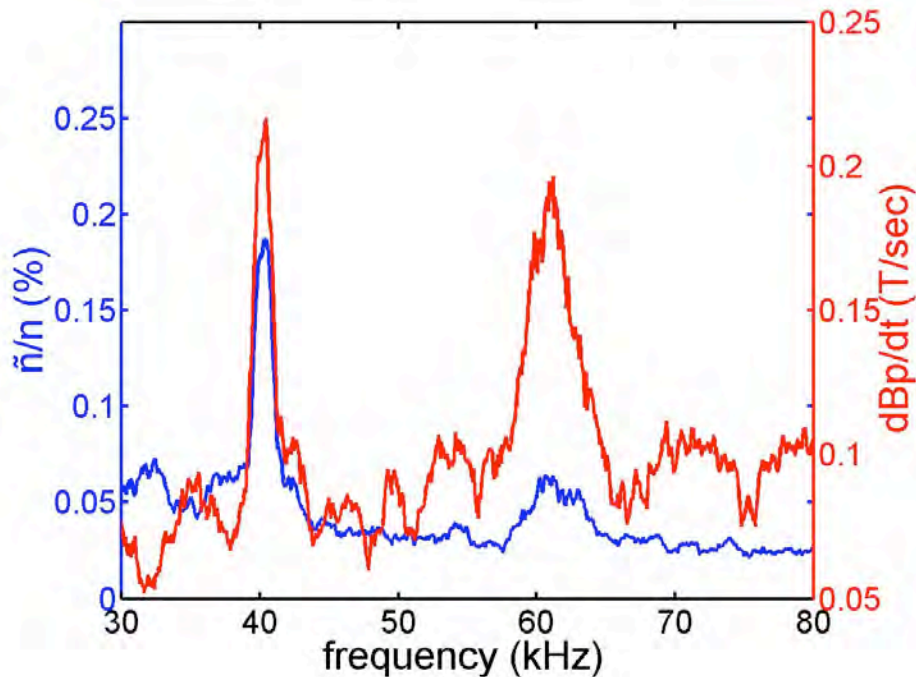
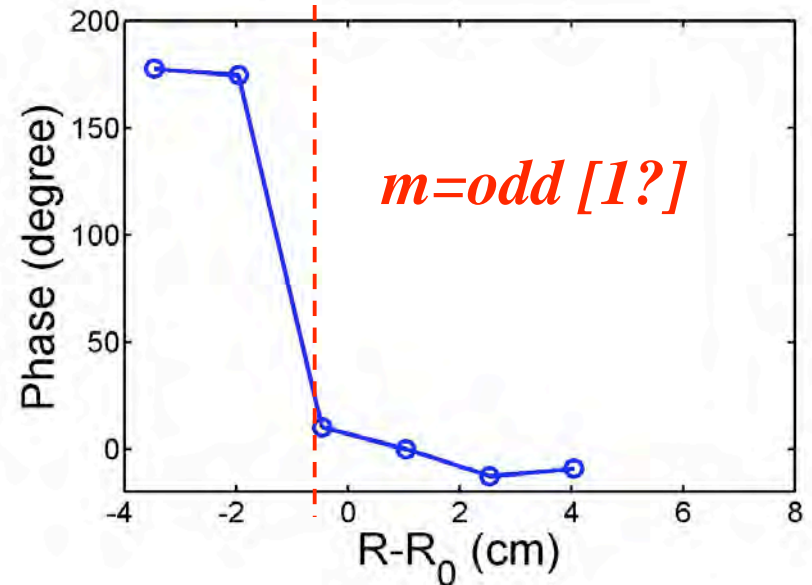


10% Mirror perturbation

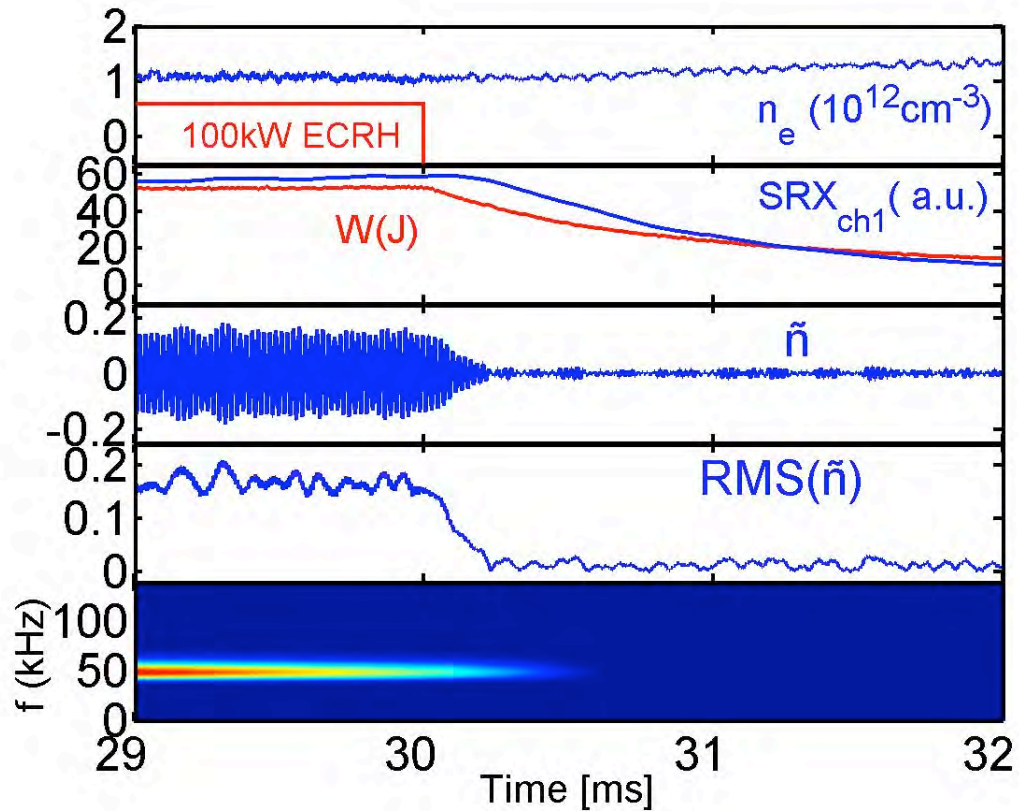


Fluctuation Features

- only observed in QHS plasmas
- coherent, $m=1$ ($n=?$)
- localized to steep gradient region
- satellite mode appears at low densities, $\Delta f \sim 20$ kHz
- **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: $T_i \sim 20$ eV) $T_{e\perp} \gg T_{e\parallel}$

Modes 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

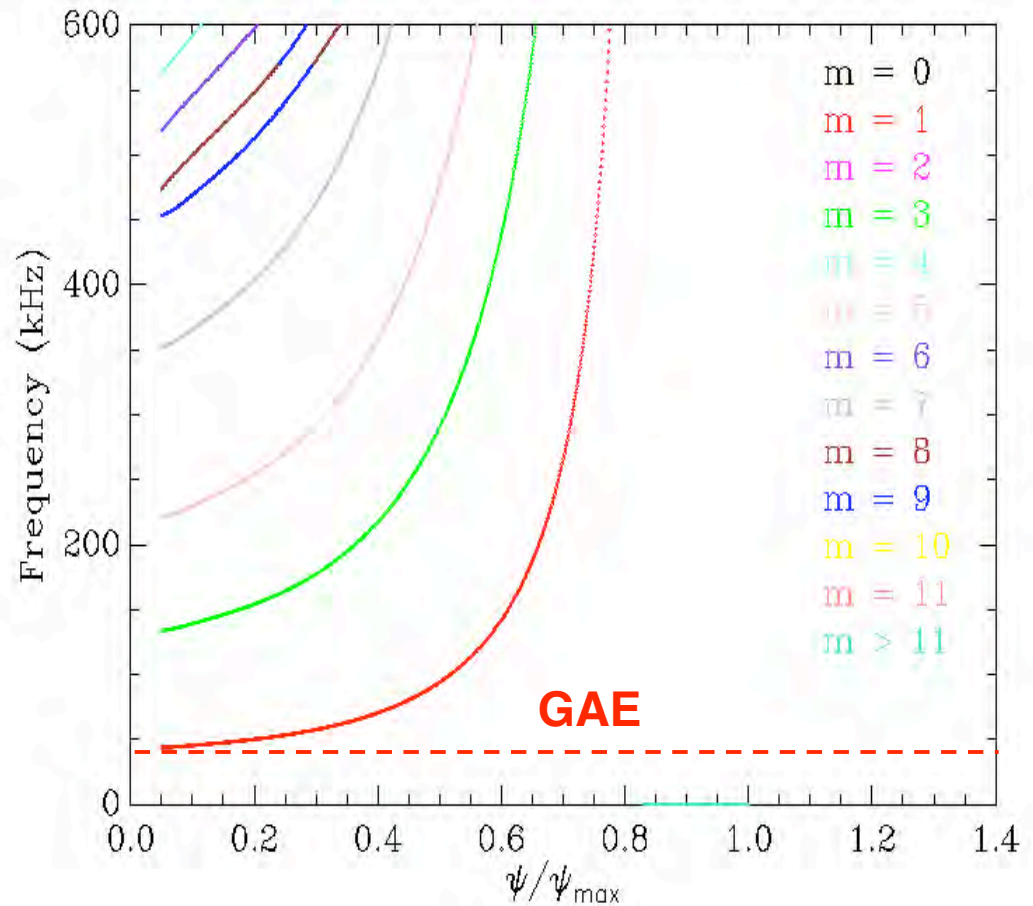
2. unstable when: $\omega_{dia}^* > \omega_{Alfven}$
where ω_{dia}^* is the diamagnetic drift frequency

energetic ions or electrons can drive instability

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

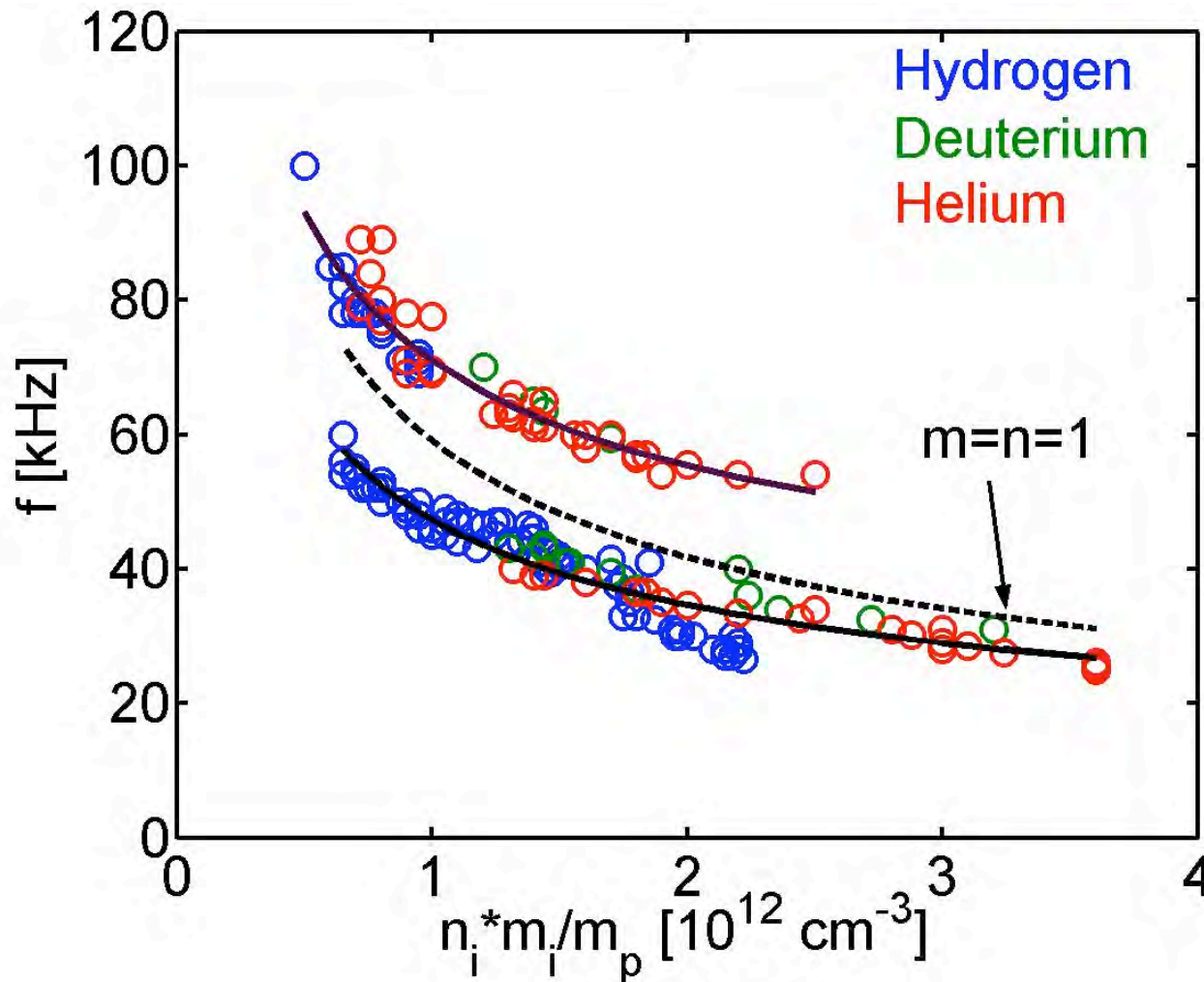
- GAE Gap: $B=0.5$ T
0 - 50 kHz for $m=1, n=1$
 $n_e(0)=1.8 \times 10^{12} \text{ cm}^{-3}$
- Only minor changes for mirror configuration

B=0.5 T



3-D STELLGAP code (D. Spong)

Mode frequency scaling with ion mass density

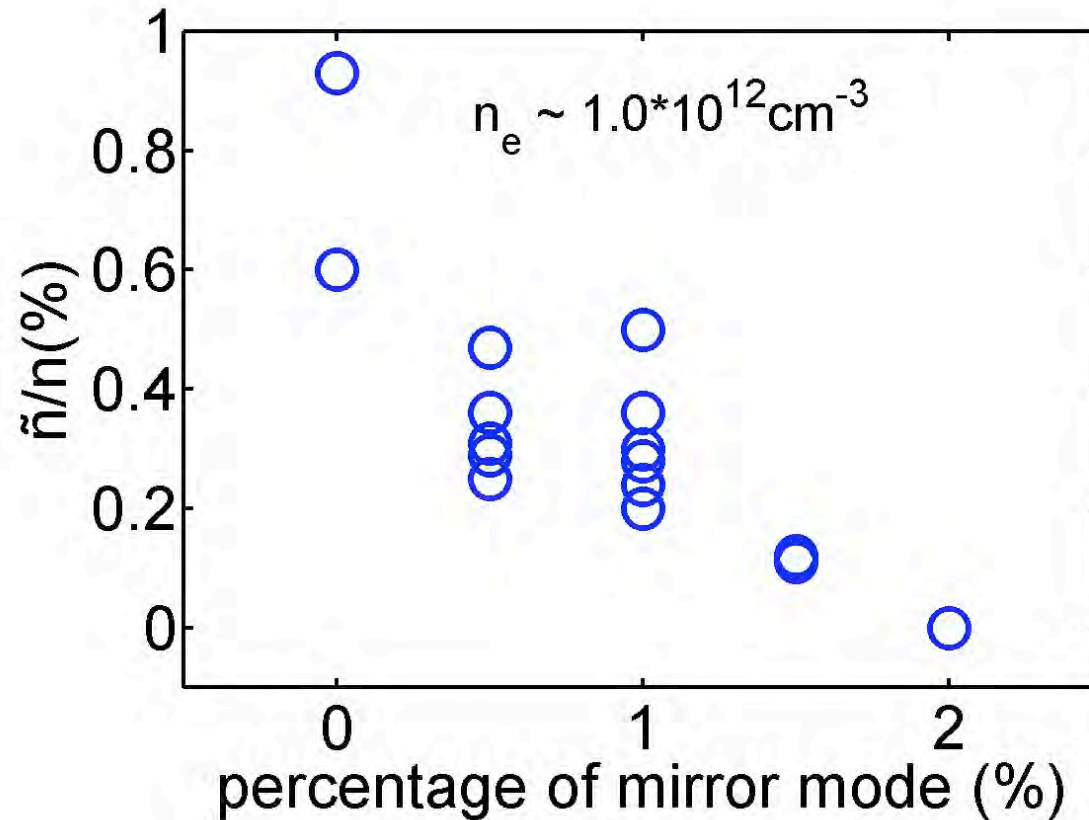


$$\omega_{GAE} \approx k_{||} v_A = \frac{(m \frac{v}{n})}{R} \frac{B}{\sqrt{4 n_i m_i}}$$

*What about B scaling?
Future 1 T operation*

- frequency and mass density scaling consistent with Alfvénic mode
- If ι is lowered < 1 , GAE gap disappears and mode not observed

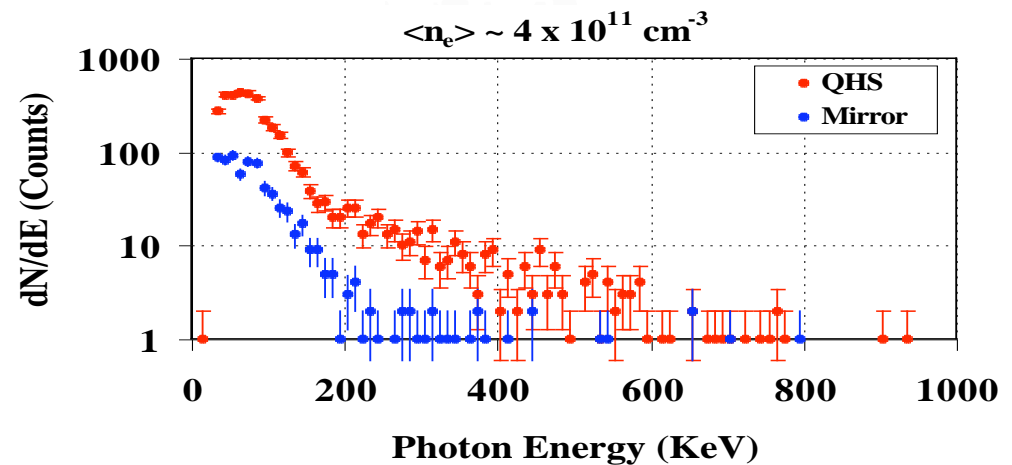
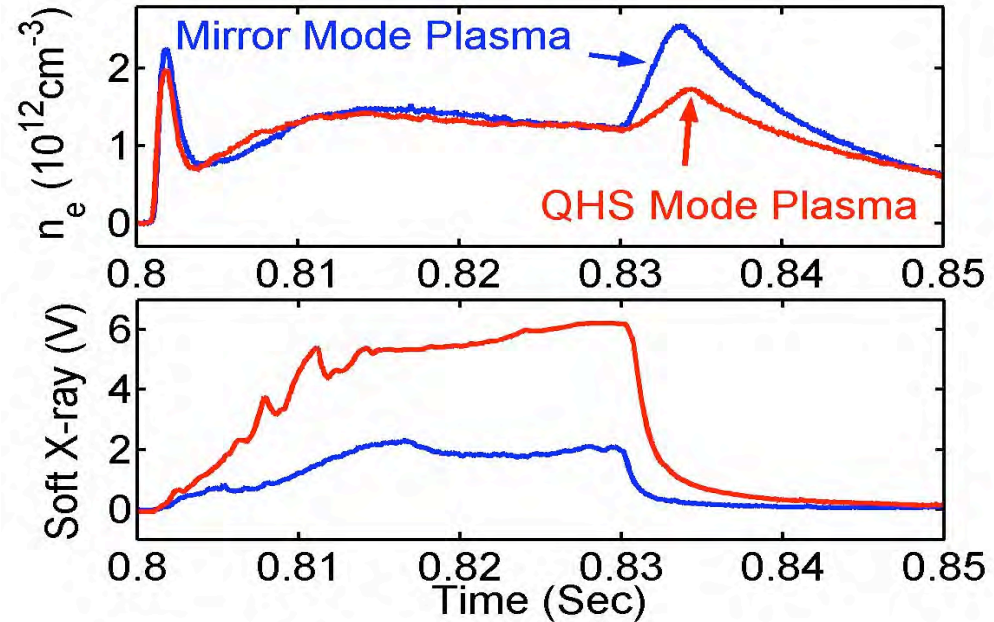
Density fluctuations **decrease** with introduction of symmetry breaking (toroidal mirror) term



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

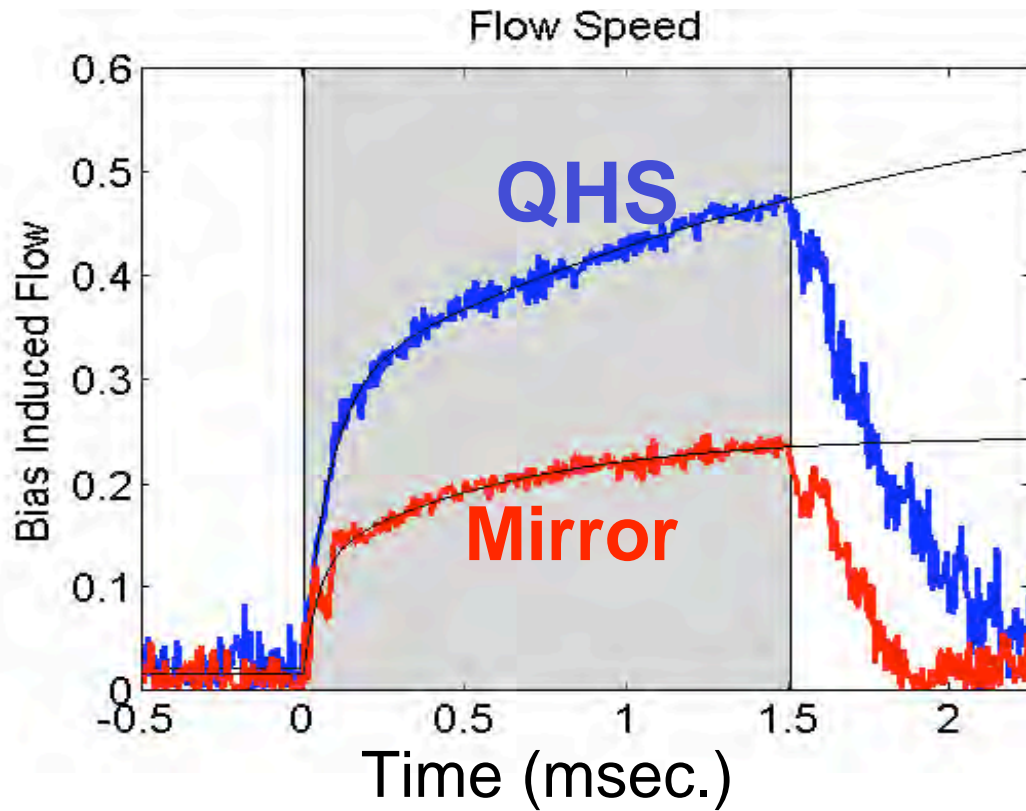
Soft X-ray, Hard X-ray Emission for QHS and Mirror

- 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



- 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



**QHS: 8 A of
electrode current**

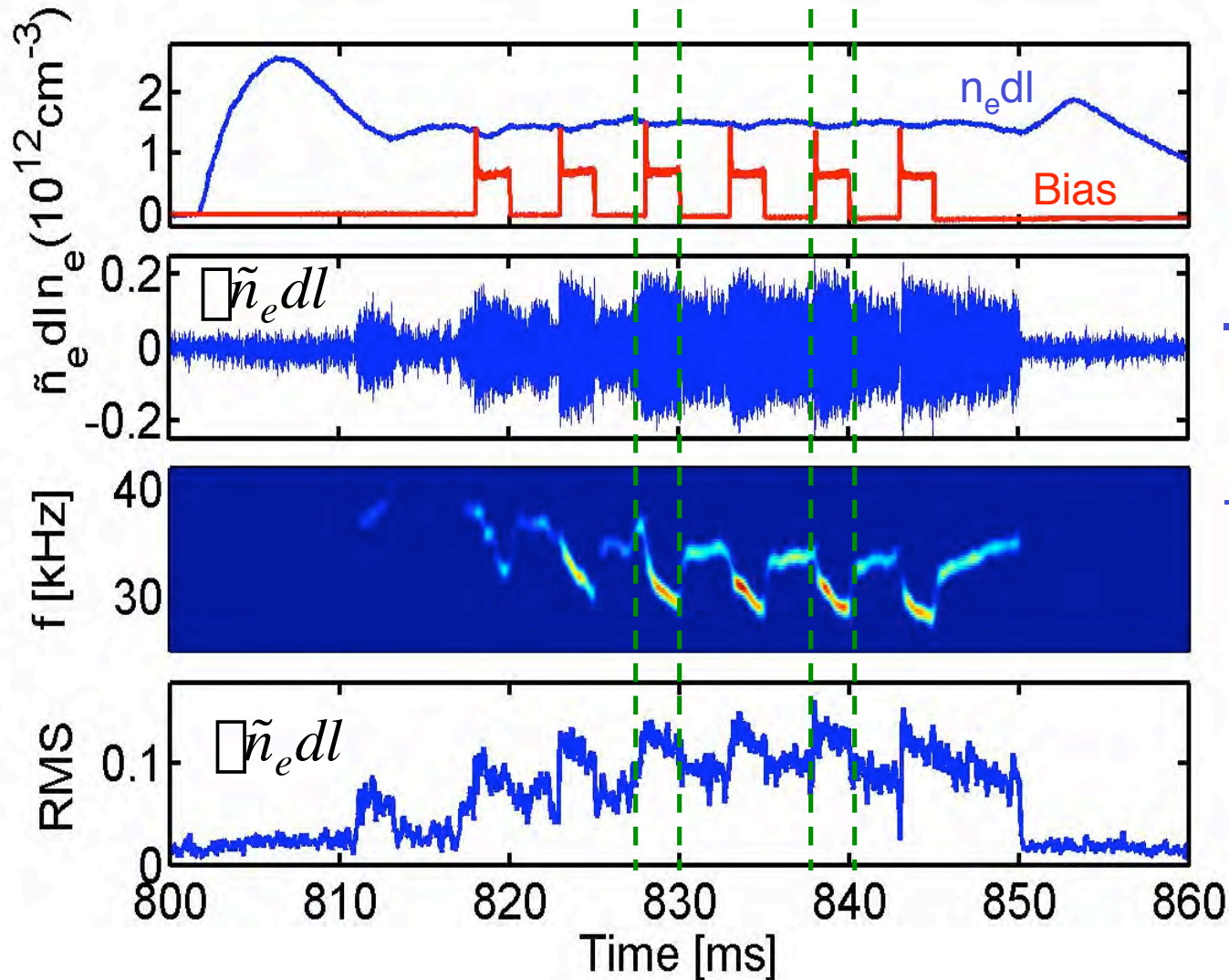
$$M = \frac{V_f}{\sqrt{T_e/m_i}} \approx 0.5$$

**Mirror: 10 A of
electrode current**

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

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

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

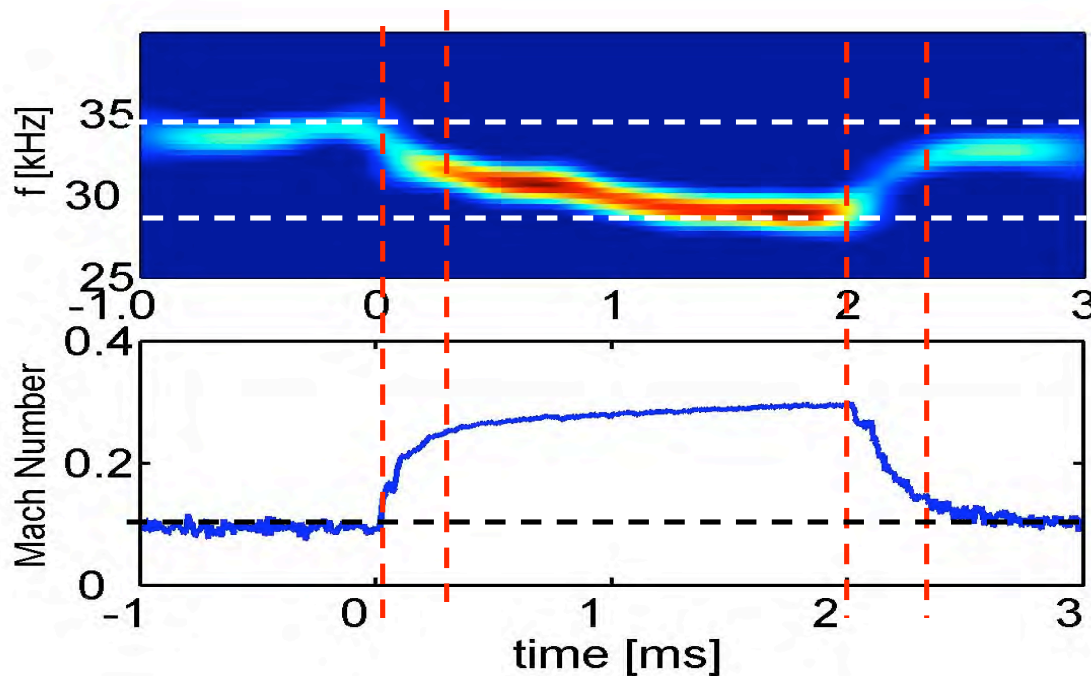


- amplitude increases 50-100%

-frequency decreases 10-20%

$$\bar{n}_e \geq 1.5 \times 10^{12} \text{ cm}^{-3}$$

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 (+)

$E \times B$ flow in ion drift direction

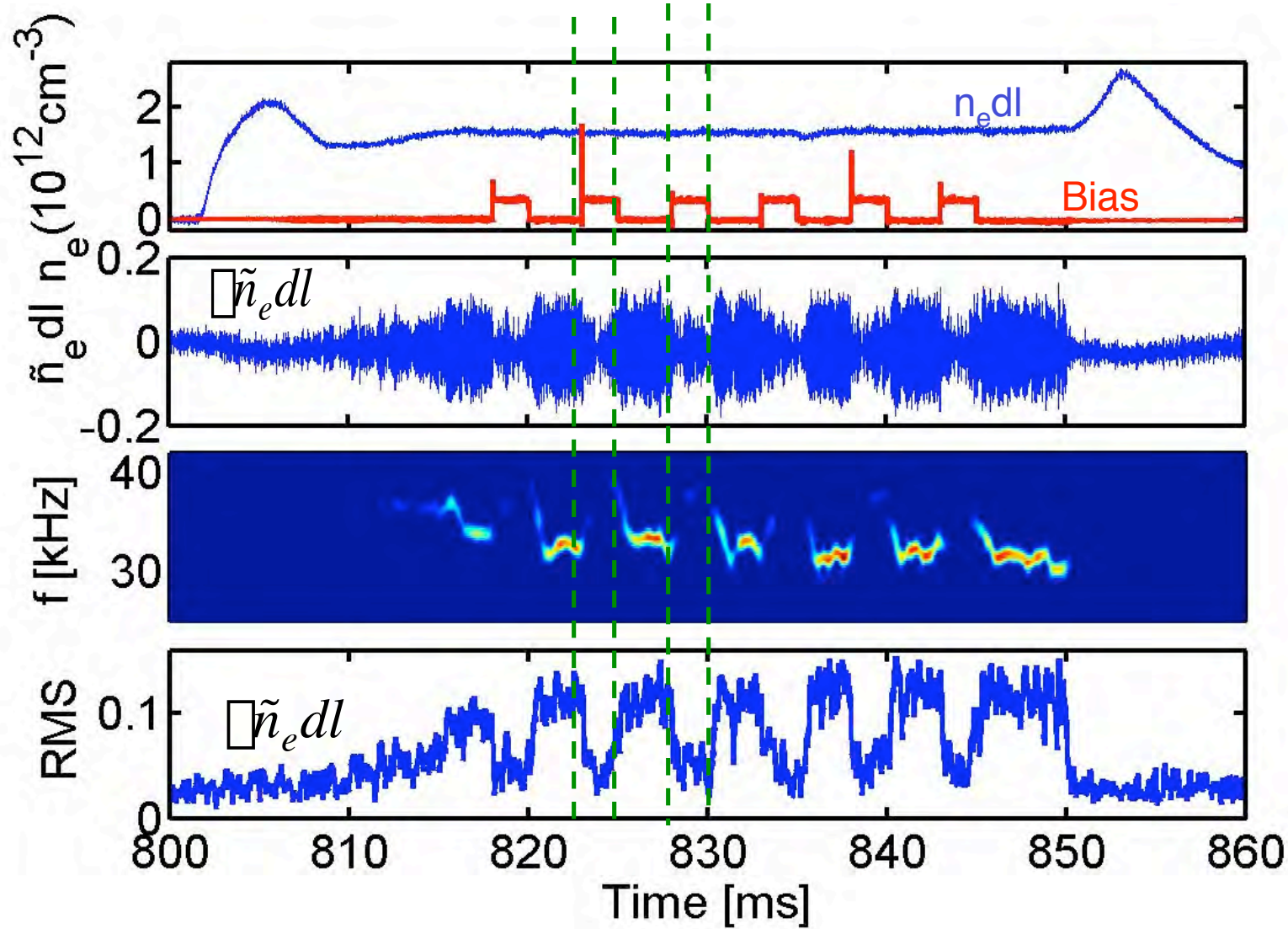
Alfvenic mode propagates in electron diamagnetic drift direction?

$$f_{lab} = f_{GAE} + f_{Doppler} = f_{GAE} + \frac{1}{2\pi} k \cdot v_{Doppler} = f_{GAE} + \frac{m}{r} \frac{E_r}{2\pi B_0}$$

$$\Delta f_{lab} = f_{lab} |_{w/bias} - f_{lab} |_{w/o\ bias} = \Delta f_{Doppler} = \frac{m}{r} \cdot \frac{\Delta E_r}{2\pi B_0}$$

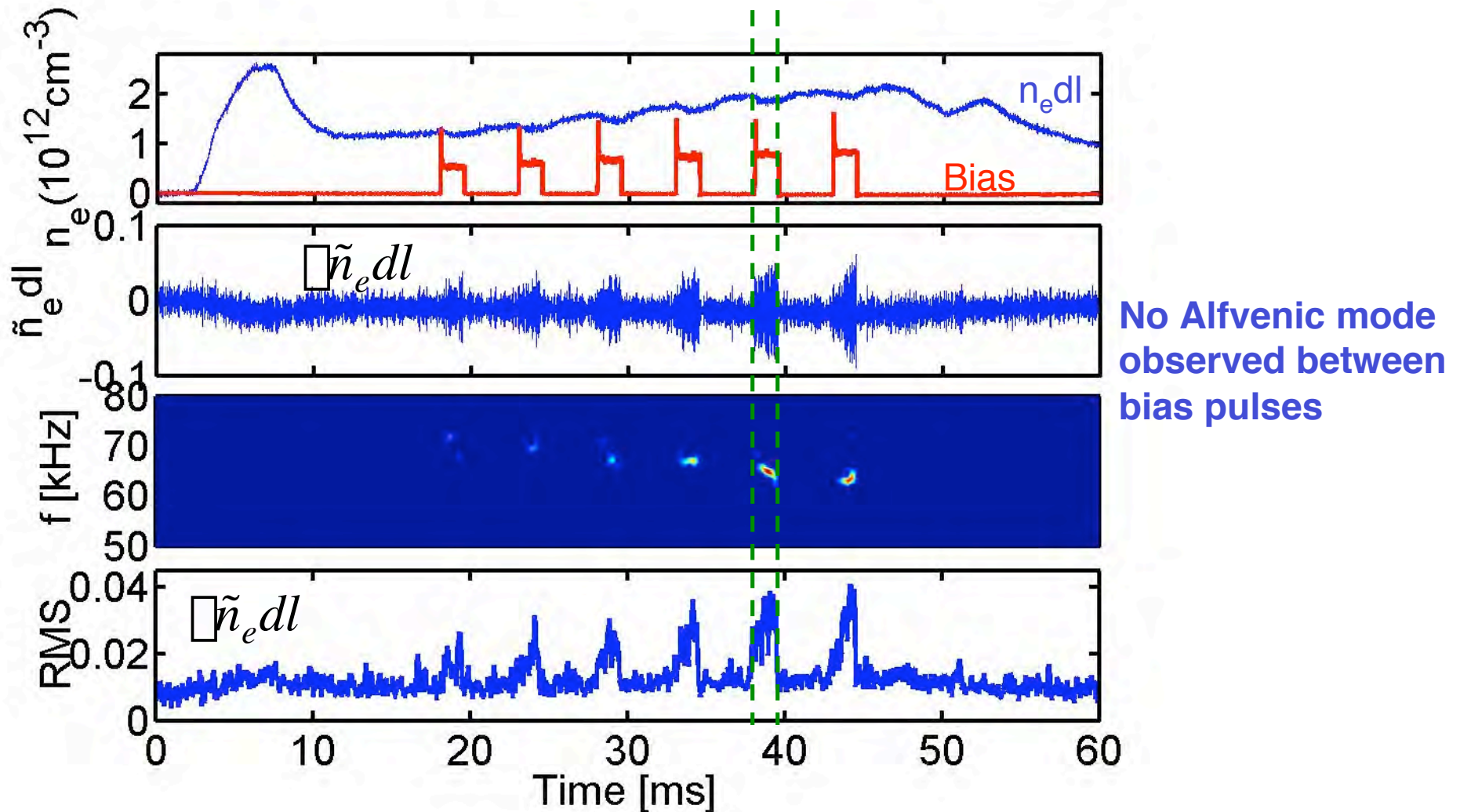
$$\Delta f_{lab} \approx 5 \text{--} 10 \text{ kHz}; \quad \Delta |E_r| \approx 5 \text{--} 10 \text{ V/cm} \quad \text{for plasma core with bias}$$

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



- Biasing against direction of ambient flow

Mirror Mode: Alfvénic Mode observed with + biasing



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

Evidence for fast-electron-driven Alfvénic modes in HSX

1. Calculations of Alfvén 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 **Alfvénic** mode (B scaling unknown).
3. Measurements suggest that the fluctuation is most likely driven by non-thermal electrons
4. Alfvénic Mode is only observed for QHS configuration, not for Mirror Configuration (2%): improved (trapped) particle confinement for QHS
5. Biasing: Δf_{lab} may provide information on core E_r and flow dynamics!
- How do flows affect to Alfvénic mode growth rate?

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

Open Issues

1. **Mode propagation direction: odd if E_r becomes more (+) with biasing. Expect mode to propagate in diamagnetic drift direction of driving species**
2. **Mode structure [m =odd (1?), n =?]: External magnetics suggest $m=0$? Differences between magnetic and density measurements.....**
3. **B scaling?: need to know E_r profile. Can 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 Alfvénic mode to mirror perturbation (2%). Which particles are resonant with mode? How are they affected by mirror perturbation?**
6. **Biasing: Δf_{lab} may provide information on core E_r and flow dynamics!**
 - How do flows affect to Alfvénic mode growth rate?
 - E_r measurements in plasma core..... How is potential profile modified by biasing? What is potential profile for non-biased plasmas?

Investigation of Alfvénic modes in HSX has just begun!