

Energetic-Electron-Driven Instability in the Hellically Symmetric Experiment

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Outline

1. Characteristics of observed fluctuation

- frequency
- mode number
- scaling

2. Candidates of Instability

- Alfvénic
- acoustic
- other?

HSX

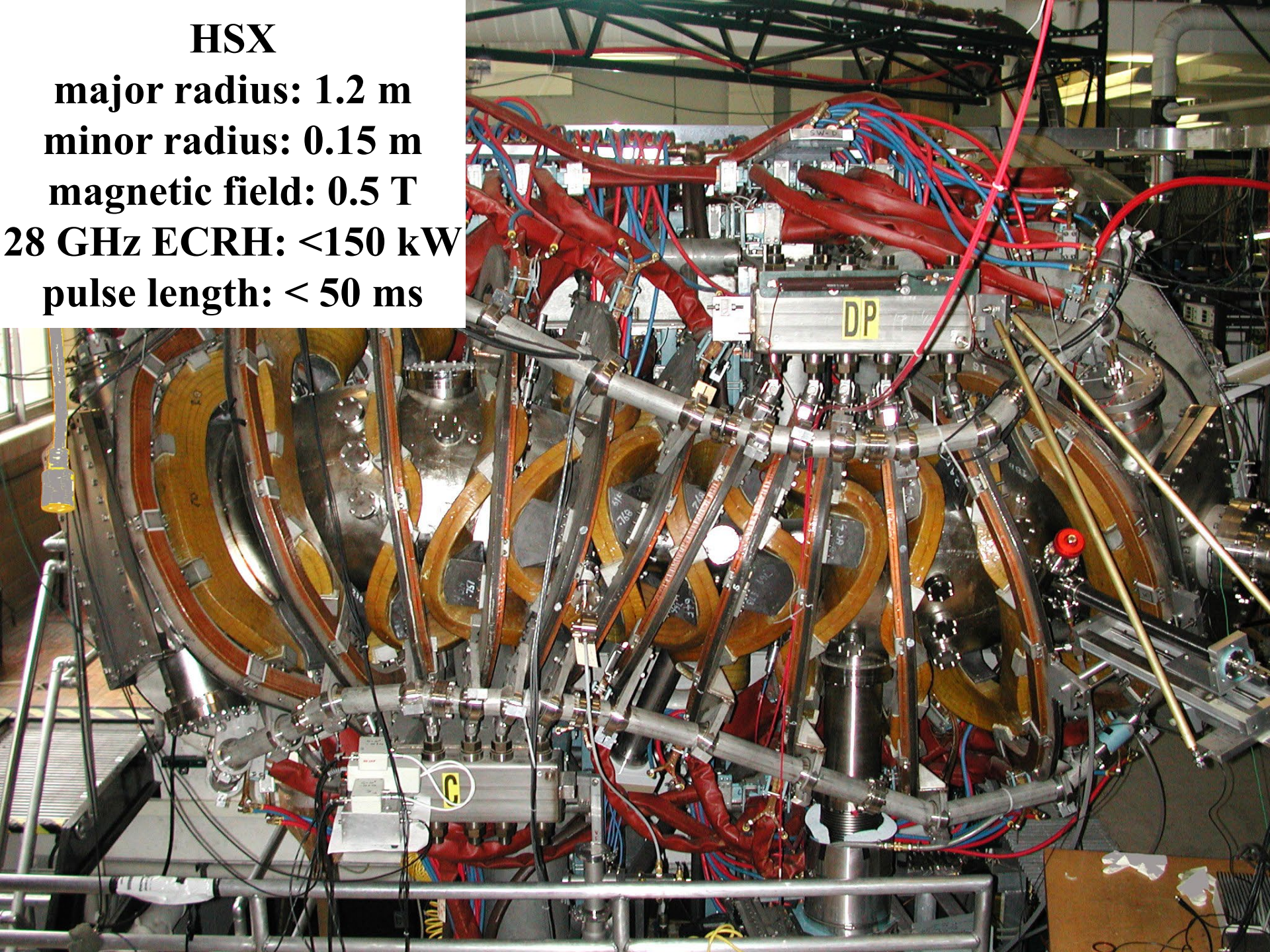
major radius: 1.2 m

minor radius: 0.15 m

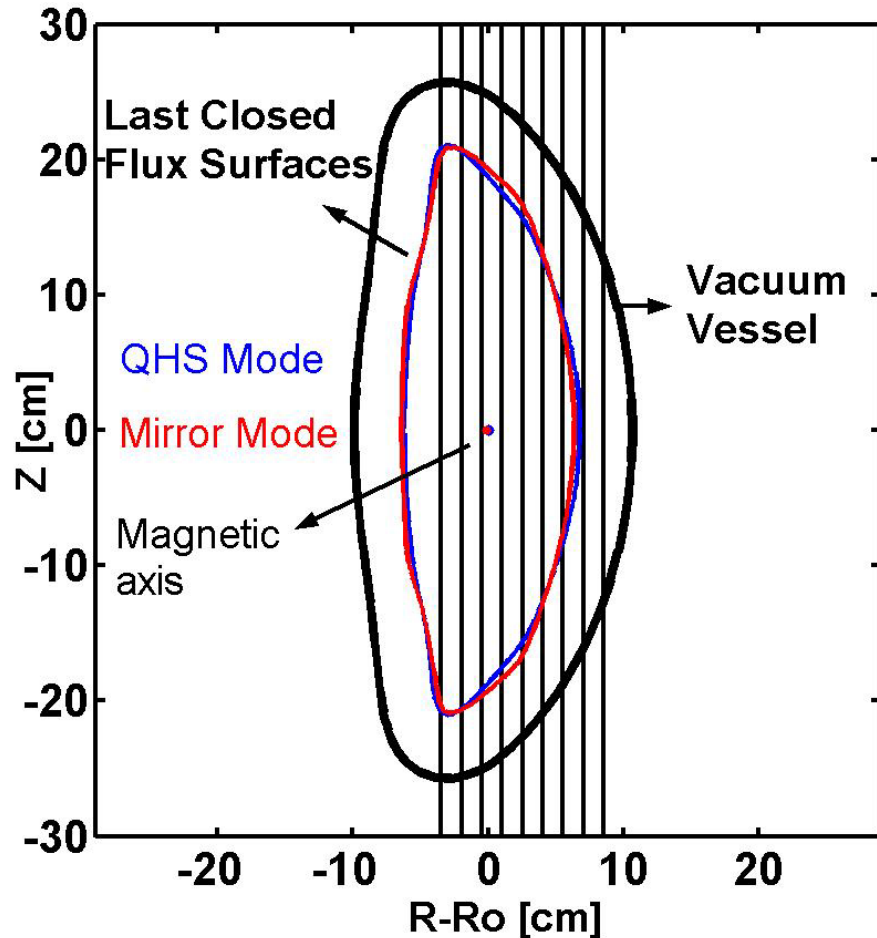
magnetic field: 0.5 T

28 GHz ECRH: <150 kW

pulse length: < 50 ms



Flux Surfaces and Interferometer Chords

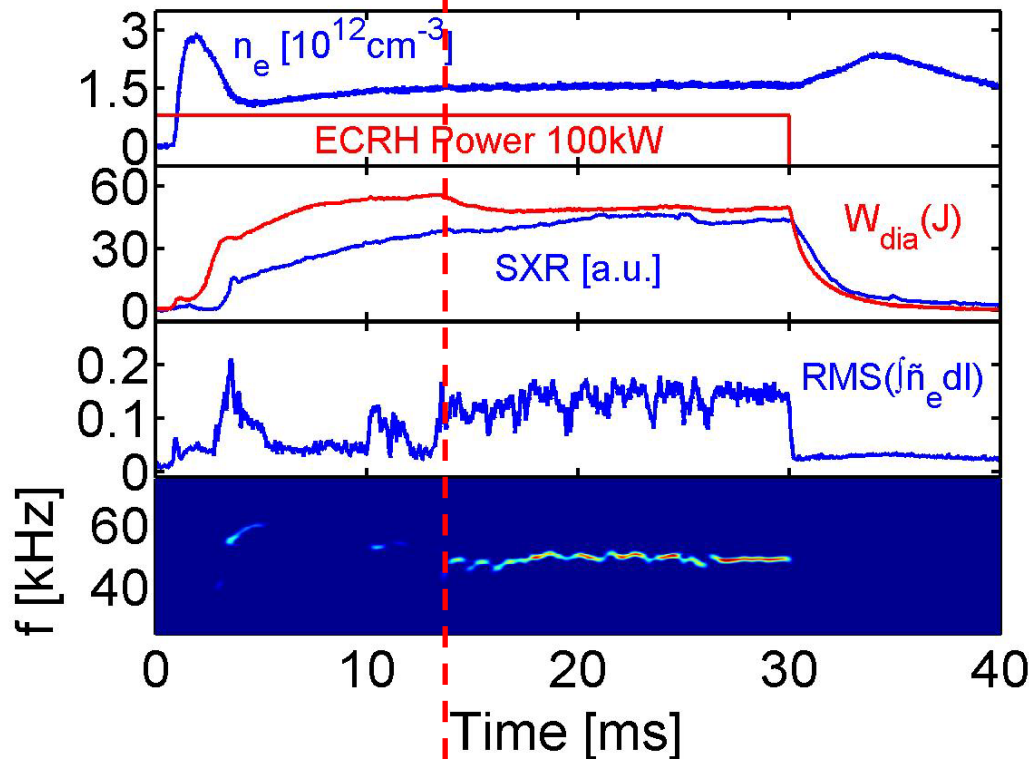


Interferometer System:

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

Coherent Density Fluctuations during QHS

QHS plasma



Heating:

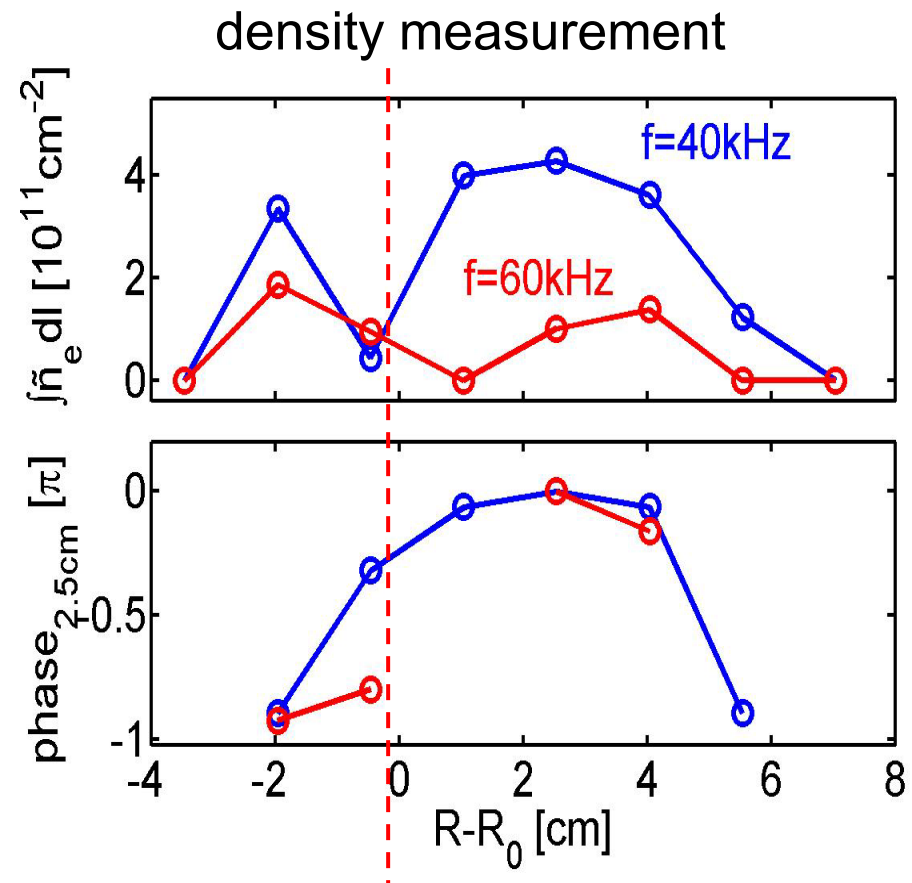
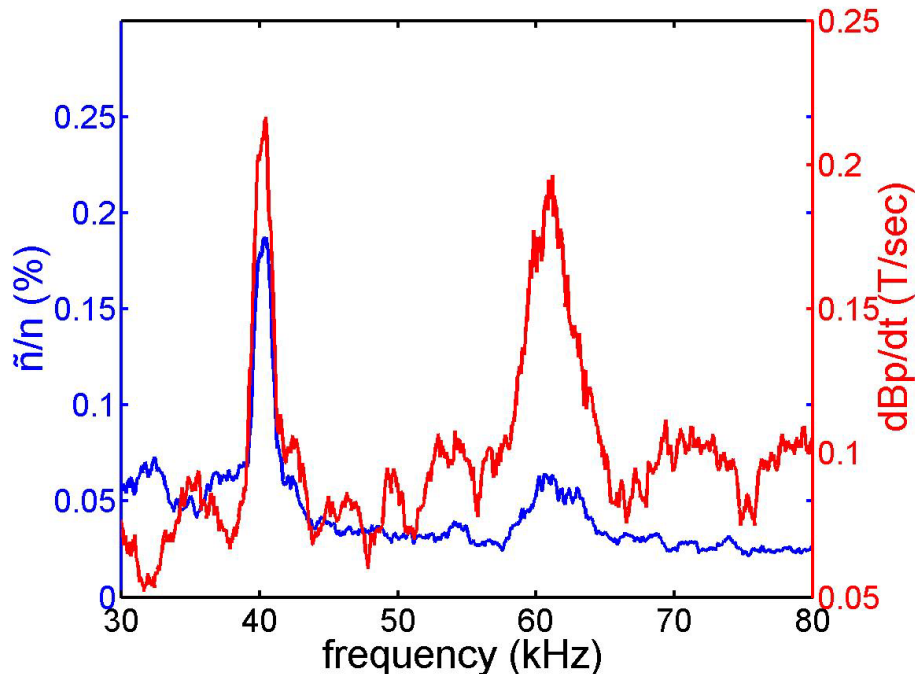
- 28 GHz ECRH
- 2nd Harmonic X-mode
for $B_T = 0.5 \text{ T}$, generates fast
electrons $T_{e\perp} \gg T_{e\parallel}$

- Bulk $T_e \approx 700 \text{ eV}$
 $T_i \approx 20 \text{ eV}$

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

Fluctuation Features

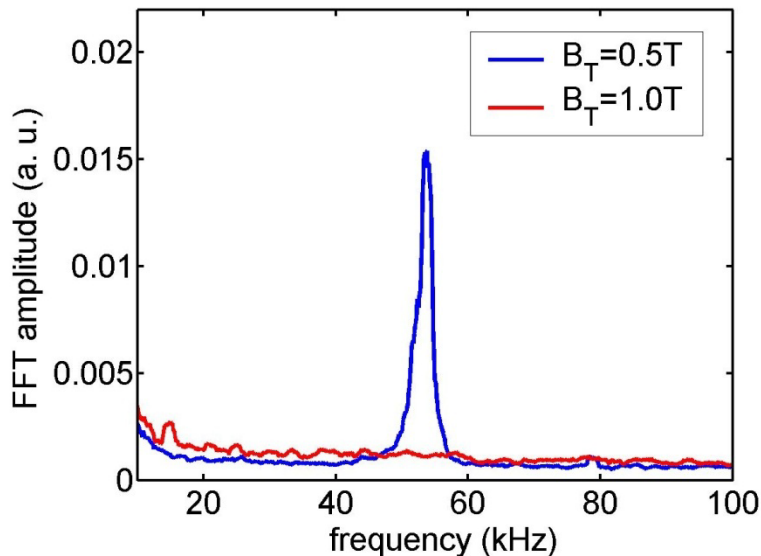
- Only observed in QHS plasmas
- $m=\text{odd}, >1?, n=1$ (density)
- $m=?, n=1$ (magnetic)
- Satellite mode appears at low densities, spacing $\Delta f \sim 20$ kHz
- Propagates electron drift direction
- **magnetic** and **density** perturbation



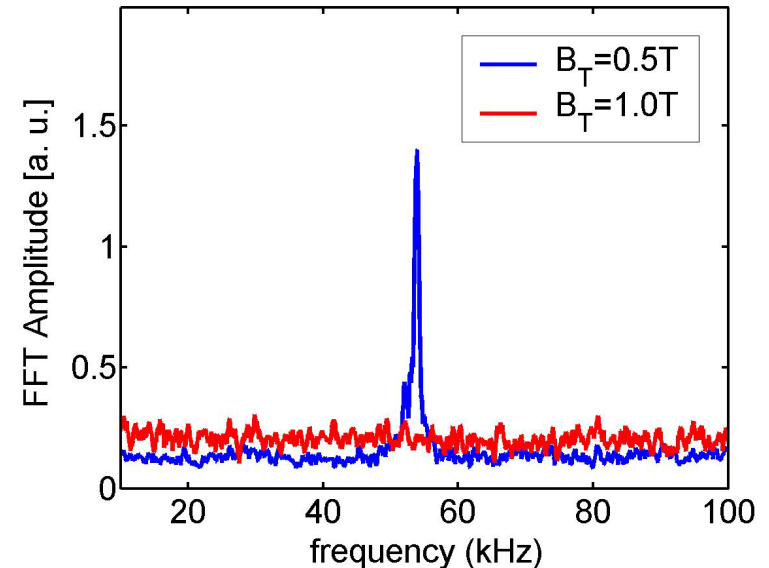
$m=\text{odd} (>1)$
higher f peaks at larger r/a

Fluctuation Mode not Observed in 1 Tesla QHS Plasma

Density Fluctuations

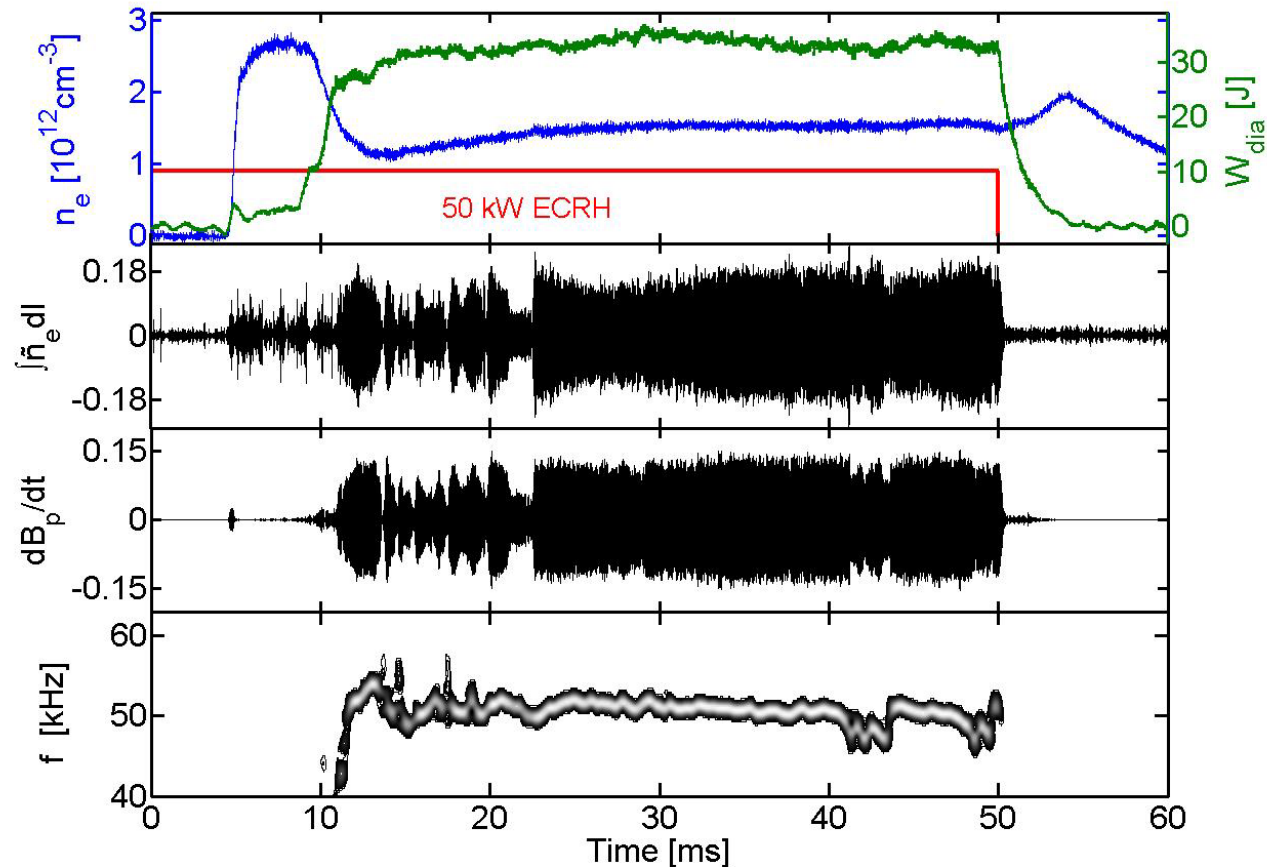


Magnetic Field Fluctuations



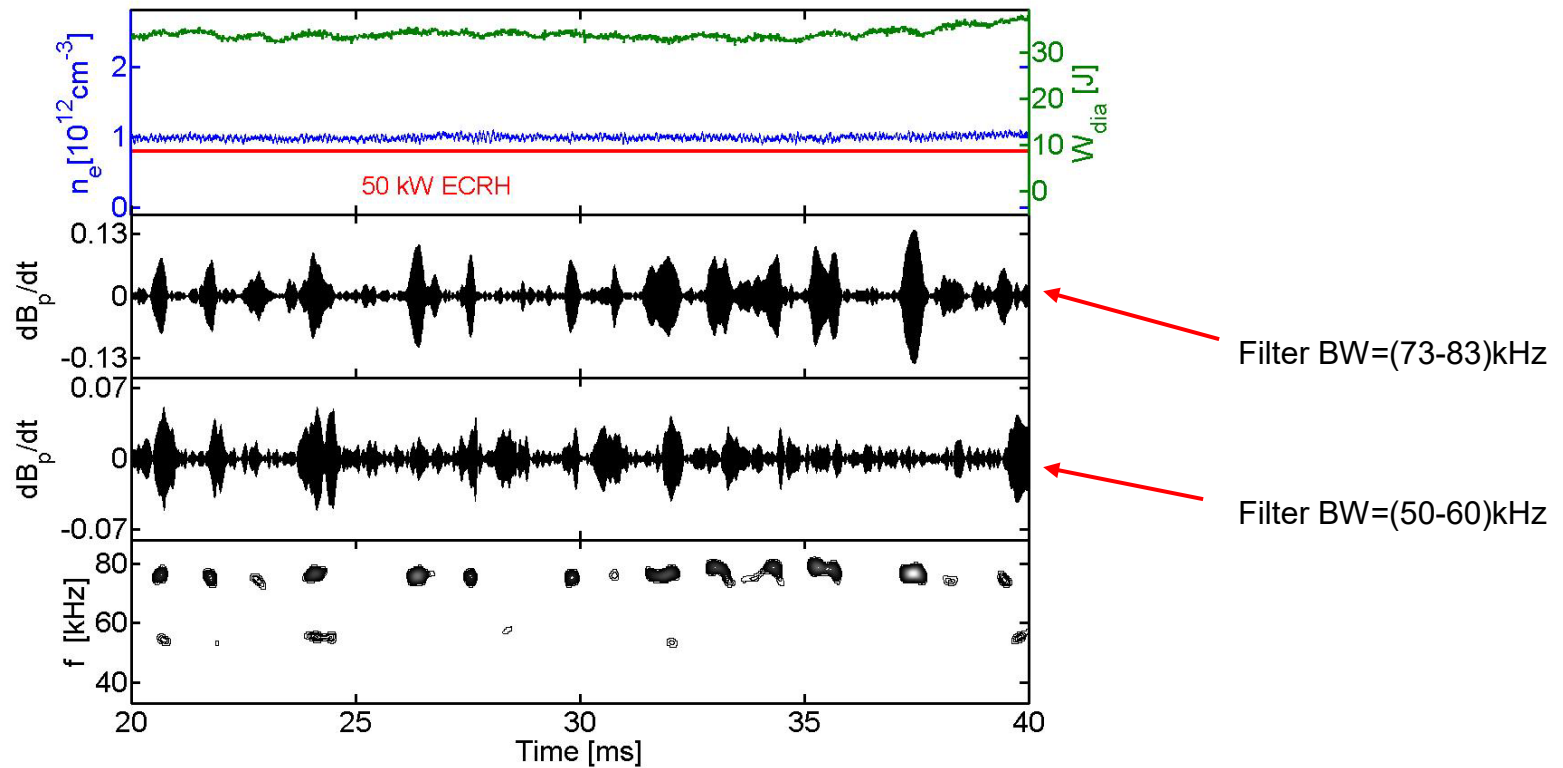
Fundamental O-mode ECRH for $B_T = 1\text{T}$ does not drive energetic electron population => no drive for fast-electron mode

Mode can appear continuous in time



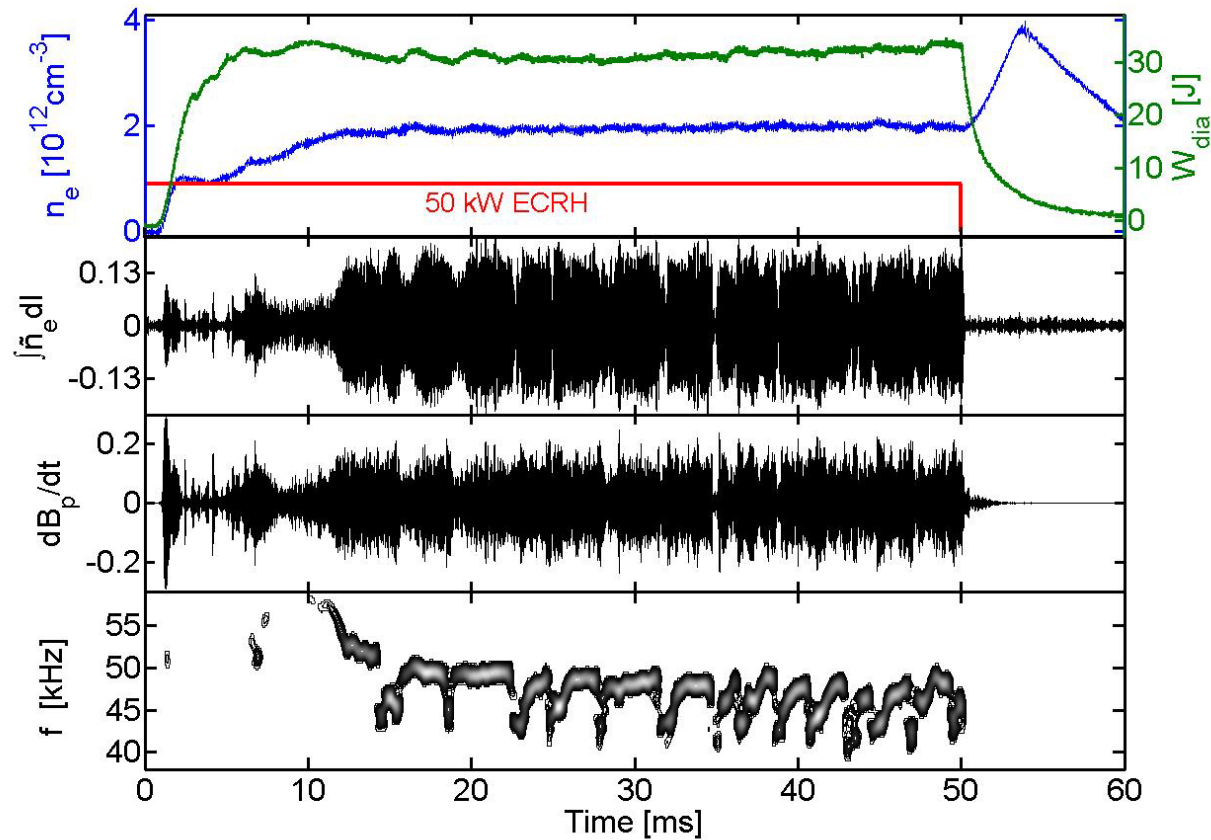
For some plasma densities $\sim 1.5 \times 10^{12} \text{cm}^{-3}$ and ECH power, mode is continuous

Mode can exhibit bursting behavior



- at low electron density, $n_e \sim 1.0 \times 10^{12} \text{ cm}^{-3}$,
primary mode and satellite appear as short bursts

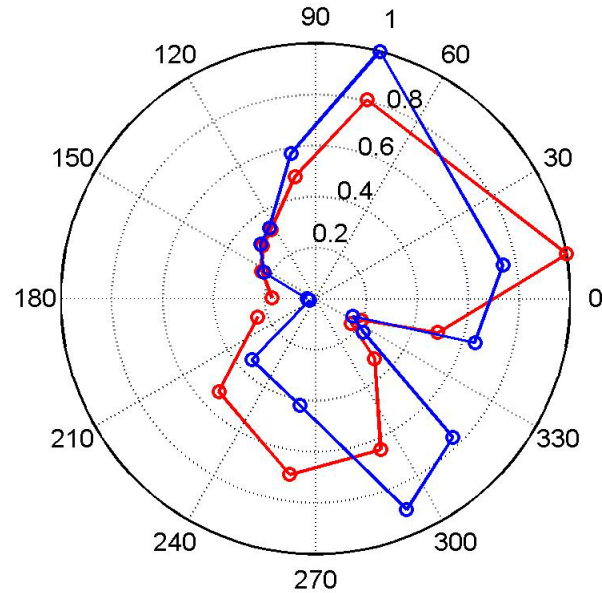
Frequency chirping



- frequency chirping with frequency change of 10 kHz over ~3 msec is also observed

Mode magnetic fluctuation distribution

Amplitude of Poloidal Array



Blue circles are magnetic fluctuation amplitude (normalized to 1) plotted against the poloidal positions of the each coil. Poloidal positions are in Boozer coordinates calculated for flux surface with $r/a=0.5$.

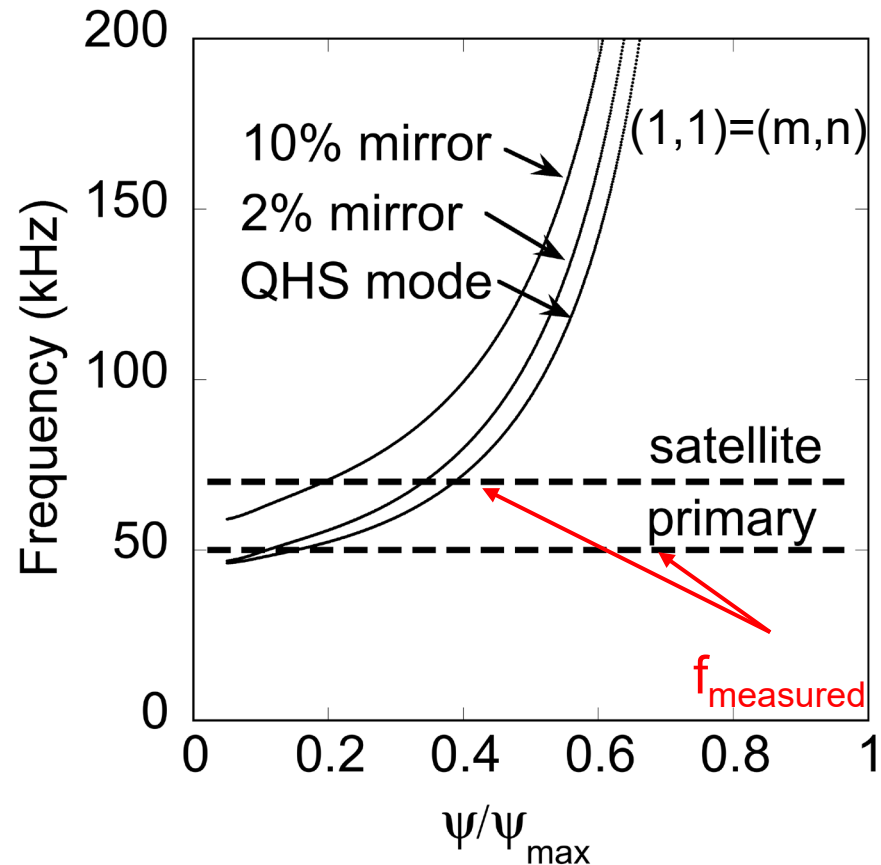
Red circles are calculated for $m=5$ using straight cylindrical model.

Quasi-Helically Symmetric (QHS) configuration

Normal mode Alfvén continua: $n = 1$ mode family

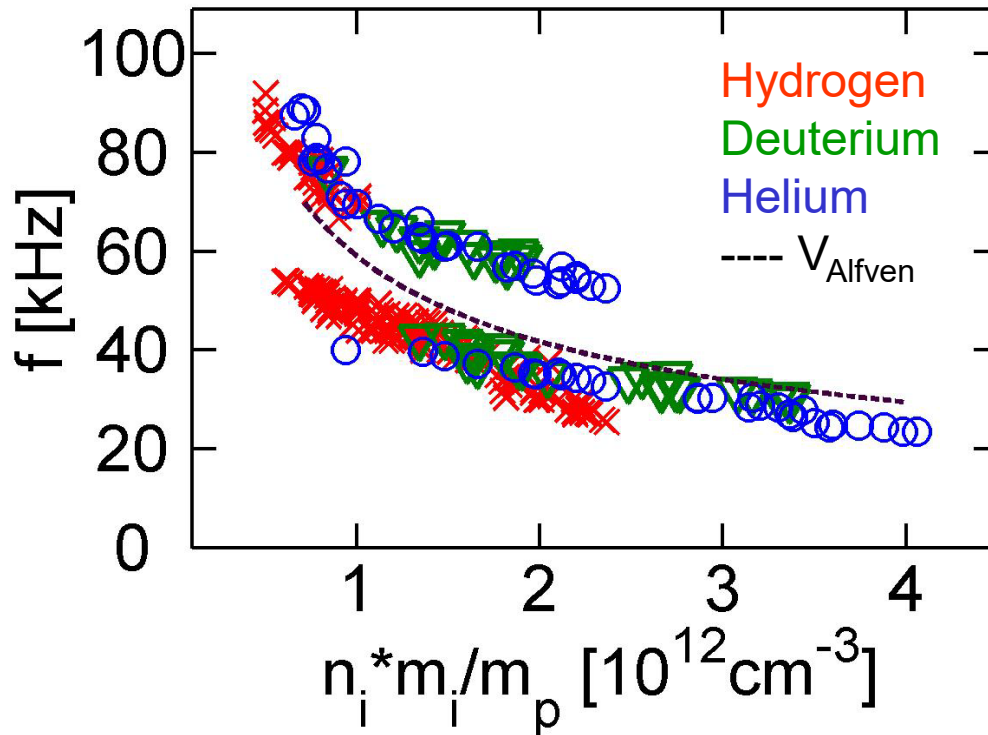
- $B=0.5$ T
0 - 50 kHz for $m=1, n=1$
 $n_e(0)=1.8 \times 10^{12} \text{ cm}^{-3}$
- Only minor changes for mirror configuration
- Observed mode frequency is near Alfvén continuum for (1,1)
- Alfvénic mode requires $(m,n)=(1,1)$
- Continuum frequency errors at 20% due to iota sensitivity
- E_r effects on ω unknown

$$\omega_{\text{Alfvén}} = k_{\parallel} V_A = (m - n) \frac{V_A}{R}$$



STELLGAP code (D. Spong) including ad hoc pressure term: $\omega = \left(\omega_A^2 + \omega_{GAM}^2 \right)^{1/2}$

Frequency scaling with ion mass density



$$V_{\text{Alfven}} = \frac{B}{(Mn)^{1/2}}$$

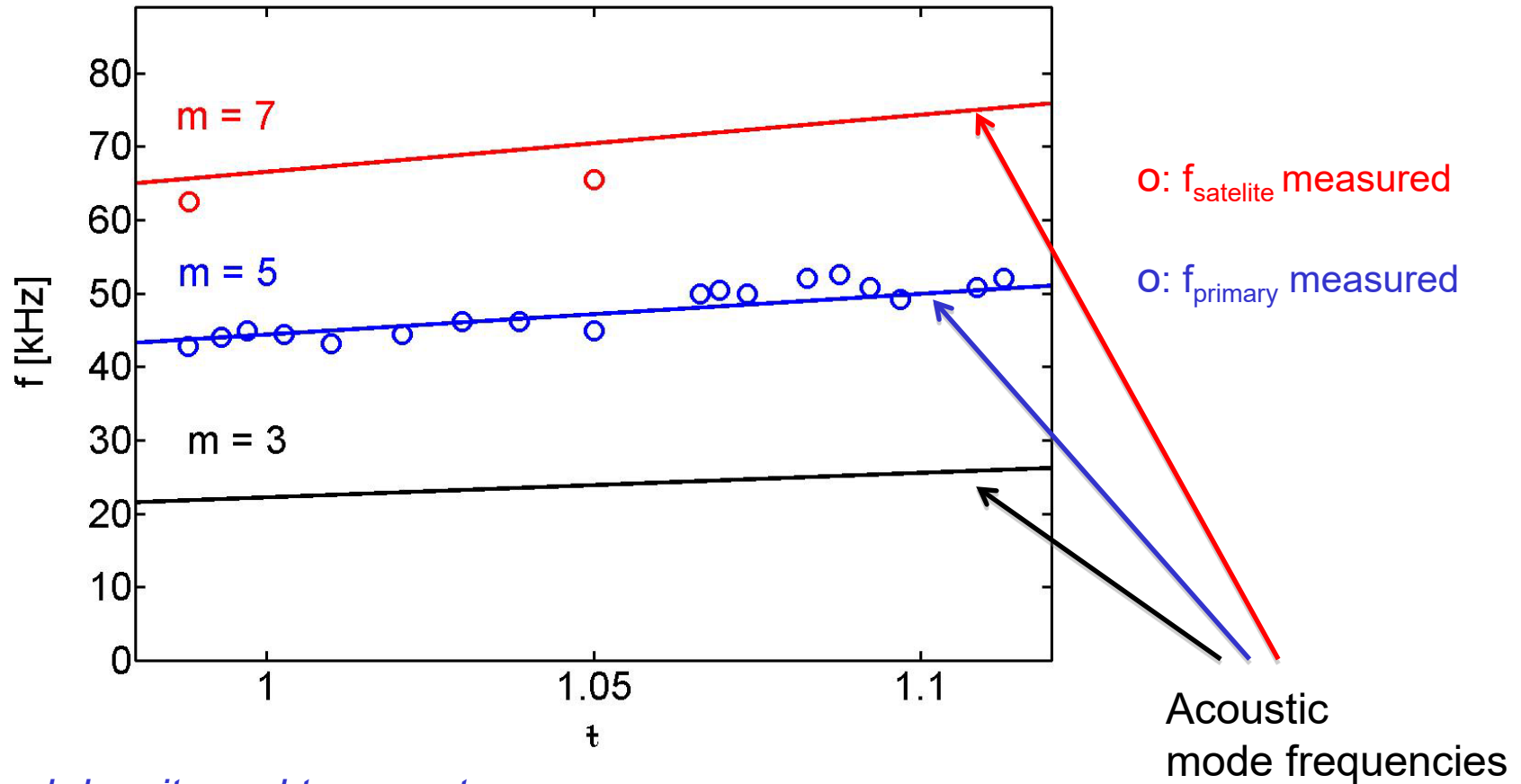
$$C_s = \left(\frac{T_e}{M} \right)^{1/2}$$

$$\omega_{\text{acoustic}} = k_{//} C_s$$

Mode frequency scaling with density

1. Mass scaling for Alfvénic and acoustic modes is identical
2. Temperature also scales with density
 - If $T_e \sim 1/n_e$, V_{Alfven} and C_s would be indistinguishable from density scaling
 - B scaling not possible due to ECRH heating

Frequency scaling with ι ($=1/q$) is weak



for fixed density and temperature....

1. no frequency scaling for ($\iota < 1.04$) is consistent with finite pressure effects
2. no frequency scaling for ($1.04 < \iota < 1.10$) suggests mode is not Alfvénic...

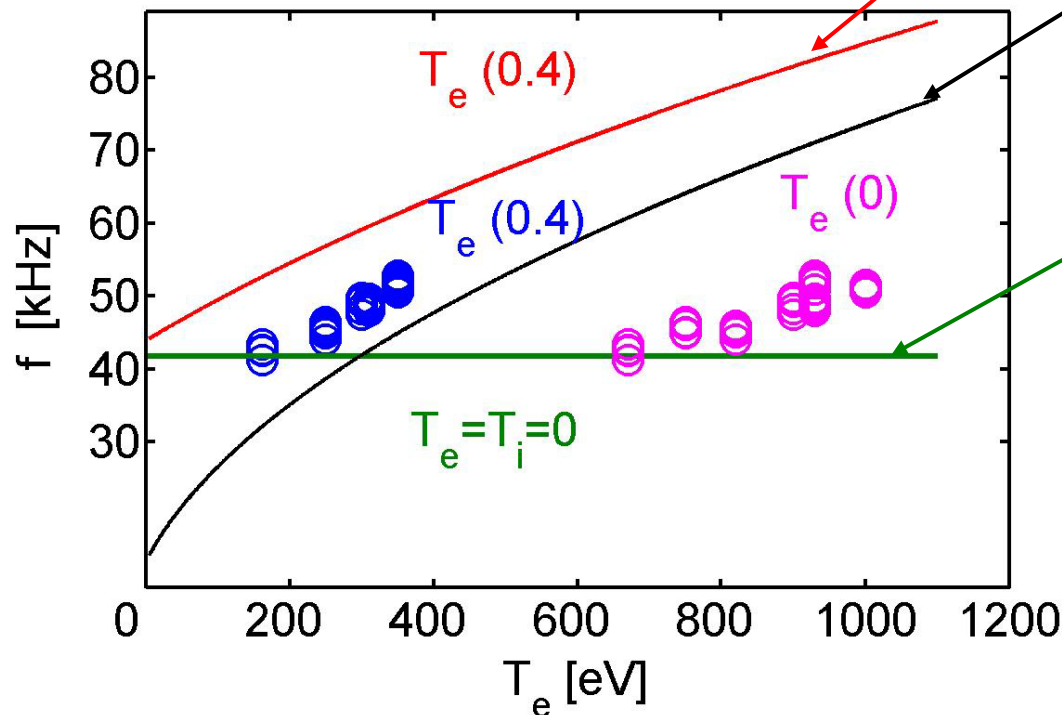
.....acoustic mode insensitive to ι with Δf consistent with measurements

Mode Frequency Scaling with Electron Temperature

Breizman, PoP **12**,112506(2005)

$$\omega = (\omega_A^2 + \omega_{GAM}^2)^{1/2} = \left[(mt-n)^2 \frac{V_A^2}{R^2} + \frac{2T_e}{m_i R^2} \left(1 + \frac{7}{4} \frac{T_i}{T_e} \right) \left(1 + \frac{t^2}{2} \right) \right]^{1/2}$$

- vary P_{ECRH} and hold n_e constant



$$\omega = \omega_{GAM} = \left[\frac{2T_e}{m_i R^2} \left(1 + \frac{7}{4} \frac{T_i}{T_e} \right) \left(1 + \frac{t^2}{2} \right) \right]^{1/2}$$

$$\omega = \omega_{Alfven} = (mt-n) \frac{V_A}{R}$$

o: f_{mode} measured

o: f_{mode} measured

$n_e = 3 \times 10^{12} \text{ cm}^{-3}$
 $B_T = 0.5 \text{ T}$
 $T_i = 20 \text{ eV}$

T_e scaling consistent with finite pressure effects even at low β

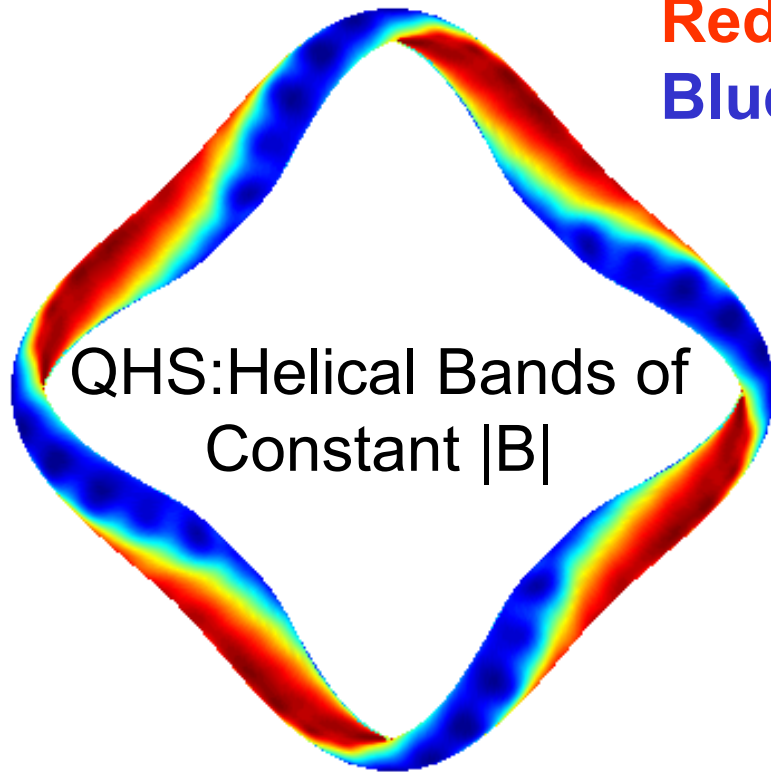
HSX Provides Access to Configurations With and Without Symmetry

QHS: helical axis of symmetry in $|B|$

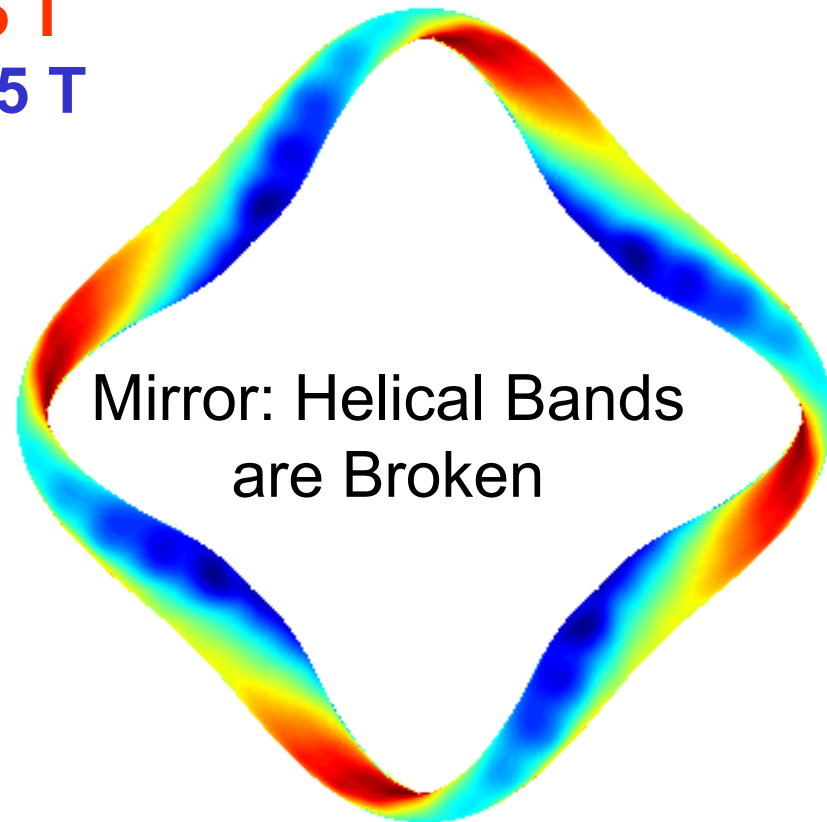
Mirror: quasi-helical symmetry broken by adding a mirror field.

QHS

Red $\rightarrow |B| > 0.5 \text{ T}$
Blue $\rightarrow |B| < 0.5 \text{ T}$



Mirror



Coupled Equations for Acoustic and Shear Alfven Waves

Lagrangian Formulation

$$\frac{g}{B^2} \frac{\partial^2 \eta}{\partial t^2} - \frac{1}{4\pi\rho} (\mathbf{B} \cdot \nabla) \frac{g}{B^2} (\mathbf{B} \cdot \nabla) \eta = C_s^2 [(\mathbf{B} \cdot \nabla) \zeta - \eta G] G$$

$$B^2 \frac{\partial^2 \zeta}{\partial t^2} - C_s^2 (\mathbf{B} \cdot \nabla) (\mathbf{B} \cdot \nabla) \zeta = -C_s^2 (\mathbf{B} \cdot \nabla) (\eta G)$$

Notations:

$C_s(\psi) \equiv$ sound speed

$G \equiv \left(\nabla \psi \bullet \text{curl} \frac{\bar{B}}{B^2} \right)$ is a coordinate-dependent coupling factor (related to curvature)

$\mathbf{B} \equiv$ equilibrium magnetic field

$\rho \equiv$ equilibrium mass density

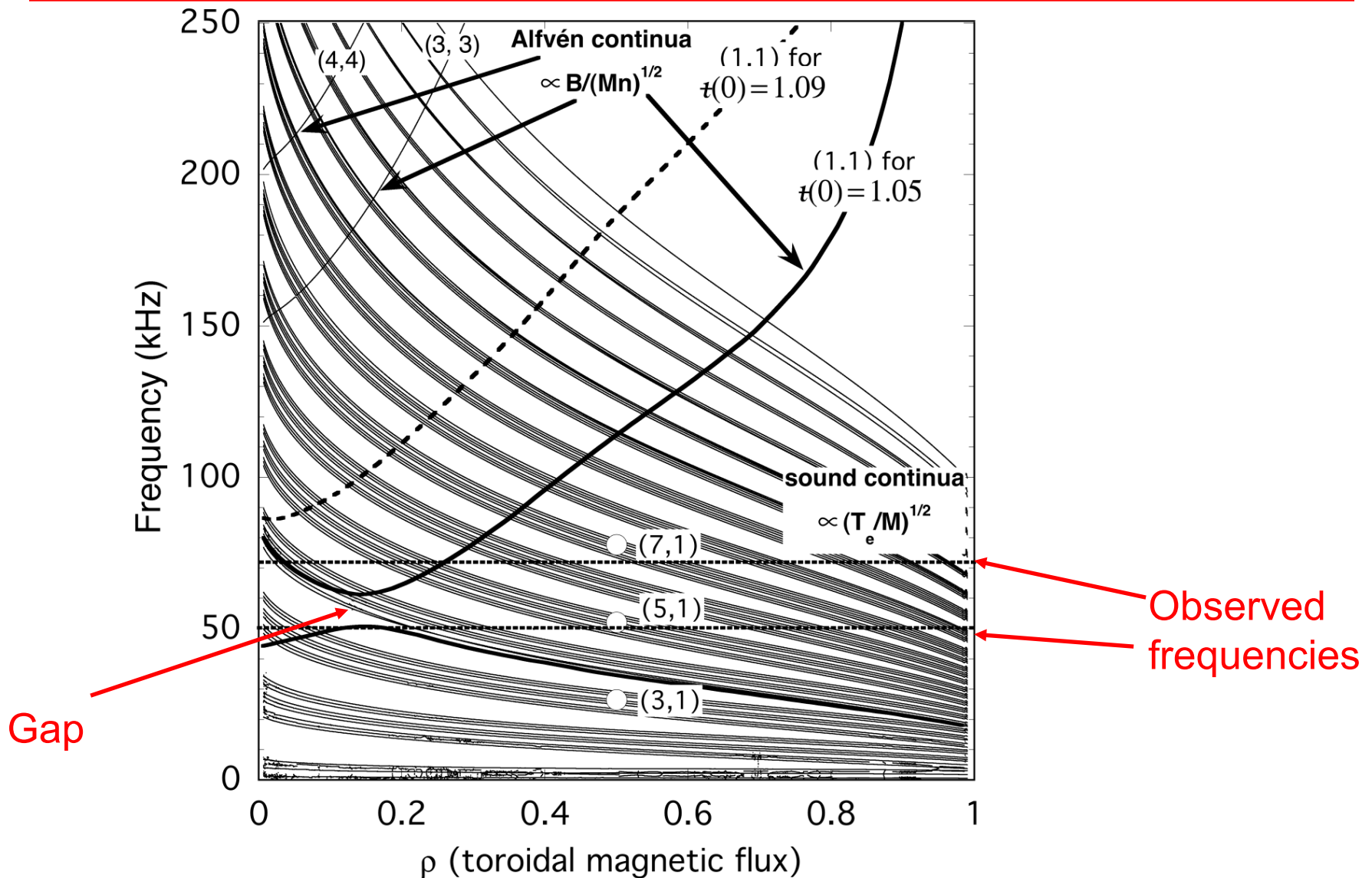
$g \equiv (\nabla \psi \bullet \nabla \psi)$ is a component of metric tensor

$\eta \equiv$ shear Alfven eigenfunction

$\zeta \equiv$ acoustic eigenfunction

Equations capture Alfven continuum, acoustic continuum and GAM

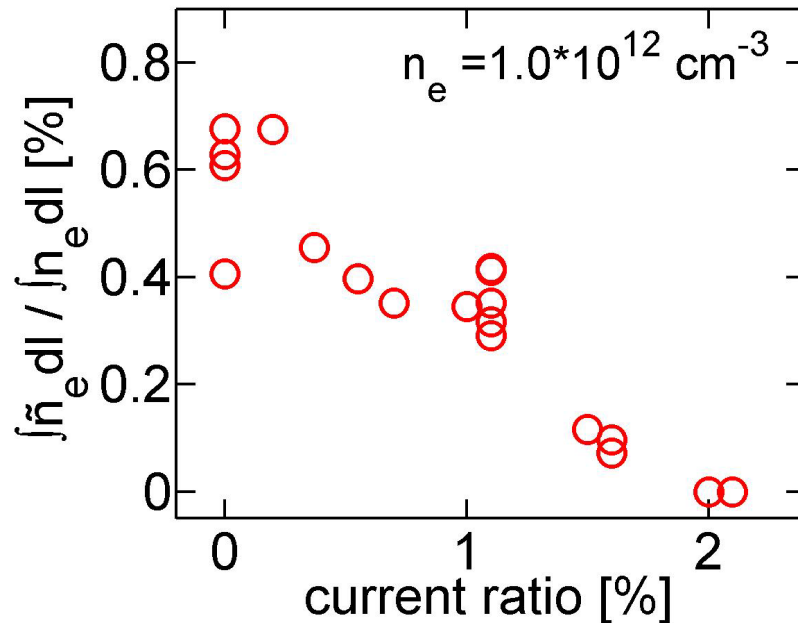
Coupled Alfvénic-Acoustic Modes



Coupled Alfvén/acoustic continua for $n=0$ and 1 mode families, $\iota(0)=1.05$.

Mode not observed when Quasi-Symmetry Broken

Scaling with Mirror perturbation
(magnetic ripple)



(conventional stellarator configuration:
~10% mirror perturbation)

Acoustic mode

$$V_{\parallel} = C_s$$

$$V_{\perp} = V_{th} \quad \frac{V_{\parallel}}{V_{\perp}} = \sqrt{\frac{m}{M}}$$

$$\sqrt{\frac{\Delta B}{B}} > \frac{V_{\parallel}}{V_{\perp}} = \sqrt{\frac{m}{M}} \approx 0.025$$

Alfvenic mode

$$V_{\parallel} = V_A \quad V_{\perp} = V_{th}$$

$$\sqrt{\frac{\Delta B}{B}} > \frac{V_{\parallel}}{V_{\perp}} = \sqrt{\frac{m}{M}} \frac{1}{\sqrt{\beta}} > 0.25$$

Acoustic mode much more sensitive to magnetic ripple

Fast Electron Driven Instability in HSX

Mode identification ...

If Alfvénic instability: with finite pressure effects

- continuum calculation shows $m=n=1$ is only candidate
- for low m, n : mode frequency is very sensitive to $iota$

data show

- 1) $m > 1$ (?)
- 2) mode frequency not sensitive to $iota$
- 3) mode sensitive to magnetic ripple
- 3) $\omega = k_{\parallel} V_A$ varies strongly with radius leading to phase mixing

Other mode candidates....

Acoustic instability (coupled to shear Alfvén wave)

- $m > 1$ expected
- no $iota$ scaling sensitivity
- $\omega = k_{\parallel} C_s$ fairly constant with radius
- $T_e \gg T_i$ small Landau damping
- very sensitive to mirror term

Drift modes under consideration.....

Summary

- Coherent modes excited by energetic electrons observed for QHS plasmas in HSX
- Modes propagate along electron diamagnetic drift direction.
- Modes can appear continuous, bursting, or with frequency chirping.
- Mode frequency has weak ι scaling and amplitude is sensitive to magnetic ripple – both features inconsistent with Alfvénic mode
- Mode identification ...
 - Acoustic instability (coupled to shear Alfvén wave)
 - $m > 1$ and $\Delta f \sim 20$ kHz expected
 - weak ι scaling sensitivity
 - $\omega = k_{\parallel} C_s$ fairly constant with radius
 - $T_e \gg T_i$ small Landau damping
 - sensitive to magnetic ripple (mirror term)
- Theory predicts coupling between Alfvénic and acoustic waves

Reference: C.B. Deng, D.L. Brower, et al., Phys. Rev. Lett. 103, 025003(2009).

Future Plans.....

- Theory:

- compute mode growth (damping) rates and their relationships with magnetic ripple, population and energy of energetic particles
- calculate eigenmode radial structure

Experimental:

- determine magnetic mode number (m , n) using newly installed magnetic probe arrays
- Compare interferometer and magnetic coil data with theory calculation: **synthetic diagnostic**