

Fast-Electron-Driven Instability in the HSX Stellarator

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Outline

1. Characteristics of observed fluctuation

- frequency
- mode number
- scaling

2. Candidates of Instability

- Alfvenic
- acoustic
- other?

HSX

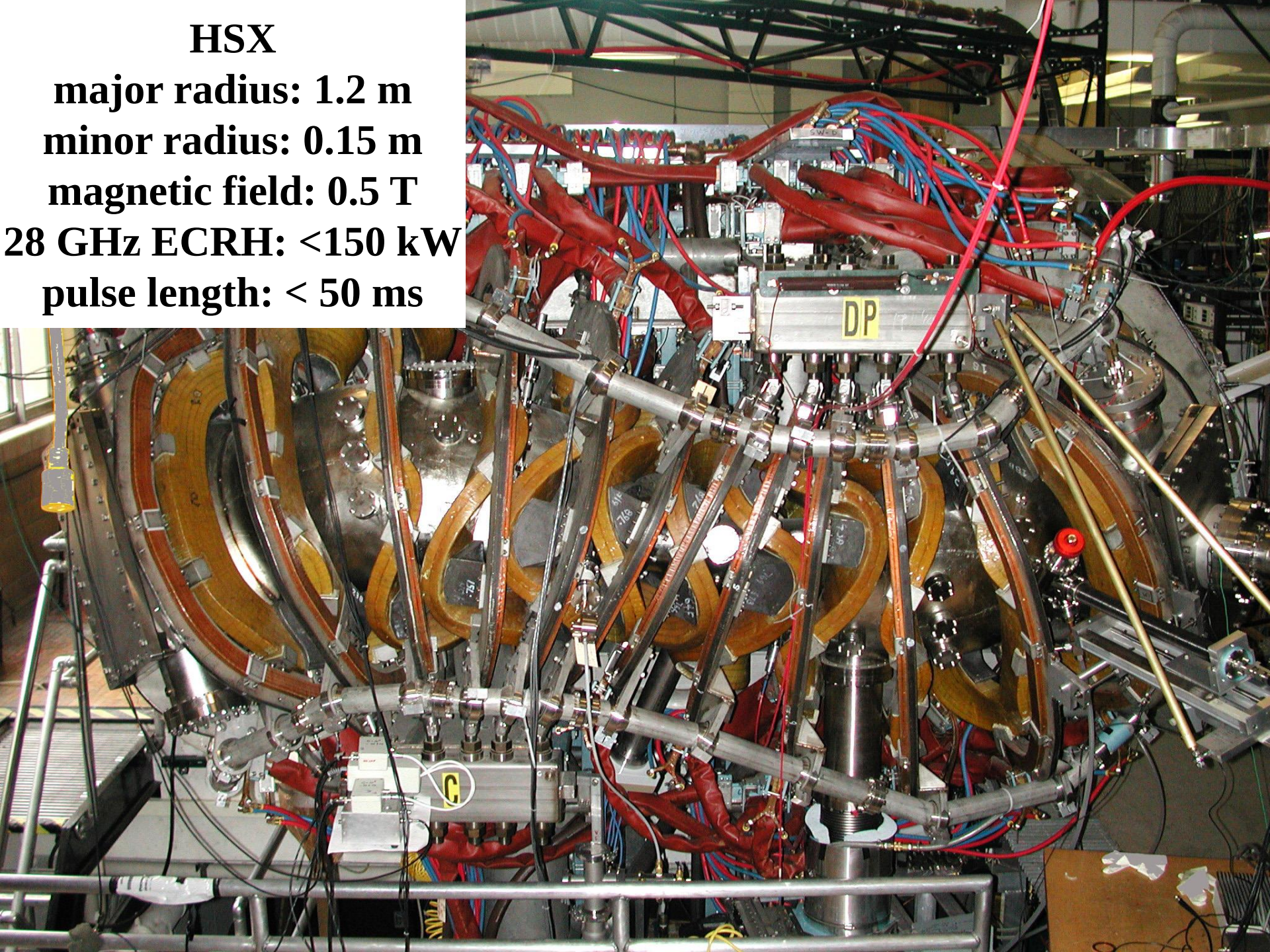
major radius: 1.2 m

minor radius: 0.15 m

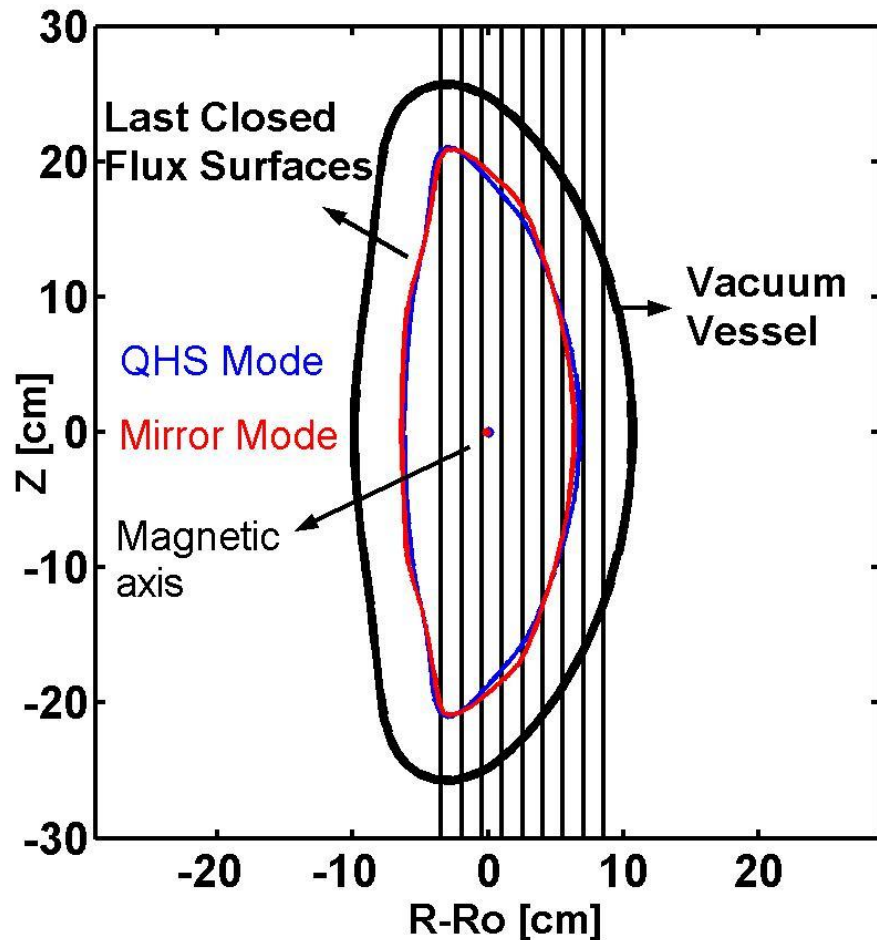
magnetic field: 0.5 T

28 GHz ECRH: <150 kW

pulse length: < 50 ms



Flux Surfaces and Interferometer Chords

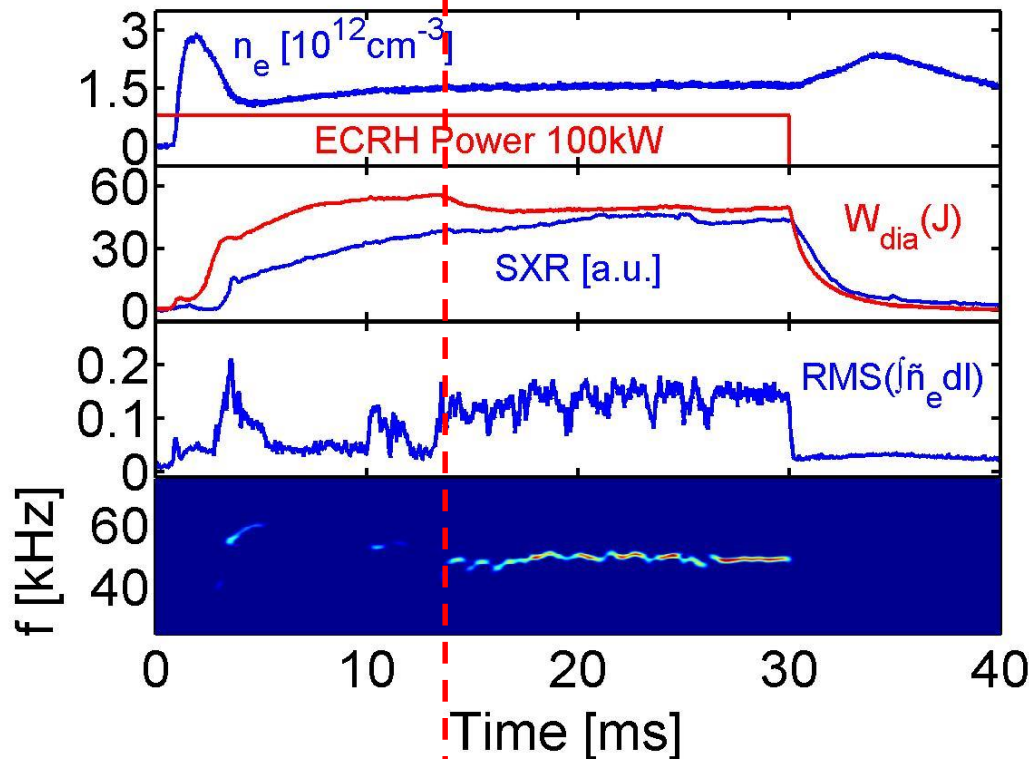


Interferometer System:

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

Coherent Density Fluctuations during QHS

QHS plasma



Heating:

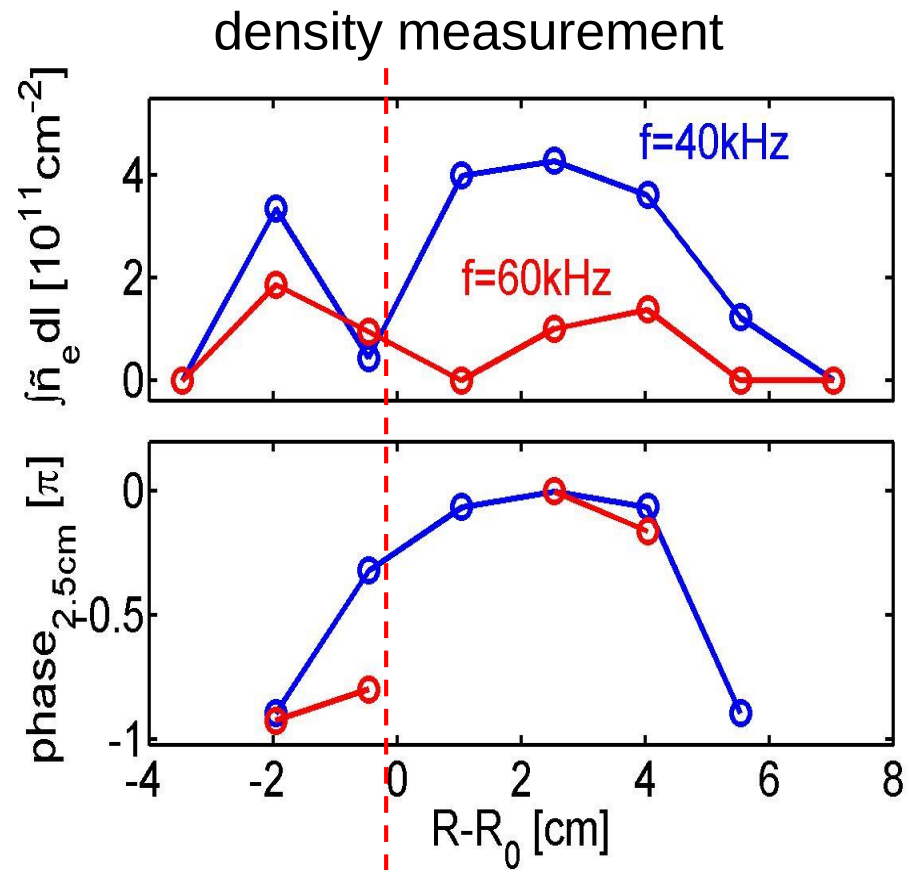
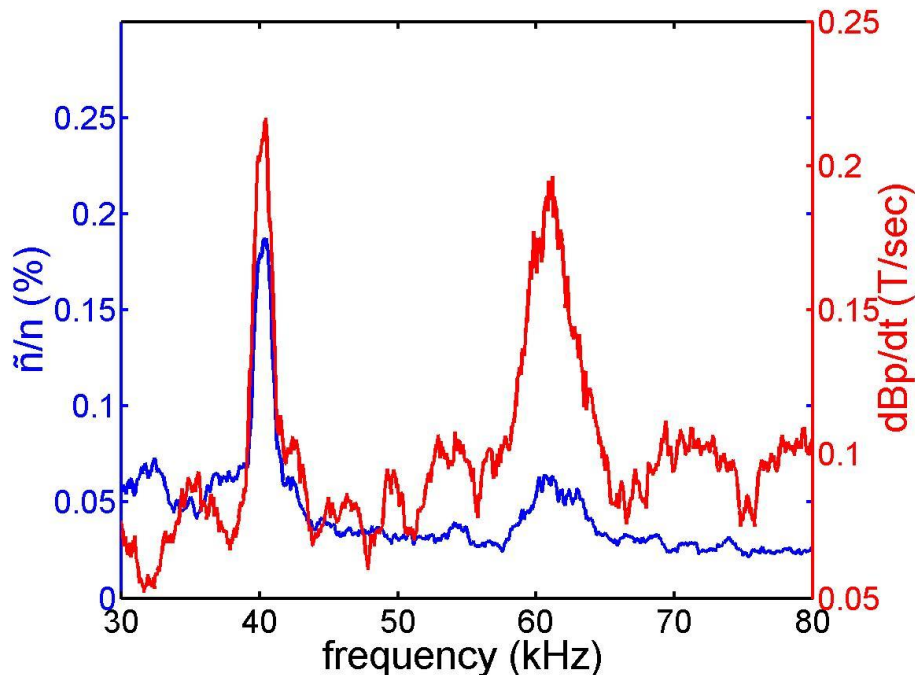
- 28 GHz ECRH
- 2nd Harmonic X-mode
for $B_T = 0.5 \text{ T}$ generates fast
electrons $T_{e\perp} \gg T_{e\parallel}$

- 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

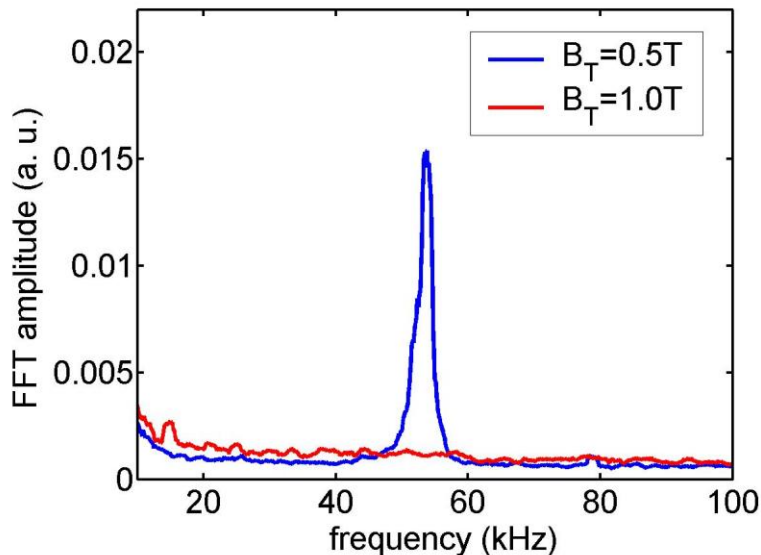
- Only observed in QHS plasmas
- $m=\text{odd}, >1?, n=1$ (density)
- $m=?, n=1$ (magnetic)
- Satellite appears at low densities, $\Delta f \sim 20$ kHz
- Propagates electron drift direction
- **magnetic** and **density** perturbation



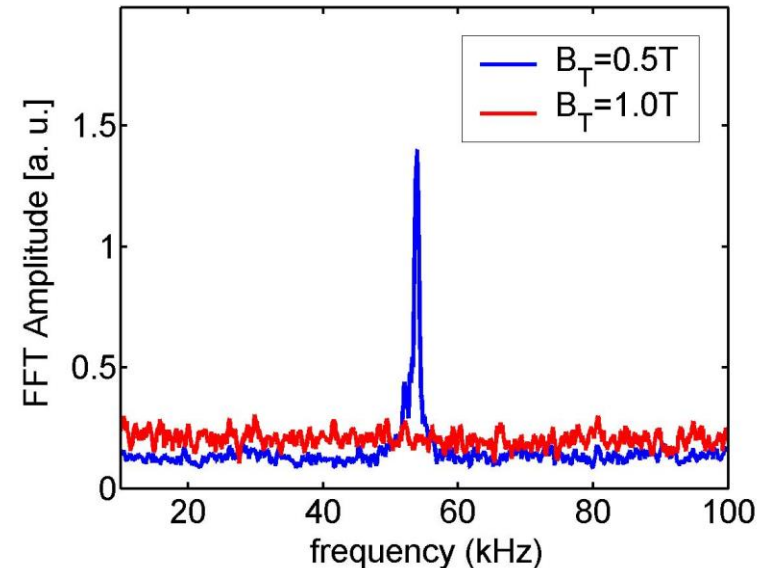
$m=\text{odd} (>1)$
 higher f peaks at larger r/a

Fluctuation Mode not Observed in 1 Tesla QHS Plasma

Density Fluctuations



Magnetic Field Fluctuations



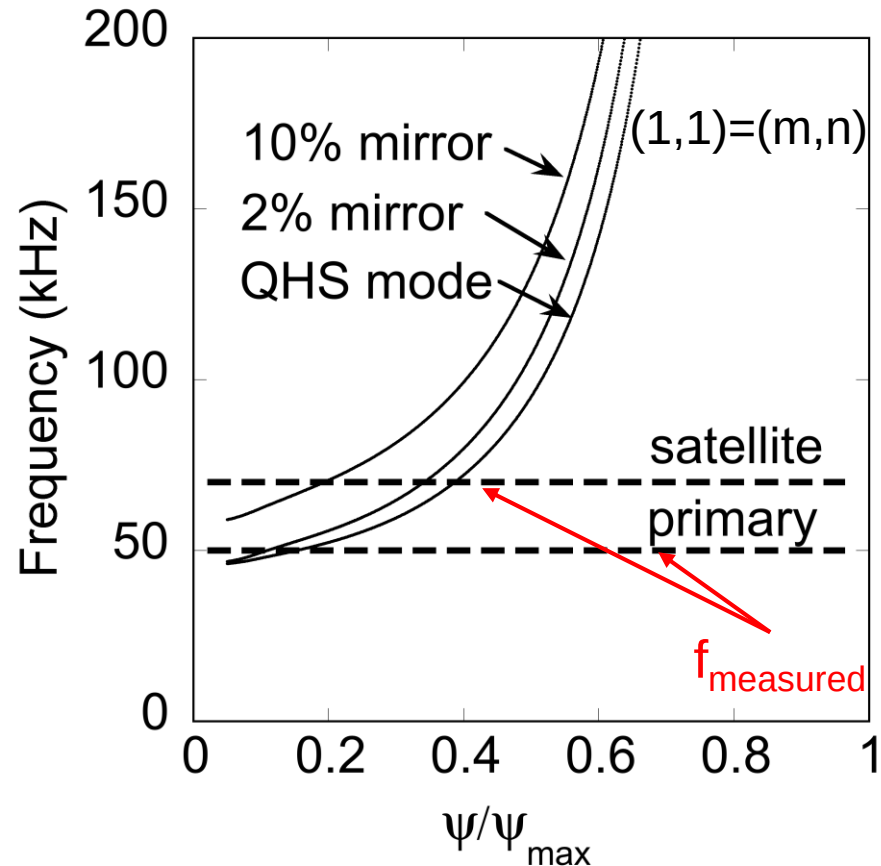
Fundamental O-mode ECRH for $B_T = 1T$ does not drive energetic electron population => no drive for fast-electron mode

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)
- Continuum frequency errors at 20% due to iota sensitivity
- E_r effects on ω unknown

$$\omega = \omega_{\text{Alfvén}} = (ml - n) \frac{V_A}{R}$$



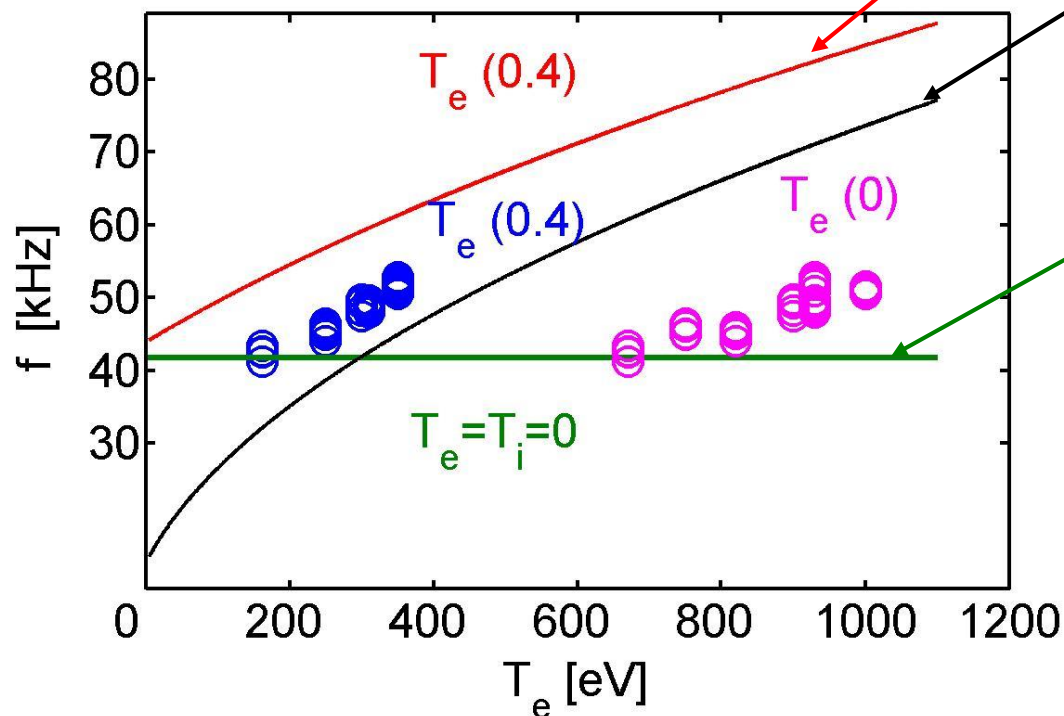
STELLGAP code (D. Spong) including ad hoc pressure term: $\omega = \left(\omega_A^2 + \omega_{GAM}^2 \right)^{1/2}$

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



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

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

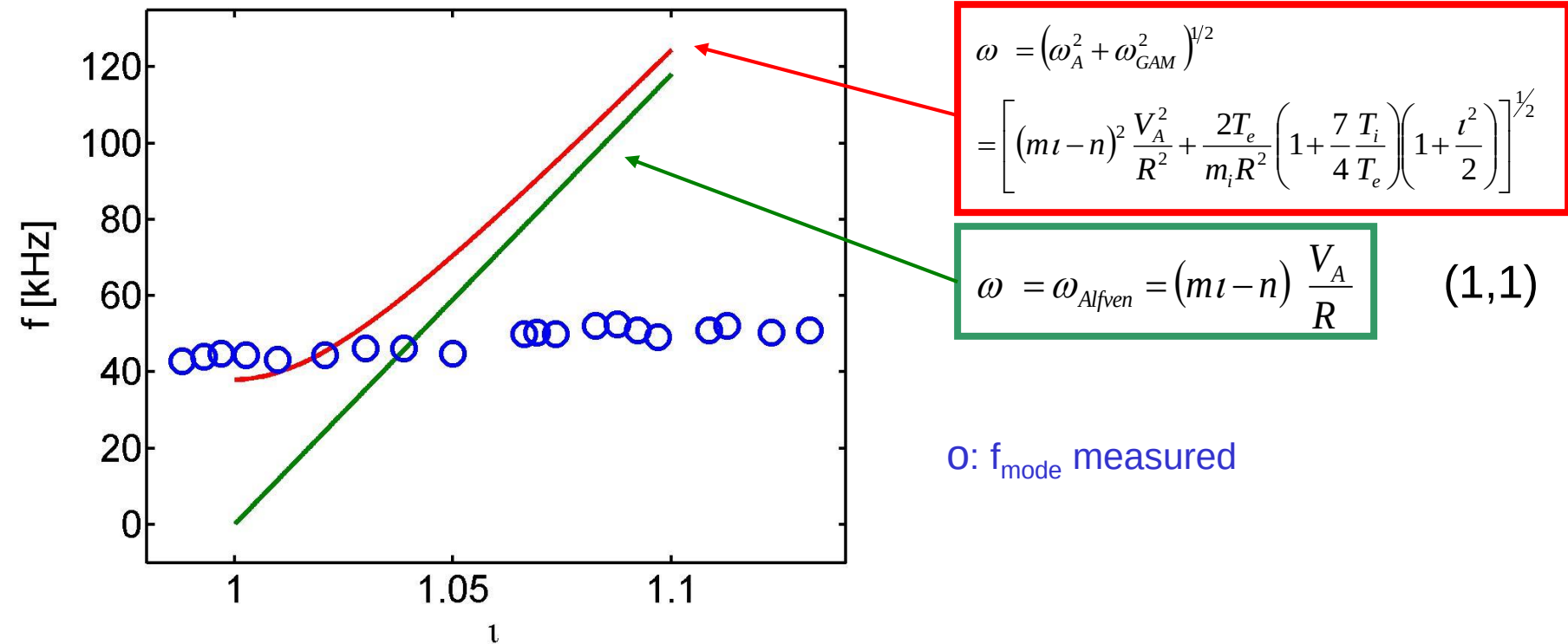
o: f_{mode} measured

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

Mode Frequency Scaling with iota ($\iota=1/q$)

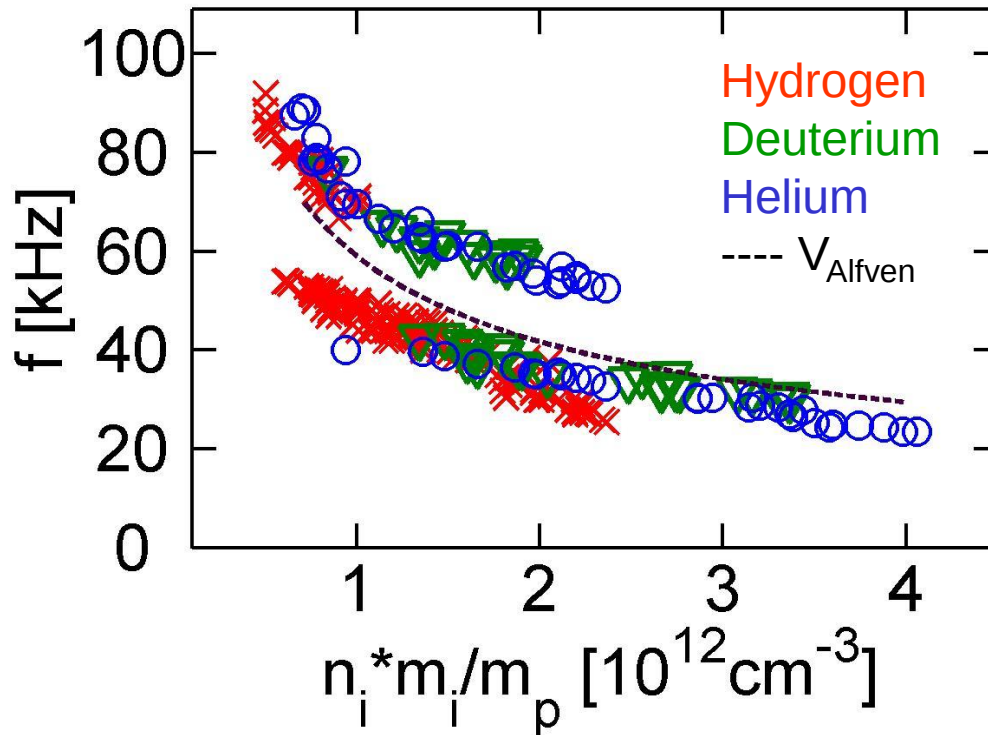


for fixed density and temperature....

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 iota

Frequency scaling with ion mass density



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

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

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

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

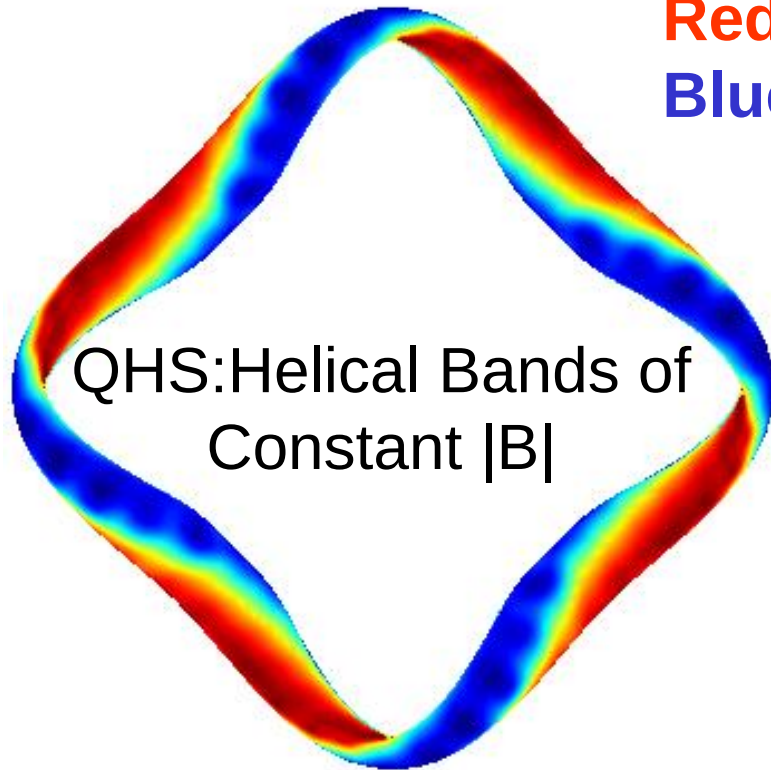
HSX Provides Access to Configurations With and Without Symmetry

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

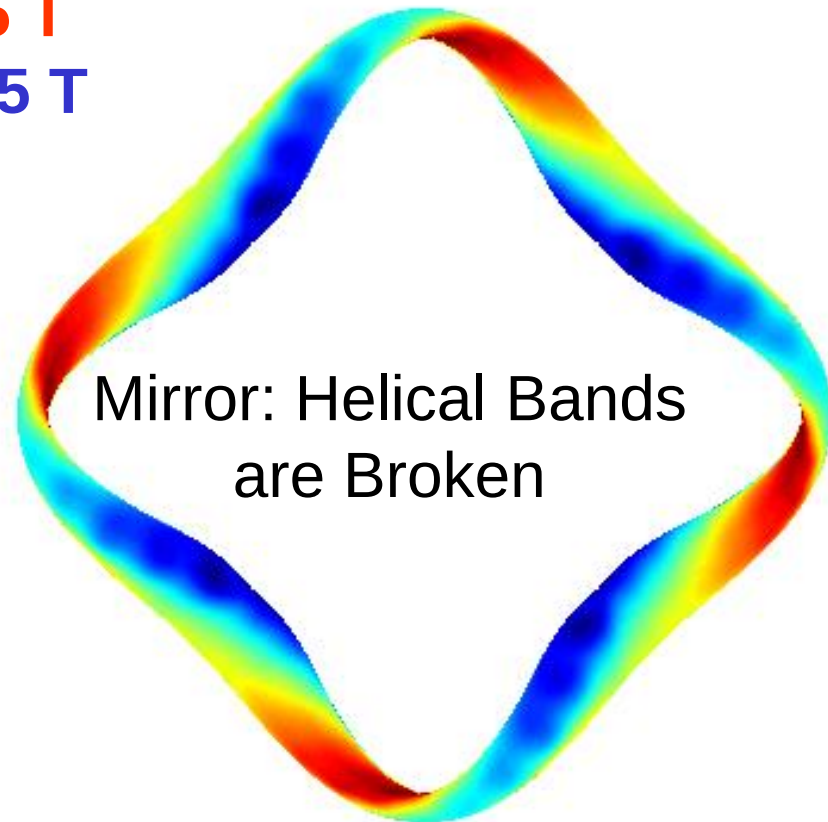
Mirror: quasi-helical symmetry broken by adding a mirror field.

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

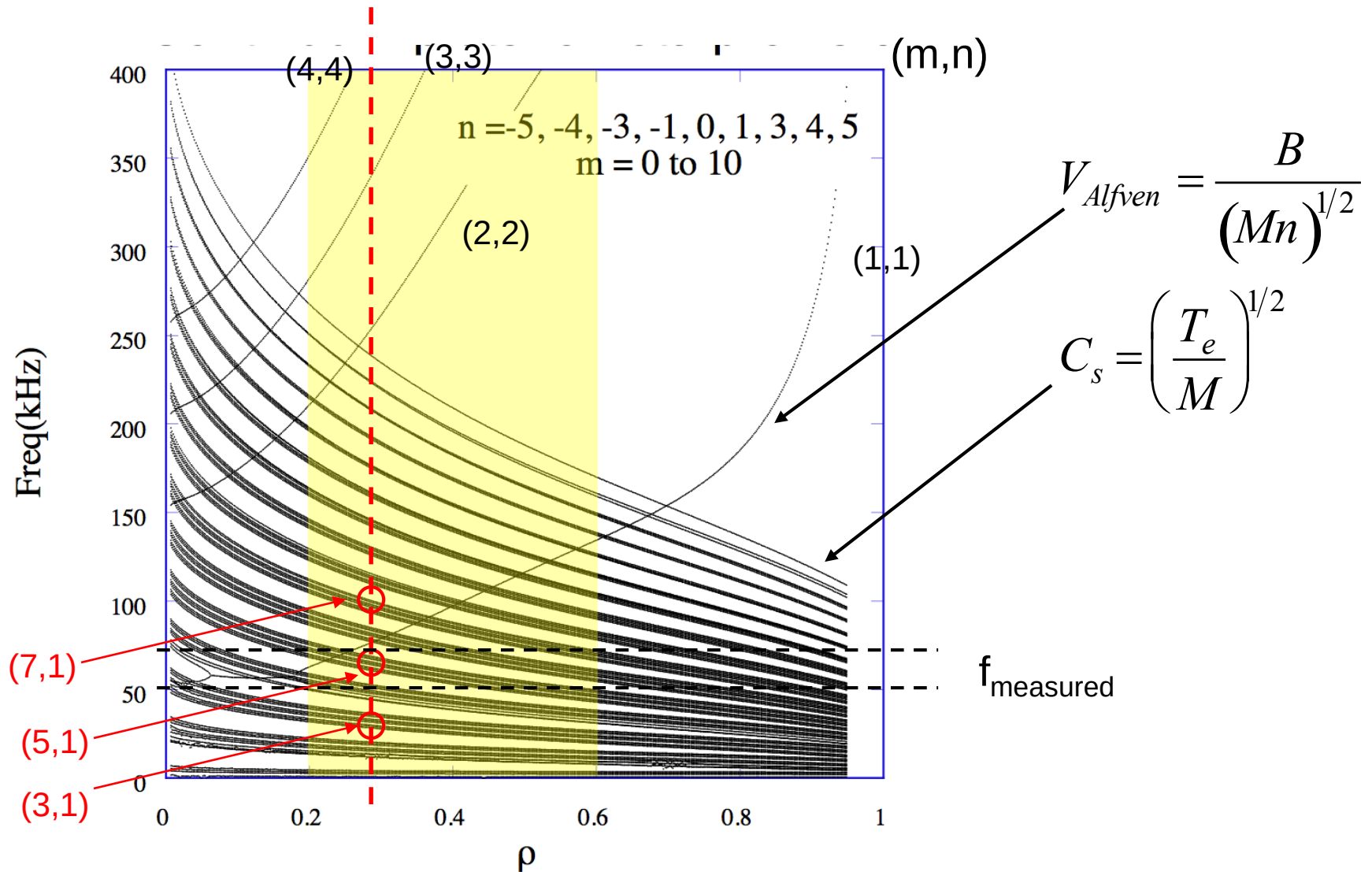
$g \equiv (\nabla \psi \bullet \nabla \psi)$ is a component of metric tensor

$\eta \equiv$ shear Alfven eigenfunction

$\zeta \equiv$ acoustic eigenfunction

Equations capture Alfven continuum, acoustic continuum and GAM

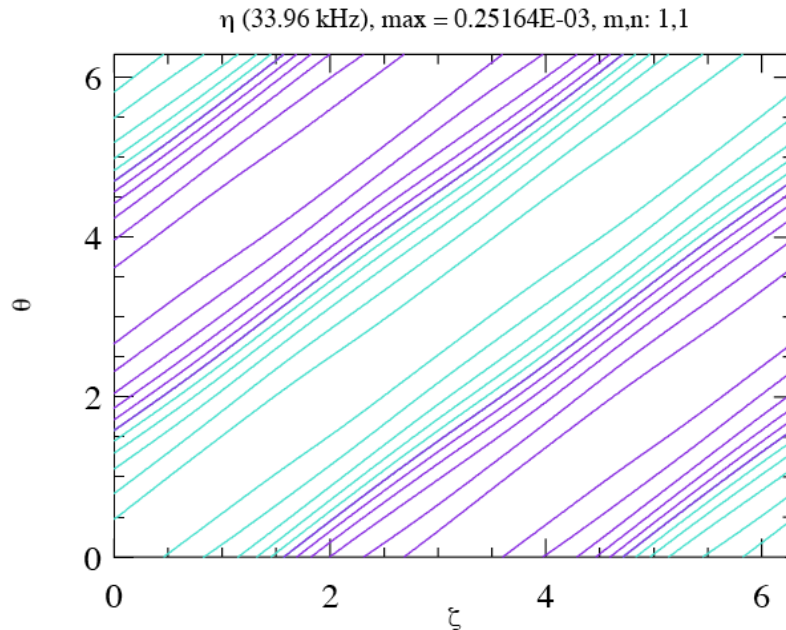
Coupled Alfvenic-Acoustic Modes



Coupled Alfvenic-Acoustic Modes

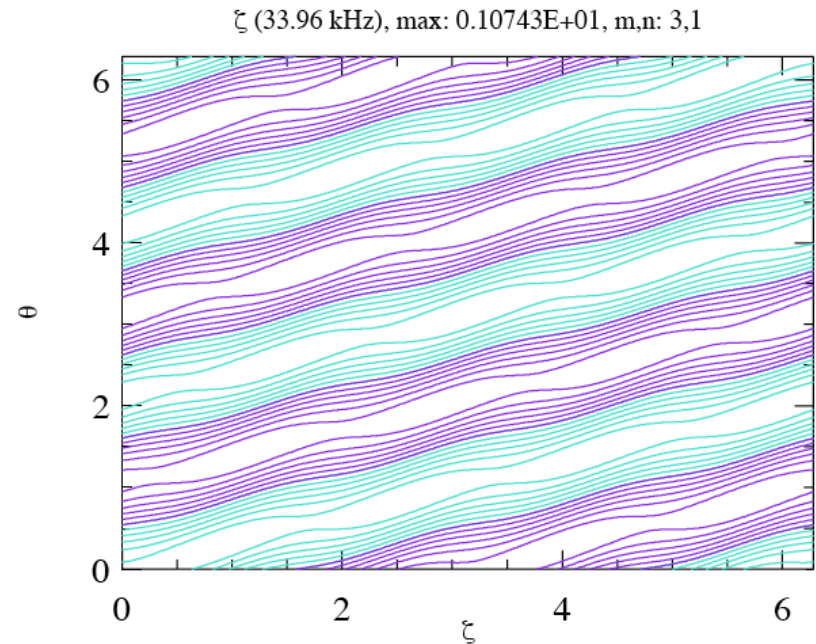
f=34 kHz

Alfvenic: m=1, n=1



r/a=0.267

acoustic: m=3, n=1



$$\omega = k_{//}^A V_{\text{Alfven}} = k_{//}^S C_s$$

$$V_{\text{Alfven}} \gg C_s \Rightarrow k_{//}^A \neq k_{//}^S$$

- Mode is largely acoustic.....
- Alfvenic and acoustic modes have different m,n

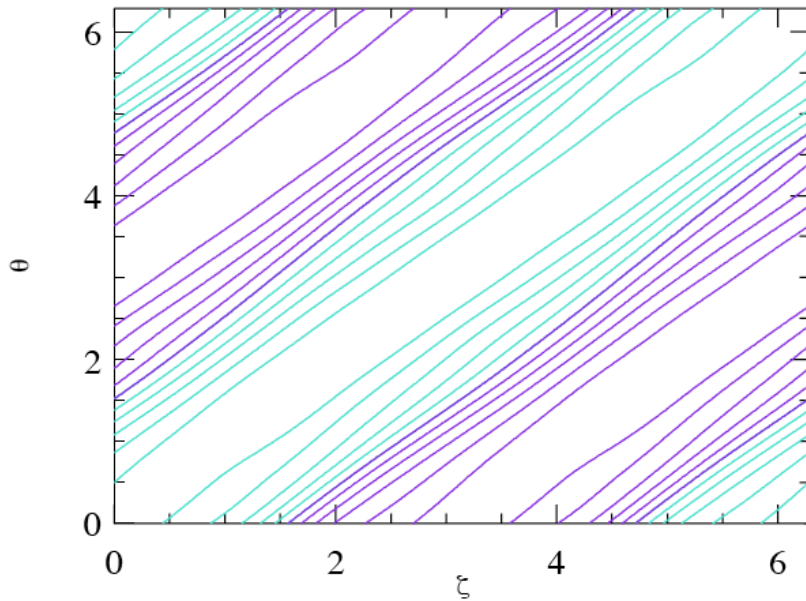
Continuum code: D. Spong

Coupled Alfvenic-Acoustic Modes

f=67 kHz

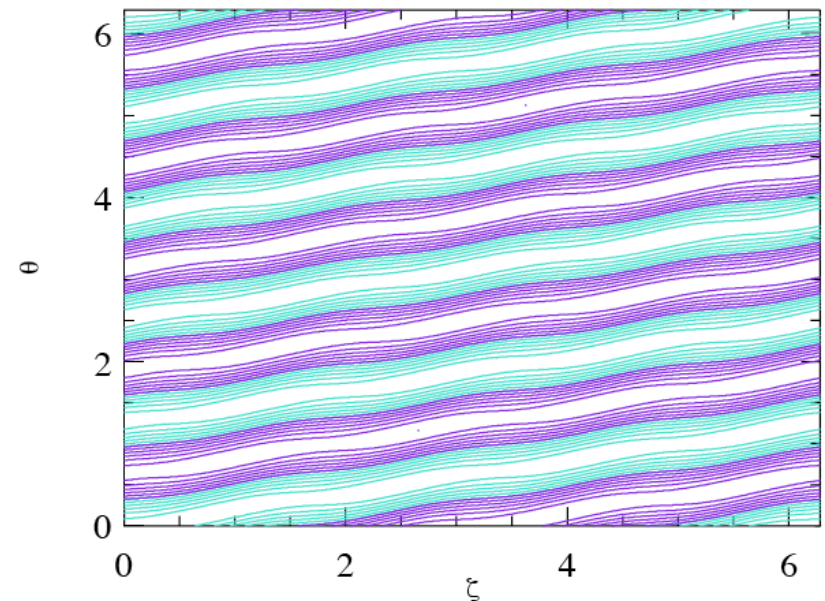
Alfvenic: m=1, n=1

η (66.99 kHz), max = 0.12837E-03, m,n: 1,1



acoustic: m=5, n=1

ζ (66.99 kHz), max: 0.10468E+01, m,n: 5,1



r/a=0.267

$$\omega = k_{//}^A V_{Alfven} = k_{//}^S C_s$$

$$V_{Alfven} \gg C_s \Rightarrow k_{//}^A \neq k_{//}^S$$

- Mode is largely acoustic.....
- Alfvenic and acoustic modes have different m,n

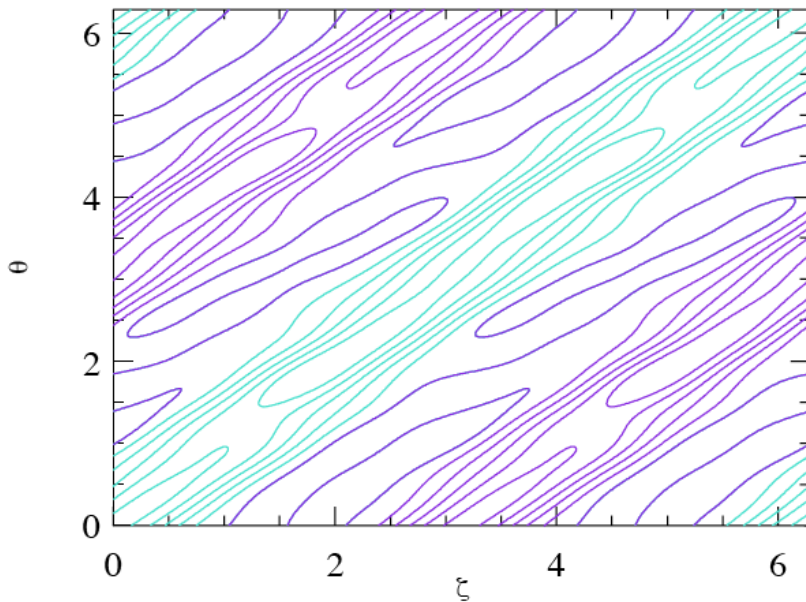
Coupled Alfvenic-Acoustic Modes

f=100 kHz

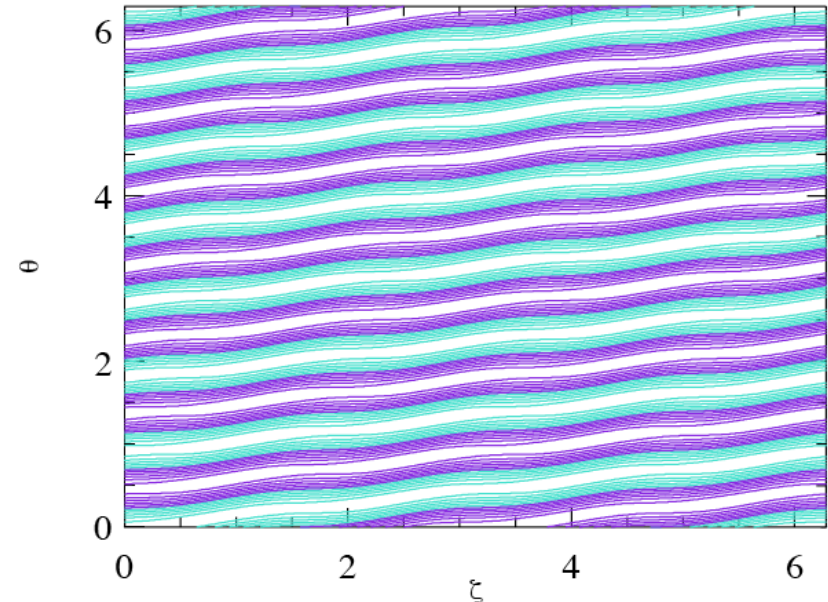
Alfvenic: m=1, n=1

acoustic: m=7, n=1

η (100.05 kHz), max = 0.16270E-04, m,n: 1,1



ξ (100.05 kHz), max: 0.10519E+01, m,n: 7,1



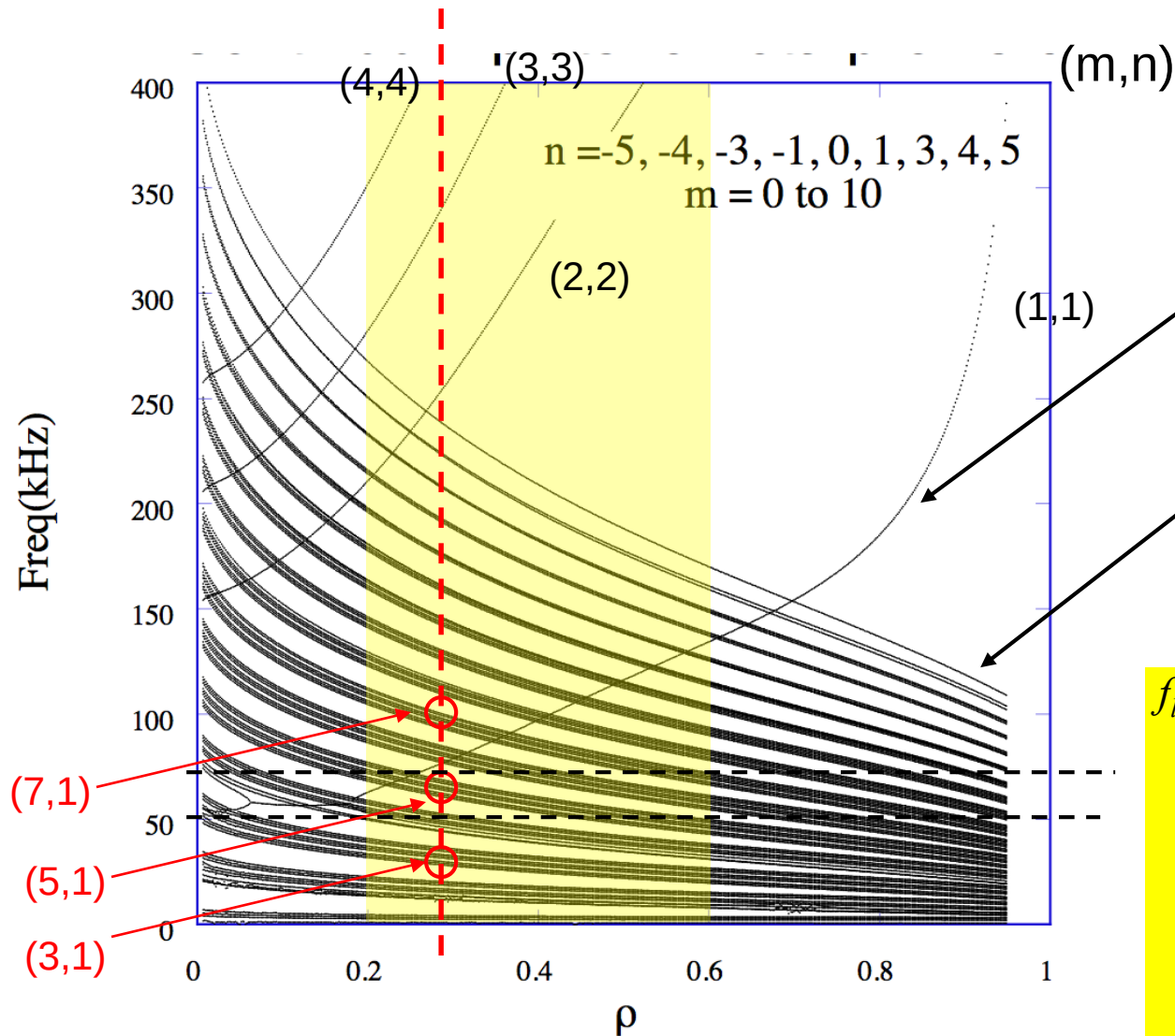
r/a=0.267

$$\omega = k_{//}^A V_{Alfven} = k_{//}^S C_s$$

$$V_{Alfven} \gg C_s \Rightarrow k_{//}^A \neq k_{//}^S$$

- Mode is largely acoustic.....
- Alfvenic and acoustic modes have different m,n

Coupled Alfvenic-Acoustic Modes



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

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

$$f_{lab} = f_{mode} + f_{Doppler}$$

$$= f_{mode} + \frac{1}{2\pi} k \cdot v_{Doppler}$$

$$= f_{mode} + \frac{m}{r} \frac{E_r}{2\pi B_0}$$

$$5-10 \text{ kHz}; \Rightarrow |E_r| \approx 5 \text{ V/cm}$$

Mode Structure

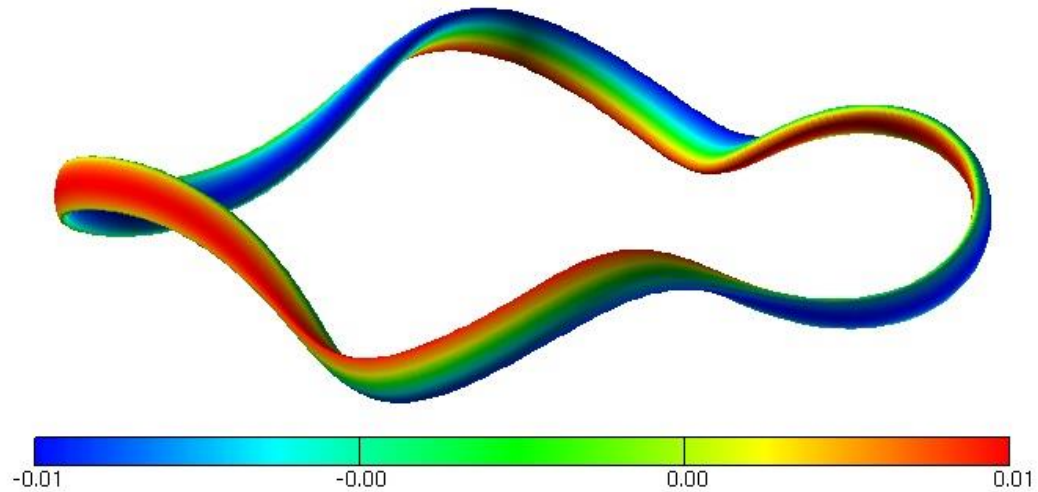
$f=53$ kHz

$r/a=0.2$

magnetic

(1,1)

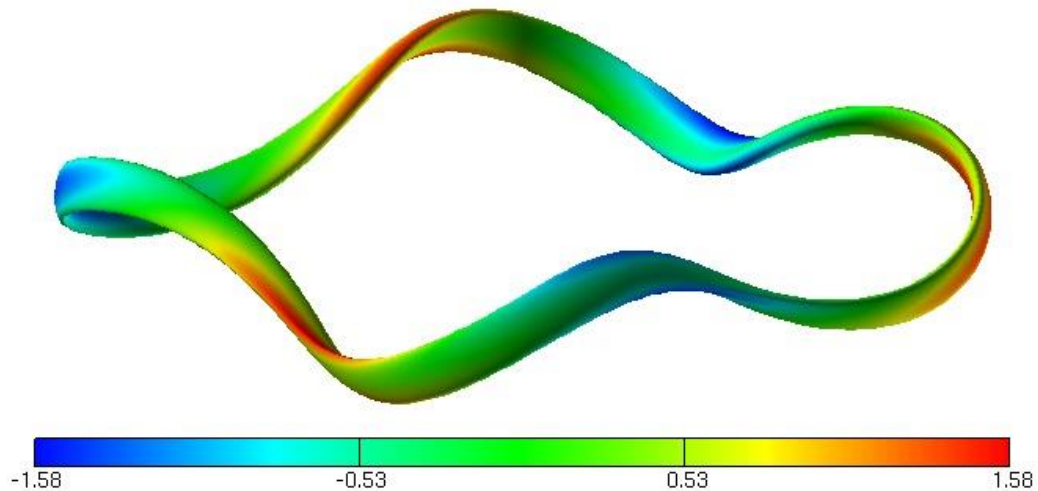
η



density

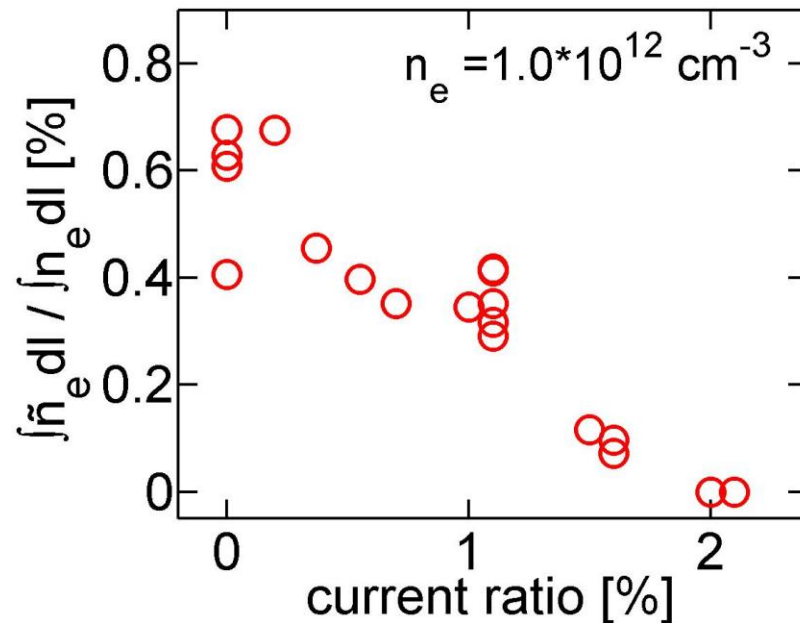
(0,3)

ζ



Mode not observed when Quasi-Symmetry Broken

Scaling with Mirror perturbation
(magnetic ripple)



(conventional stellarator configuration:
~10% mirror perturbation)

Acoustic mode

$$V_{||} = C_s$$

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

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

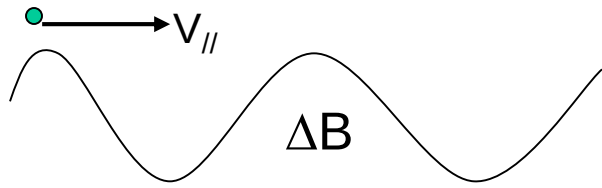
Alfvenic mode

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

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

Acoustic mode much more sensitive to magnetic ripple

Mode not observed when Quasi-Symmetry Broken



magnetic moment. $\mu = \frac{1}{2} \frac{m v_{\perp}^2}{B} \equiv \text{constant}$

Total energy: $E_{Tot} = \frac{1}{2} m (v_{\parallel}^2 + v_{\perp}^2) \equiv \text{constant}$

$$E_{Tot} = \frac{1}{2} m v_{\parallel}^2 + \mu B \Rightarrow \frac{m}{2} \Delta(v_{\parallel}^2) + \mu \Delta B = 0$$

$$|(\Delta v_{\parallel})^2| = \left| \frac{2\mu}{m} \Delta B \right| = \left| v_{\perp}^2 \frac{\Delta B}{B} \right|$$

Magnetic Ripple

$$\frac{\Delta v_{\parallel}}{v_{\perp}} = \left(\frac{\Delta B}{B} \right)^{1/2} \quad v_{\perp} = v_{th}$$

resonance lost when

Acoustic mode

$$\Delta v_{\parallel} = v_{\perp} \sqrt{\frac{\Delta B}{B}} > C_s$$

$$\frac{\Delta B}{B} > \frac{m}{M}$$

Alfvenic mode

$$\Delta v_{\parallel} = v_{\perp} \sqrt{\frac{\Delta B}{B}} > V_A$$

$$\frac{\Delta B}{B} > \frac{m}{M} \frac{1}{\beta}$$

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 $iota$

(new) 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.....

Future Plans.....

- Theory:

- continue to investigate what mode it could be, calculated the mode growth (damping) rates and their relationships with magnetic ripple
- calculate the 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.

Some thought for the slide 20

1. Resonant conditions

For Alvenic

$$\omega = \omega_{\text{Alfven}} = (m\ell - n) \frac{V_A}{R}$$

For acoustic

$$\omega = \omega_{\text{acoustic}} = k_{\parallel} C_s$$

2. Ratio of C_s/V_A

$$C_s/V_A = \frac{1}{\sqrt{\beta}}$$

3. Formulas in Slide 23

why $v_{\perp} = v_{th}$?

I am not sure I could explain clearly why the acoustic mode is much more sensitive to magnetic ripple.