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Global Analysis of Alfvén Eigenmodes in Reversed Shear Configuration

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Alfvén Eigenmode in Reversed Magnetic Shear Configuration

- **Experimental Observations**: **JT-60U (ICRF, NNBI), JET (ICRF)**
  - Rapidly increasing frequency
  - Simultaneous excitation with different toroidal mode numbers
  - High frequency mode with decreasing frequency
- **Numerical Analysis**
  - TAE: more stable than the case of normal shear owing to continuum damping
  - Sensitive $q_{\rm min}$ dependence of eigenmode frequency (Fukuyama, 1997)
    - — Frequency close to the lower gap
    - — **Existence of the mode without energetic particle**
- **Theoretical model**
  - **Explanation by Energetic Particle Mode (EPM)**
    - — Berk, Breizman et al (2001), Breizman, et al (2002 IAEA)
    - — Zonka et al. (2002 IAEA)
  - **Do the mode requires the presence of energetic particles ?**

3D Full Wave Code: TASK/WM

- **Magnetic flux coordinates**: (ψ, θ, φ)
  - **Non-orthogonal system**
- **Maxwell's equation** for stationary wave electric field $\boldsymbol{E}$

$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + \mathrm{i}\,\omega\mu_0\,\boldsymbol{j}_{\mathrm{ext}}$$

  - $\overleftrightarrow{\epsilon}$ **: Dielectric tensor with kinetic effects**: $Z[(\omega - n\omega_{\mathrm{c}})/k_\parallel]$
- **Fourier expansion** in poloidal and toroidal directions
  - **Exact parallel wave number**: $k_\parallel^{m,n} = (mB^\theta + nB^\varphi)/B$
- **Destabilization by energetic ions** include in $\overleftrightarrow{\epsilon}$
  - **Drift kinetic equation**

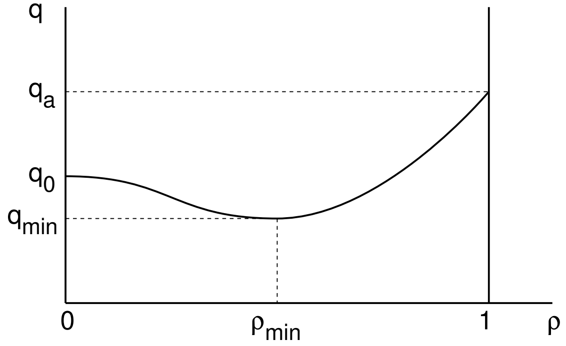
$$\left[\frac{\partial}{\partial t} + v_\parallel \nabla_\parallel + (\boldsymbol{v}_{\mathrm{d}} + \boldsymbol{v}_{\mathrm{E}}) \cdot \nabla + \frac{e_\alpha}{m_\alpha}(v_\parallel E_\parallel + \boldsymbol{v}_{\mathrm{d}} \cdot \boldsymbol{E}) \frac{\partial}{\partial \varepsilon}\right] f_\alpha = 0$$

- **Eigenvalue problem** for complex wave frequency
  - **Maximize wave amplitude** for finite excitation proportional to nne

Analysis of TAE in Reversed Shear Configuration

q_{min} Dependence of Eigenmode Frequency

Assumed q profile

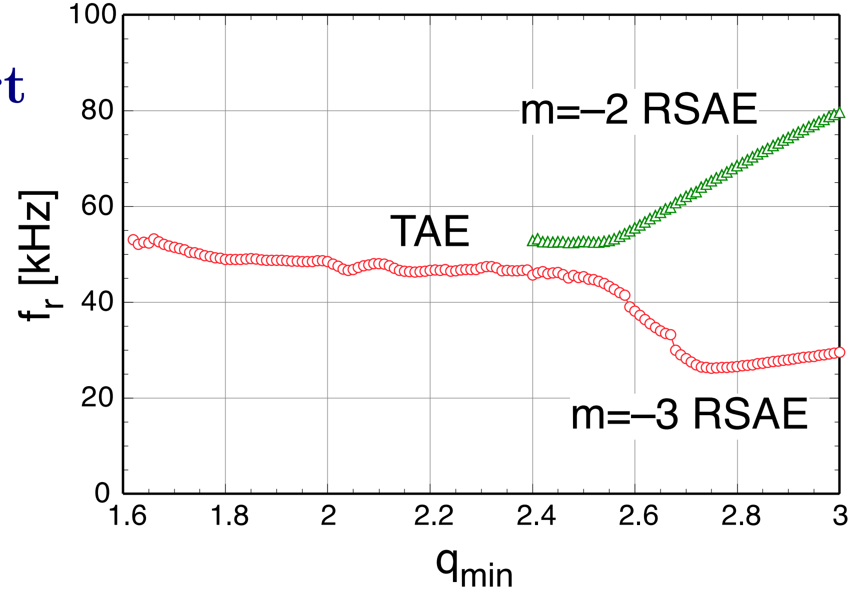


Plasma Parameters

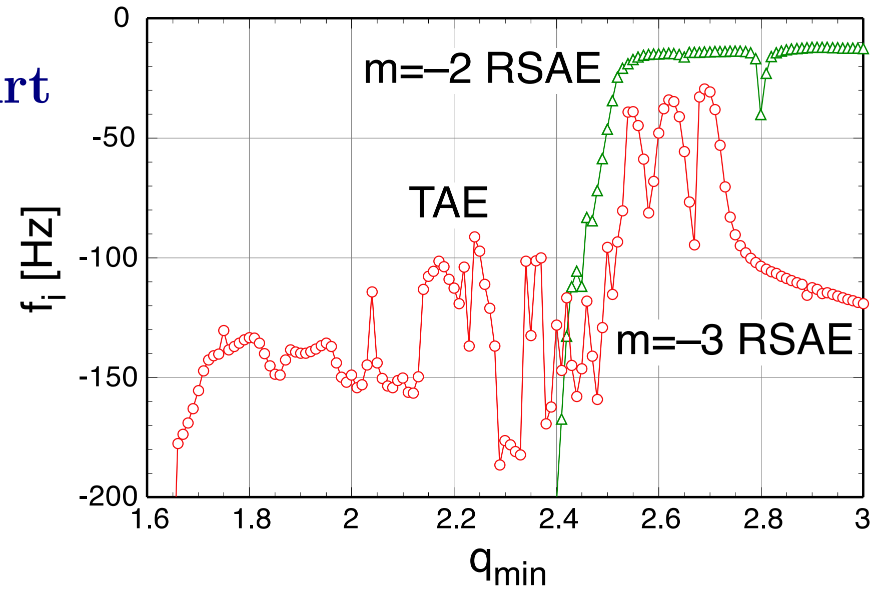
R_0	$3\,\mathrm{m}$
a	$1\,\mathrm{m}$
B_0	$3\,\mathrm{T}$
$n_e(0)$	$10^{20}\,\mathrm{m}^{-3}$
$T(0)$	$3\,\mathrm{keV}$
$q(0)$	3
$q(a)$	5
ρ_{min}	0.5
n	1

Flat density profile

Real part



Imag part



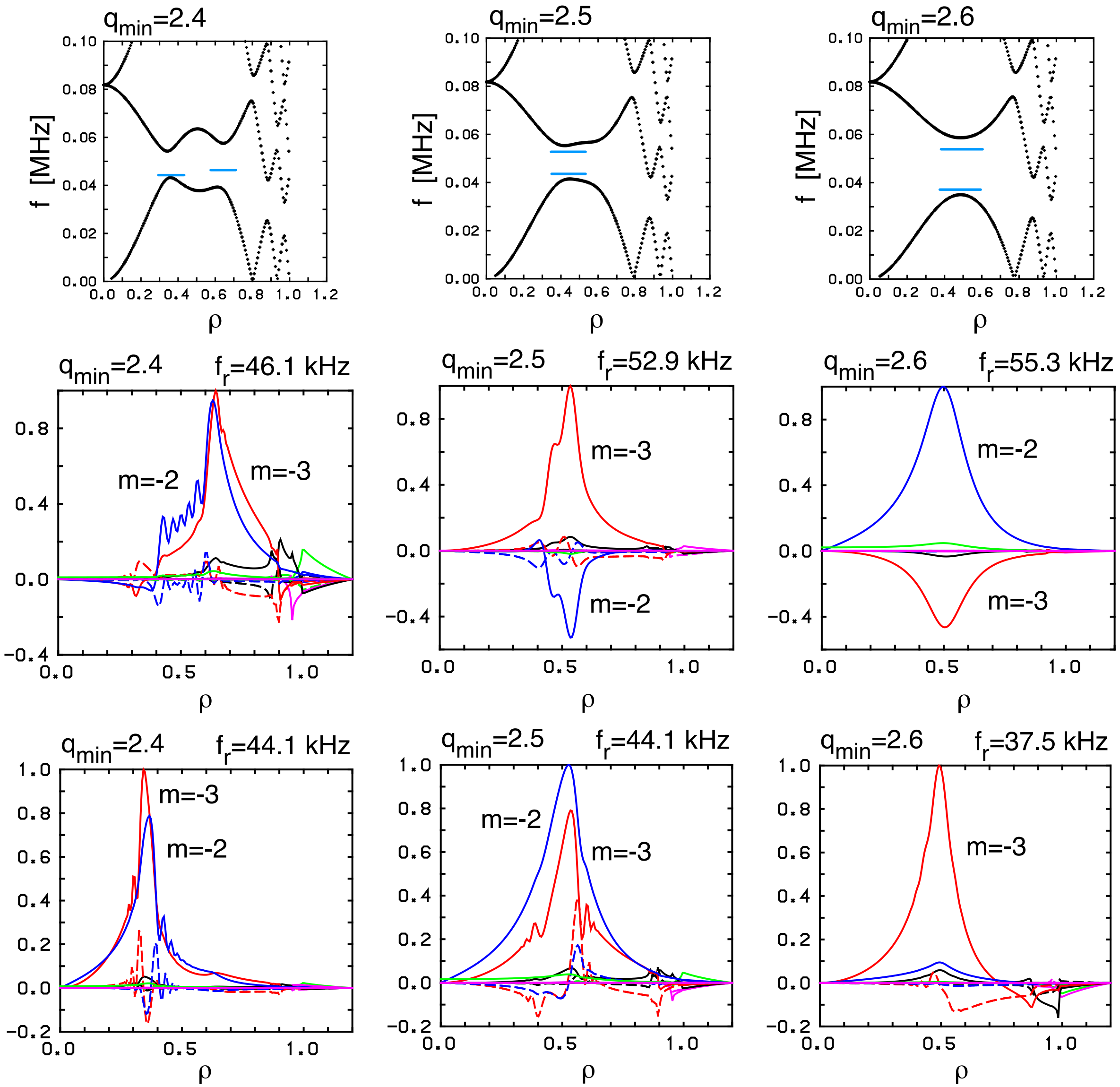
Eigenmode Structure

$q_{\min} = 2.4$ | $q_{\min} = 2.5$ | $q_{\min} = 2.6$

Alfvén resonance

Higher freq.

Lower freq.



TAEs | Double TAE | RSAE

Excitation by Energetic Particles ($q_{min} = 2.6$)

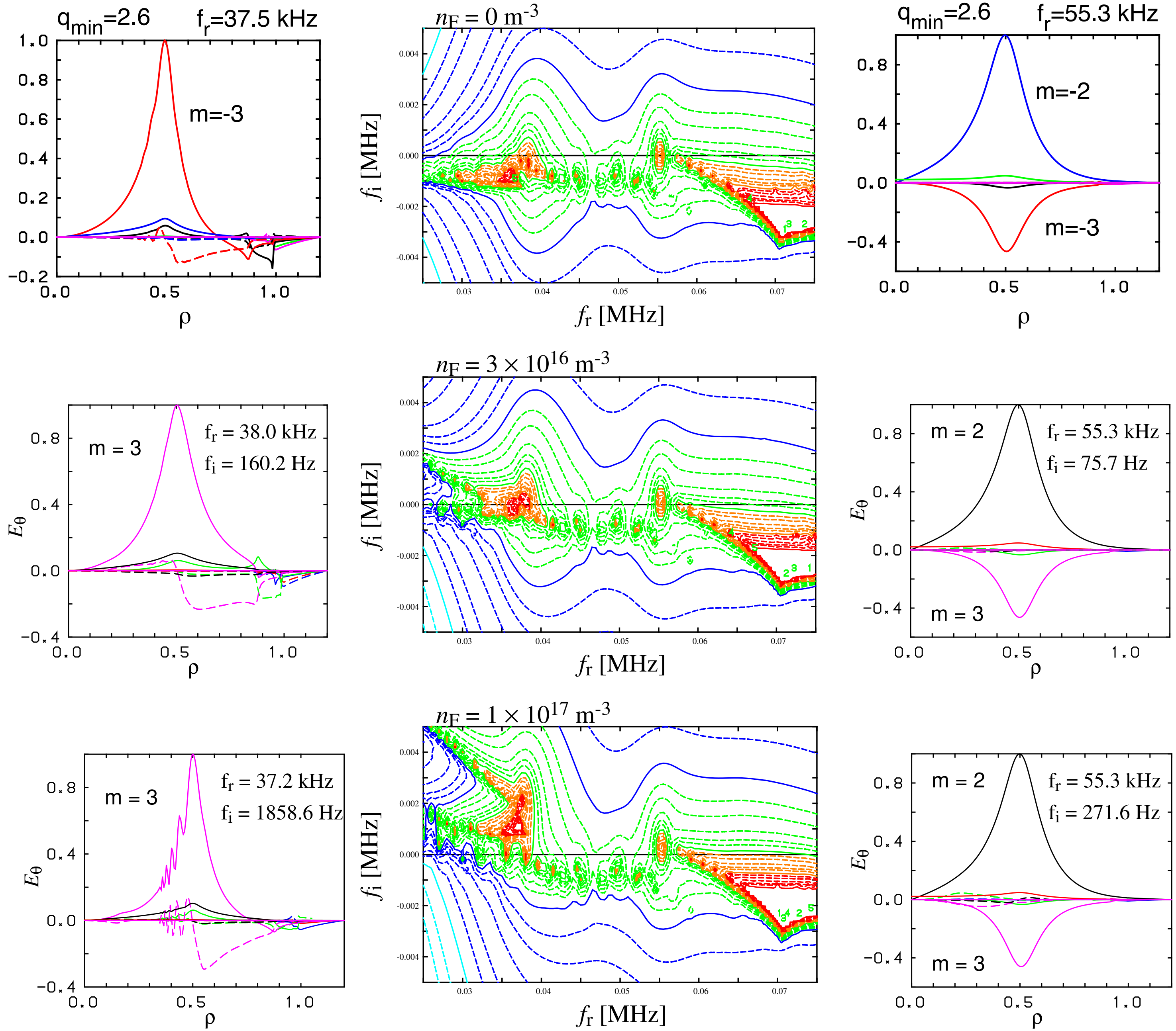
- Without EP

- With EP

  $3 \times 10^{16}\,\mathrm{m}^{-3}$
  360 keV
  0.5 m

- With EP

  $1 \times 10^{17}\,\mathrm{m}^{-3}$
  360 keV
  0.5 m



Summary

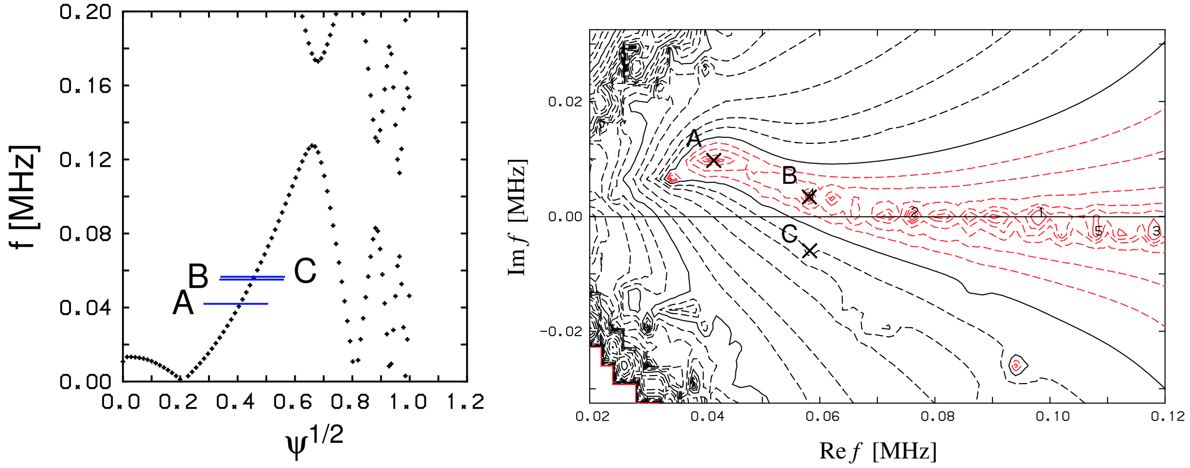
- In the reversed magnetic shear configuration, upper and lower **RSAEs** (reversed-shear-induced Alfvén eigenmode) exist for

$$\frac{m+0.5}{n} \lesssim q_{\min} \lesssim \frac{m+0.8}{n}$$

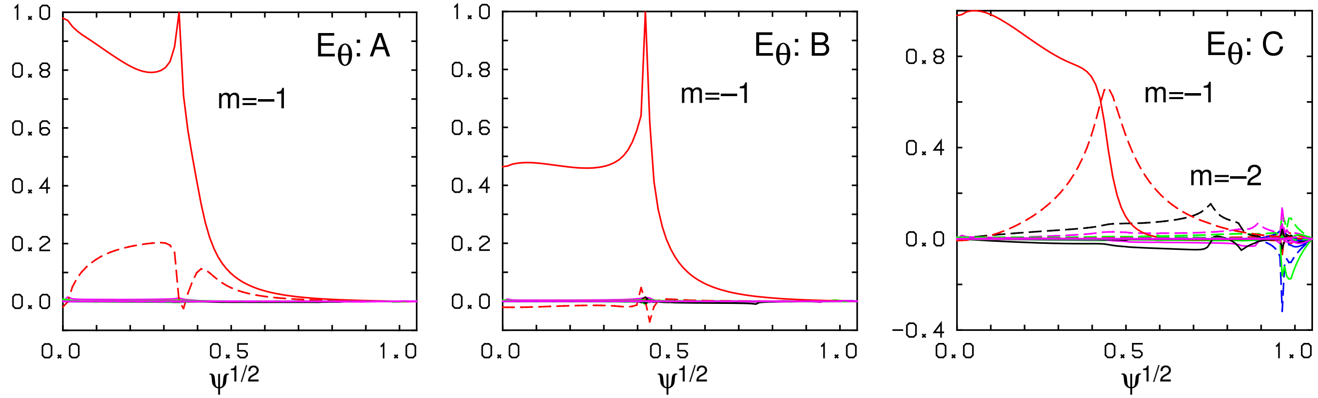
- **Upper RSAE** has an anti-ballooning structure and the damping rate is small.
- **Lower RSAE** has a single mode structure $(m+1)$ and the damping rate is larger than that of the upper RSAE.
- In the presence of a small amount of **energetic particles**, however, the growth rate of lower RSAE becomes higher than that of the upper RSAE owing to the lower frequency.
- **Future work**
  - Analysis in ITER configuration
  - Systematic analysis of low frequency EPM
  - Kinetic analysis of low-frequency modes including the effect of trapped particle

Energetic Particle Mode (EPM)

- Energetic ions can excite EPM with frequency below the TAE frequency gap.
- With β of energetic ions about 0.5%, ω_A and contour of wave amplitude

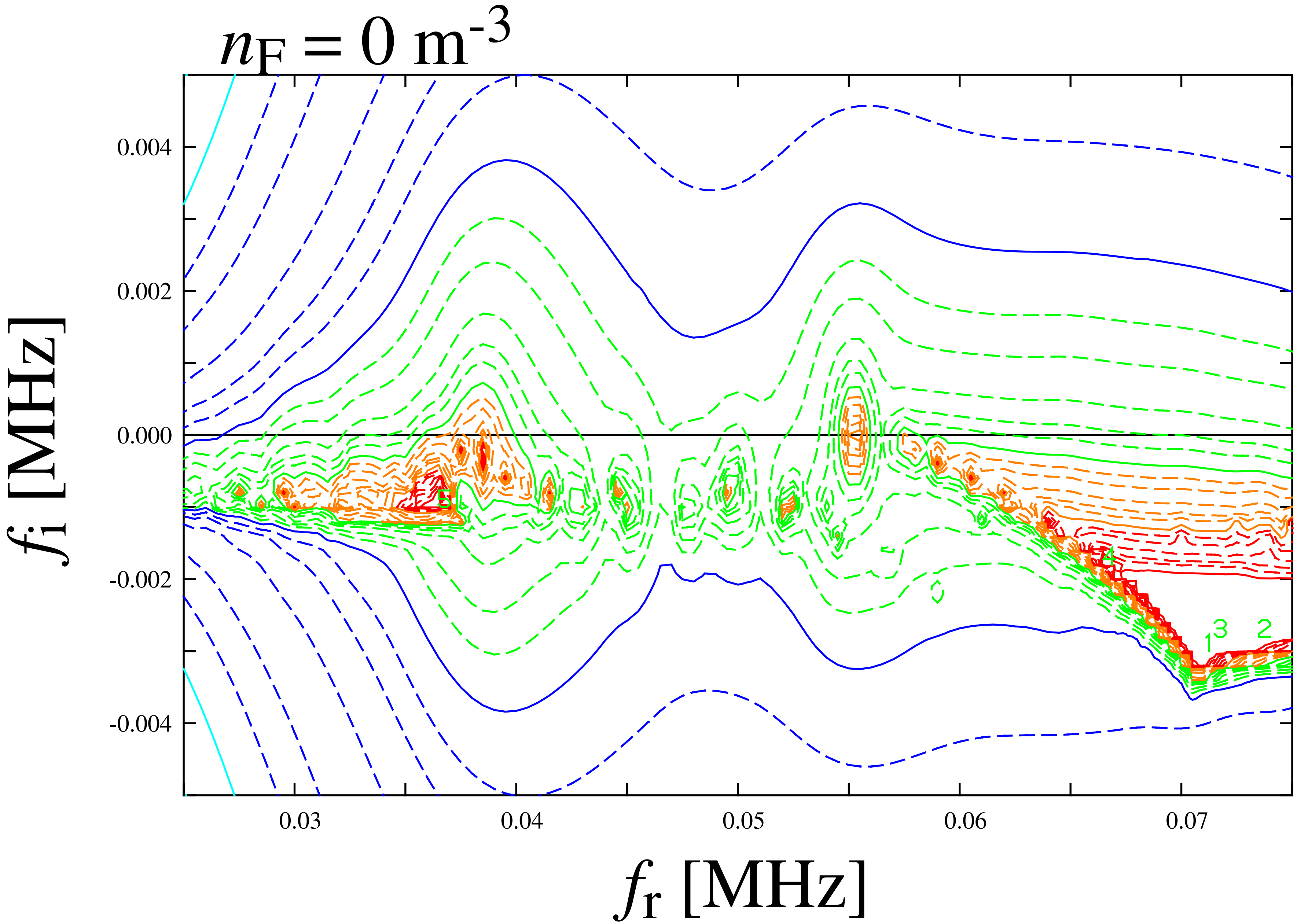


- Eigenmode structure

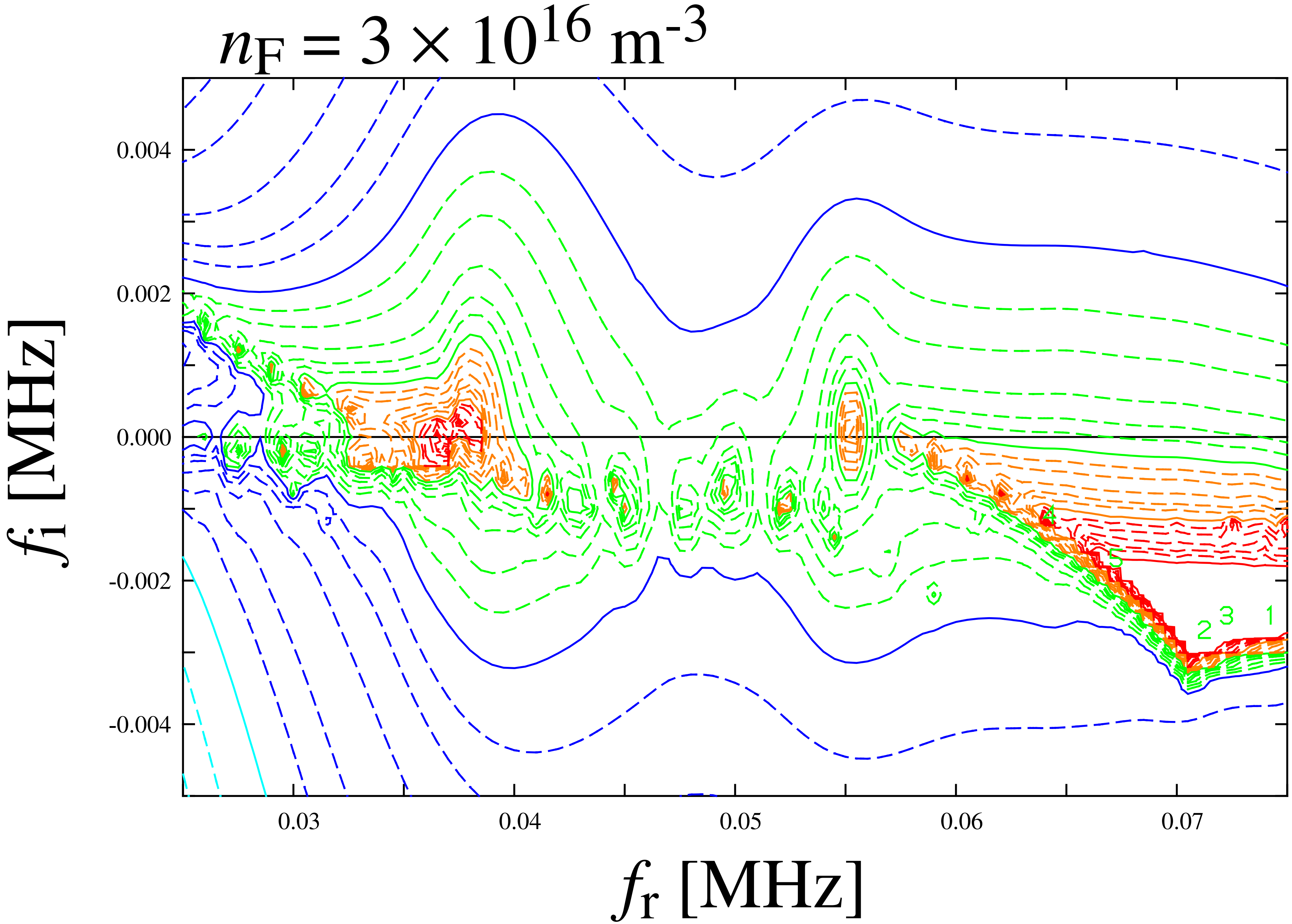


A: $f_r = 41.8\,\mathrm{kHz}$	B: $f_r = 57.7\,\mathrm{kHz}$	C: $f_r = 58.0\,\mathrm{kHz}$
A: $f_i = 8.1\,\mathrm{kHz}$	B: $f_i = 3.6\,\mathrm{kHz}$	C: $f_i = -6.0\,\mathrm{kHz}$

Without Energetic Particles



With Energetic Particles



With Energetic Particles