TASK

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  - ○ **CAE** :
  - ○ **EAE** : Ellipticity-induced Alfvén eigenmode
  - ○ **TAE** : Toroidicity-induced Alfvén eigenmode
  - ○ **GAE** : Global Alfvén eigenmode
  - ○ **EPM, RSAE, BAE** : Energetic Particle Driven mode
  - ○ **DAE** : Drift-Alfvén eigenmode

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  - ○ TAE   Nova-K
  - ○   JT-60U, JET

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  - PENN code (Jaun, Alfvén Lab)
  - TASK/WM (Fukuyama)
- n
  - HINST (Gorelenkov, Cheng)
  - 2D-WKB (Vlad, Chen, Zonka)
- **TASK/WM**
  - MHD
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-

  ○ ψ

  ○ θ

  ○ φ

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$$\boldsymbol{e}^1 = \boldsymbol{\nabla}\psi, \qquad \boldsymbol{e}^2 = \boldsymbol{\nabla}\theta, \qquad \boldsymbol{e}^3 = \boldsymbol{\nabla}\varphi$$

$$\boldsymbol{E} = E_1\boldsymbol{e}^1 + E_2\boldsymbol{e}^2 + E_3\boldsymbol{e}^3$$

- J :
$$J = \frac{1}{\boldsymbol{e}^1 \cdot \boldsymbol{e}^2 \times \boldsymbol{e}^3} = \frac{1}{\boldsymbol{\nabla}\psi \cdot \boldsymbol{\nabla}\theta \times \boldsymbol{\nabla}\varphi}$$

- g :
$$\boldsymbol{e}_i \equiv \partial \boldsymbol{r}/\partial x_i \qquad g_{ij} = \boldsymbol{e}_i \cdot \boldsymbol{e}_j$$

- $\boldsymbol{E}$ ω c

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

  ○ $\overset{\leftrightarrow}{\epsilon}$:

  ○ $\boldsymbol{j}_{\mathrm{ext}}$:

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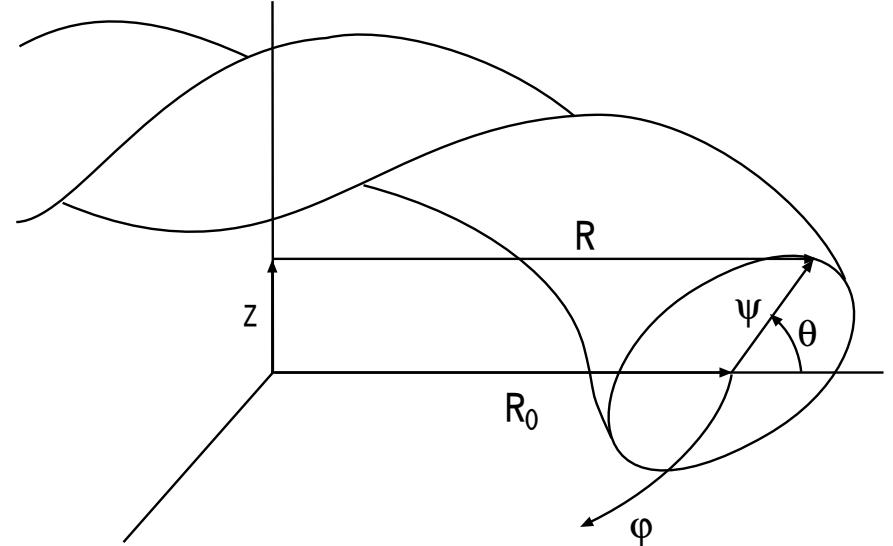
$$
(\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{E})^1 = \frac{1}{J}\left[\frac{\partial}{\partial x^2}\left\{ \frac{g_{31}}{J}\left(\frac{\partial E_3}{\partial x^2} - \frac{\partial E_2}{\partial x^3}\right) + \frac{g_{32}}{J}\left(\frac{\partial E_1}{\partial x^3} - \frac{\partial E_3}{\partial x^1}\right) + \frac{g_{33}}{J}\left(\frac{\partial E_2}{\partial x^1} - \frac{\partial E_1}{\partial x^2}\right) \right\} \right.
$$
$$
\left. - \frac{\partial}{\partial x^3}\left\{ \frac{g_{21}}{J}\left(\frac{\partial E_3}{\partial x^2} - \frac{\partial E_2}{\partial x^3}\right) + \frac{g_{22}}{J}\left(\frac{\partial E_1}{\partial x^3} - \frac{\partial E_3}{\partial x^1}\right) + \frac{g_{23}}{J}\left(\frac{\partial E_2}{\partial x^1} - \frac{\partial E_1}{\partial x^2}\right) \right\} \right]
$$

  ○ (x^1, x^2, x^3) (ψ, θ, φ)

  ○

- $\overset{\leftrightarrow}{\epsilon}$
- z

$$\hat{\boldsymbol{e}}_s = \frac{\boldsymbol{\nabla}\psi}{|\boldsymbol{\nabla}\psi|}, \qquad \hat{\boldsymbol{e}}_b = \hat{\boldsymbol{e}}_h \times \hat{\boldsymbol{e}}_\psi, \qquad \hat{\boldsymbol{e}}_h = \frac{\boldsymbol{B}_0}{|\boldsymbol{B}_0|}$$

- $\overset{\leftrightarrow}{\mu}$

$$\begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} = \overset{\leftrightarrow}{\mu} \begin{pmatrix} E_s \\ E_b \\ E_h \end{pmatrix}$$

$$\overset{\leftrightarrow}{\mu} \equiv \begin{pmatrix} \dfrac{1}{\sqrt{g^{11}}} & \dfrac{d}{\sqrt{Jg^{11}}} & c_2 g_{12} + c_3 g_{13} \\ 0 & c_3 J\sqrt{g^{11}} & c_2 g_{22} + c_3 g_{23} \\ 0 & -c_2 J\sqrt{g^{11}} & c_2 g_{32} + c_3 g_{33} \end{pmatrix}$$

$c_2 = B^\theta/B, \quad c_2 = B^\phi/B$

$d = c_2(g_{23}g_{12} - g_{22}g_{31}) + c_3(g_{33}g_{12} - g_{32}g_{31})$

$g^{11} = (g_{22}g_{33} - g_{23}g_{32})/J^2$

-

$$\overset{\leftrightarrow}{\epsilon} = \overset{\leftrightarrow}{\mu} \cdot \overset{\leftrightarrow}{\epsilon}_{sbh} \cdot \overset{\leftrightarrow}{\mu}^{-1}$$

-

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$$E(\psi, \theta, \varphi) = \sum_{mn} E_{mn}(\psi) e^{\mathrm{i}(m\theta + n\varphi)}$$

$$G(\psi, \theta, \varphi) = \sum_{lk} G_{lk}(\psi) e^{\mathrm{i}(l\theta + kN_p\varphi)}$$

$$J(\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{E}) = G(\psi, \theta, \varphi) E(\psi, \theta, \varphi) = \sum_{m'n'} [J(\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{E})]_{m'n'} e^{\mathrm{i}(m'\theta + n'\varphi)}$$

- $\quad\quad\quad N_{\mathrm{h}}$:

	n	m
$\boldsymbol{E}$	kN_{h}	l
$J(\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{E})$	n'	m'
	$n' = n + kN_{\mathrm{h}}$	$m' = m + l$

- $$\overset{\leftrightarrow}{\epsilon}(\psi,\theta,\varphi,k_\parallel^{m''n''})$$
$$Z[(\omega-N\omega_{\mathrm{cs}})/k_\parallel^{m''n''}v_{\mathrm{Ts}}]$$
$$k_\parallel^{m'',n''}$$

$$k_\parallel^{m'',n''}=-i\hat{\boldsymbol{e}}_h\cdot\boldsymbol{\nabla}=-i\hat{\boldsymbol{e}}_h\cdot(\boldsymbol{\nabla}\theta\frac{\partial}{\partial\theta}+\boldsymbol{\nabla}\varphi\frac{\partial}{\partial\varphi})=-i\hat{\boldsymbol{e}}_h\cdot(\boldsymbol{e}^2\frac{\partial}{\partial\theta}+\boldsymbol{e}^3\frac{\partial}{\partial\varphi})=m''\frac{B^\theta}{|B|}+n''\frac{B^\varphi}{|B|}$$

- $$\overset{\leftrightarrow}{\epsilon}_{sbh}$$

$$(J\overset{\leftrightarrow}{\epsilon}\cdot\boldsymbol{E})^i \;=\; J\overset{\leftrightarrow}{g}^{-1}\cdot\overset{\leftrightarrow}{\mu}\cdot\overset{\leftrightarrow}{\epsilon}_{sbh}\cdot\overset{\leftrightarrow}{\mu}^{-1}\cdot\boldsymbol{E}_i$$

| m' | | ℓ_3 | ℓ_2 | ℓ_1 | m |
| n' | | k_3 | k_2 | k_1 | n |

$$m''=m+\ell_1+\frac{1}{2}\ell_2 \qquad n''=n+k_1+\frac{1}{2}k_2$$
$$m'=m+\ell_1+\ell_2+\ell_2 \qquad n'=n+k_1+k_2+k_3$$

TASK/WM

- Fortran77 + MPI

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  - ○

  - ○

- 16   50

- $q(\rho) = q_0 + (q_a - q_0)\rho^2$, $q_0 = 1$, $q_a = 2$

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$$f_r = 81.95\,\text{kHz}$$
$$f_i = -20.32\,\text{Hz}$$

Analysis of TAE in Reversed Shear Configuration

q_{min} Dependence of Eigenmode Frequency

Assumed q profile

q

q_a

q_0

q_{min}

0   ρ_{min} 1 ρ
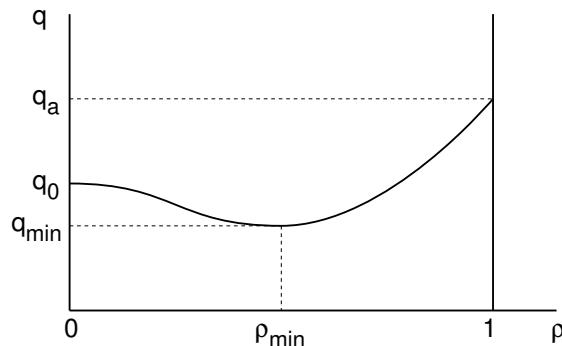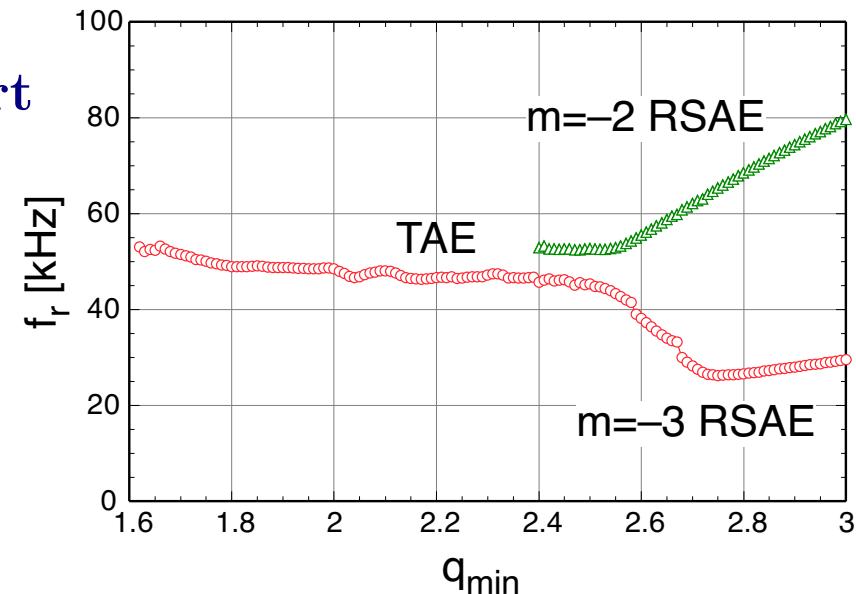
Plasma Parameters

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

f_r [kHz]

m=−2 RSAE

TAE

m=−3 RSAE

q_{min}

Imag part

f_i [Hz]

m=−2 RSAE

TAE

m=−3 RSAE

q_{min}
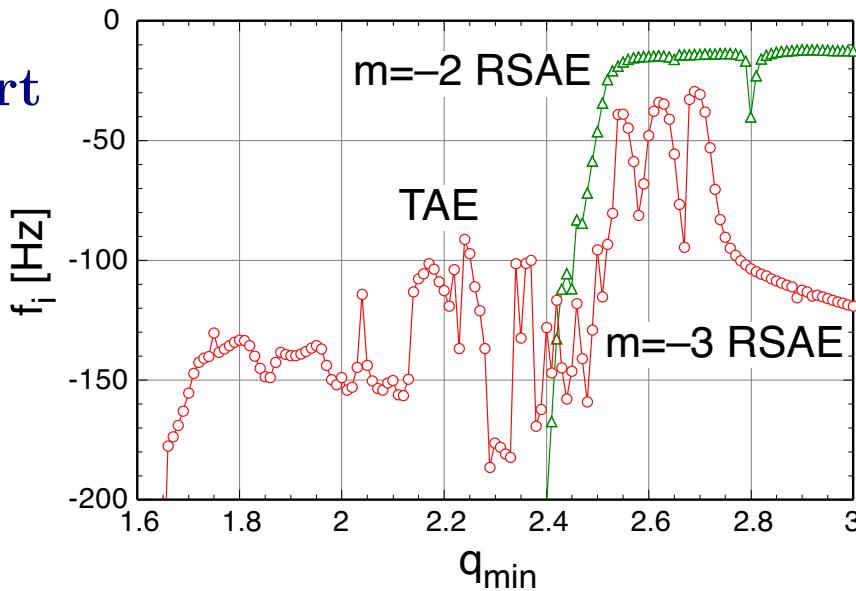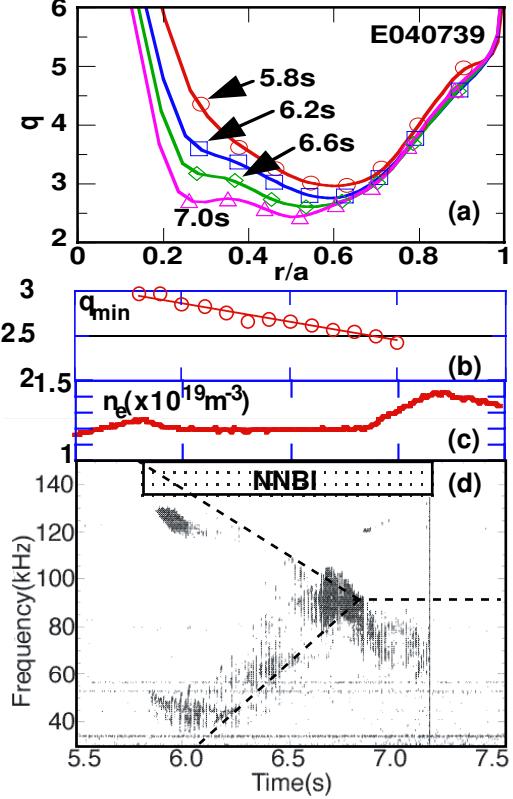
FIG. 1: (a) Temporal evolution of the q-profile measured with MSE. (b) Temporal evolution of $q_{\min}$, (c) line averaged electron density, (d) a typical behavior of frequency spectrum of the $n = 1$ AE. Broken lines denote estimated frequency from the RSAE model normalized by observed frequency at $q = 2.5$.

probes separated by about 40 degree in the toroidal direction is larger than 0.9. the only $n = 1$ AE is observed because $\beta_{\rm h}$ is relatively low ($\beta_{\rm h} < 0.2\%$). AEs with $n > 1$ are observed if $\beta_{\rm h}$ increases. The large upward/downward frequency sweeping from $t = 6.0$–6.5 s cannot be explained by the change of V_A because the electron density changed only less than 5%. In the period $t = 6.5$–6.8 s the $n = 1$ AE frequency saturates. After $t \sim 6.8$ s the $n = 1$ AE frequency decreases due to the increase of electron density.

The observed AE amplitude are enhanced during $t \approx 6.65 - 6.85$ s when the AE frequency is saturated as shown in Fig. 1(d). To investigate the dependence of mode amplitude on the q-profile change, we show the mode amplitude versus $q_{\min}$ for three shots in Fig. 2. When NNBI was injected the values of $q_{\min}$ are about 3.0, 2.8 and 2.6 for the shots of E40739, E40744 and E40743, respectively. For all these cases the $n = 1$ mode amplitude is largest

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

**Alfvén resonance**
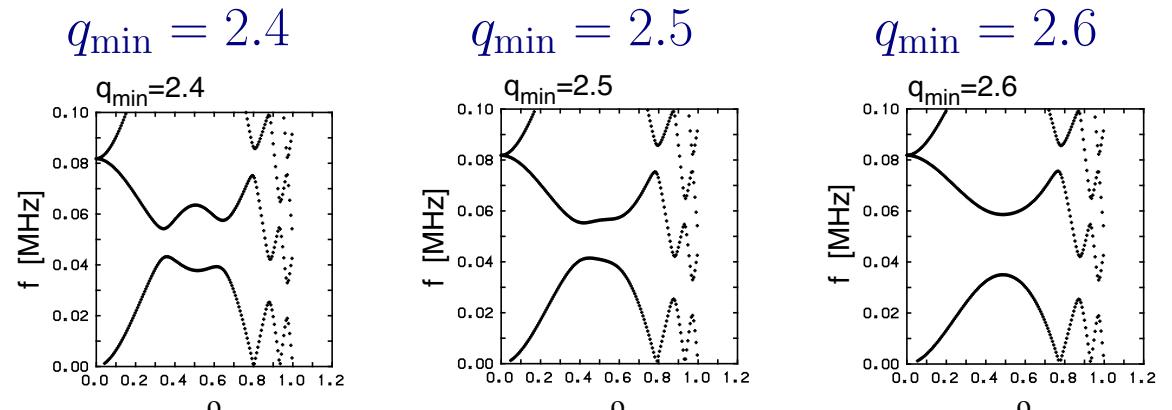
Higher freq.
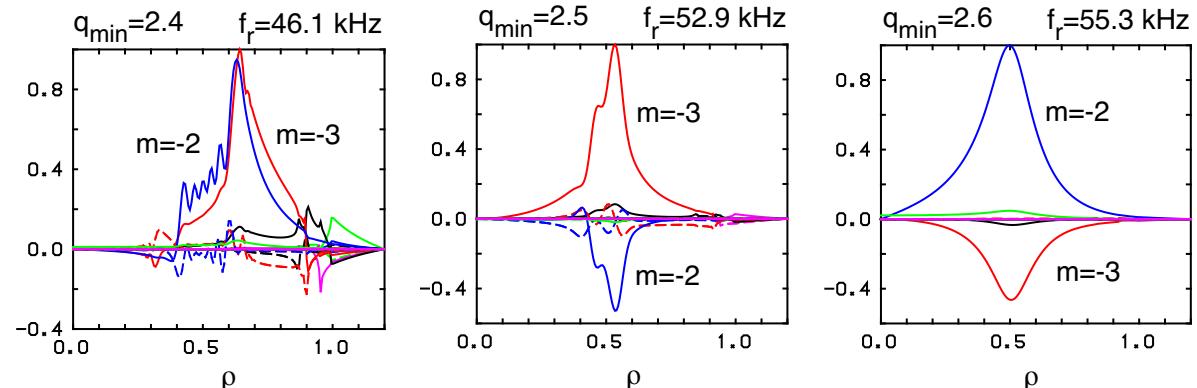
Lower freq.
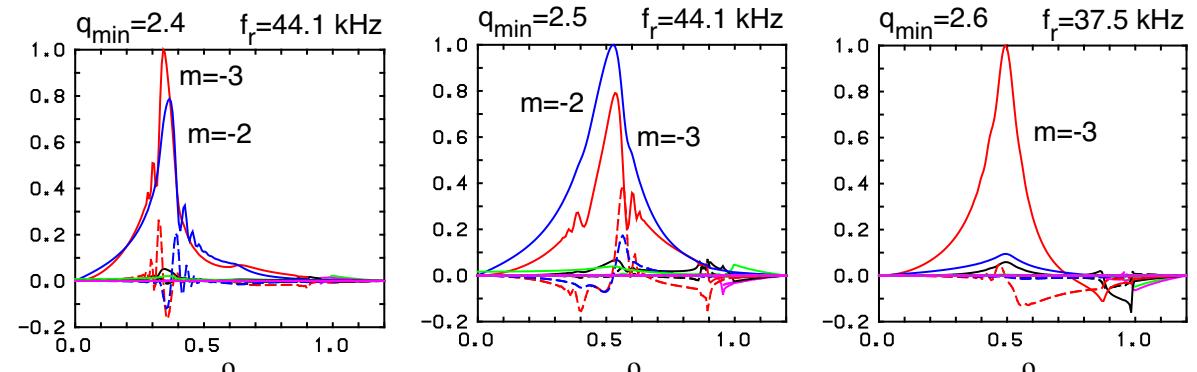
TAEs   Double TAE   RSAE

FIG. 2: Dependence of AE magnetic fluctuation amplitude on $q_{\min}$. The $n = 1$ AE amplitude is enhanced in the range of $2.4 < q_{\min} < 2.7$.


FIG. 3: Schematic drawing of the $n = 1$ spectrum of AEs in the RS plasma with (a) $q_{\min} = 2.8$, (b) $q_{\min} = 2.5$ and (b) $q_{\min} = 2.3$. Panel (d) shows the frequencies of RSAE and TAE as a function of $q_{\min}$. The bold lines denote the frequencies of the $n = 1$ AEs and thin lines are for the $n = 2$ AEs. Numbers in the parentheses are poloidal mode numbers.

in the range $2.4 < q_{\min} < 2.7$, which is independent of the time length after NNB injection.

To understand the large and rapid frequency sweeping and its subsequent saturation, we propose a model of RSAE and its transition to TAE as $q_{\min}$ decreases. Fig. 3 shows three shear Alfvén continuous spectra, frequency vs. r/a, in RS plasmas with (a) $q_{\min} = 2.8$, (b) $q_{\min} = 2.5$ and (c) $q_{\min} = 2.3$. In any cases, $n = 1$, $q(0) = 3$ at the plasma center, and $q(a) = 5$ at the plasma edge. The two gaps around the $q_{\min}$ region shown in Fig. 3(c) are

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FIG. 5: (a) Typical temporal evolution of AE frequency changes observed in a JT-60U ICRF heated RS plasma [6]. (b) The frequencies of $n=$ 1–9 LRSAEs (solid upward-sloping lines) and TAEs (horizontal aligned marks) as a function of the q_{min} decrement.

assume that q_{min} decreases in time as it does. If the modes in the experiment just trace the Alfvén dispersion relation, which is $\omega_A/V_A = |k_{//}(r)| = |n - m/q(r)|/R$, at $q = q_{min}$, and q_{min} decrease, the frequency would increase in time when $k_{//}(r_0) < 0$ and decrease in time when $k_{//}(r_0) > 0$. However, the modes with downward sweeping are suppressed in the experiment. They interpret no observation of downward frequency sweeping after upward frequency sweeping by effect of energetic particles. They assert that the only way they have found to explain the asymmetry is to describe the fast particle response in a nonperturbative manner. On the other hand, from our RSAE model, there are inherently TAEs rather than modes with downward sweeping after upward sweeping, i.e., AE transits from LRSAE to TAE. We don't observe TAE after RSAE when β_h is not sufficiently large, because damping rate of TAE is larger than that of LRSAE. When β_h is sufficiently high, TAE can be destabilized in the q_{min} transition range as observed in our NNB RS plasma

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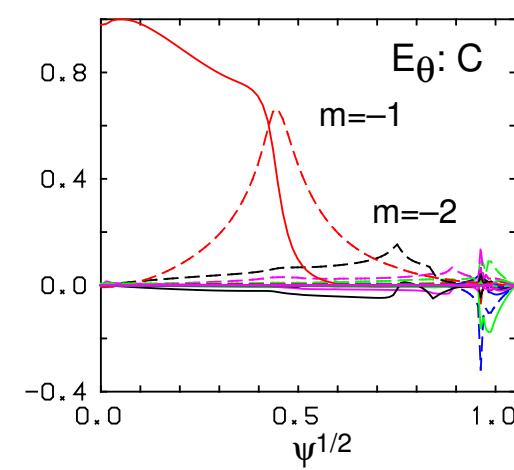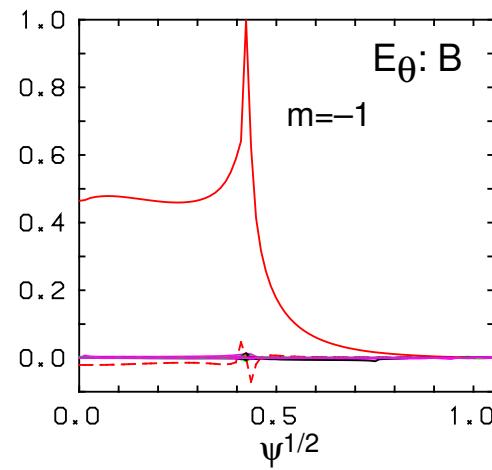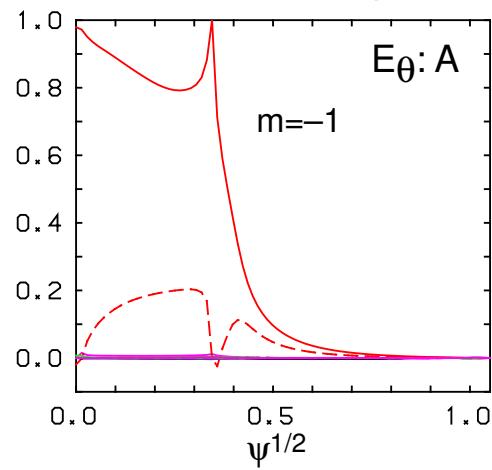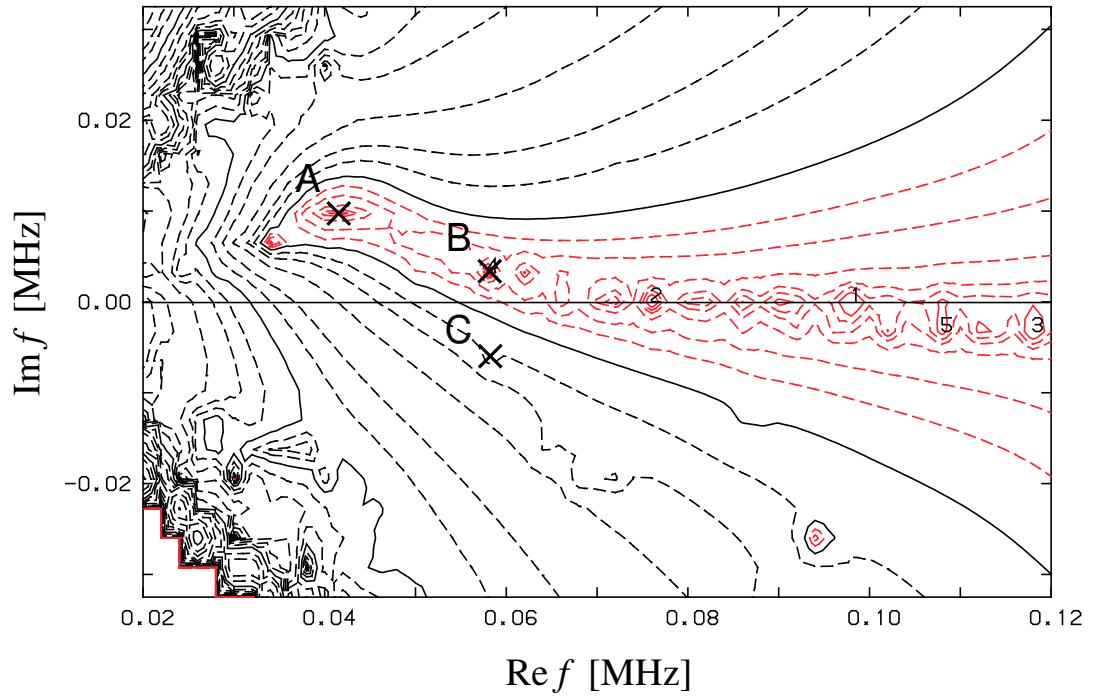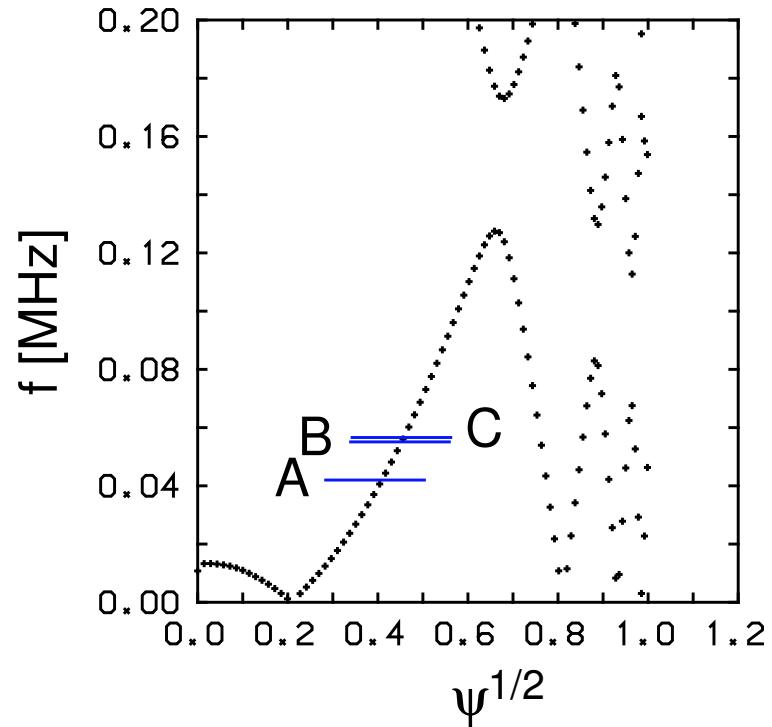
$$(f_{\mathrm{r}}, f_{\mathrm{i}}) = (41.8, 8.1)\,\mathrm{kHz} \quad (f_{\mathrm{r}}, f_{\mathrm{i}}) = (57.7, 3.6)\,\mathrm{kHz} \quad (f_{\mathrm{r}}, f_{\mathrm{i}}) = (58.0, -6.0)\,\mathrm{kHz}$$

RSAE $\qquad (q_{\min} = 2.6)$

- Without EP
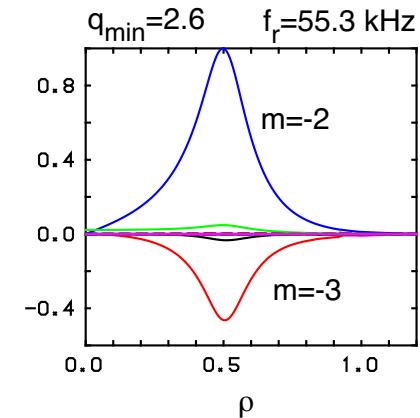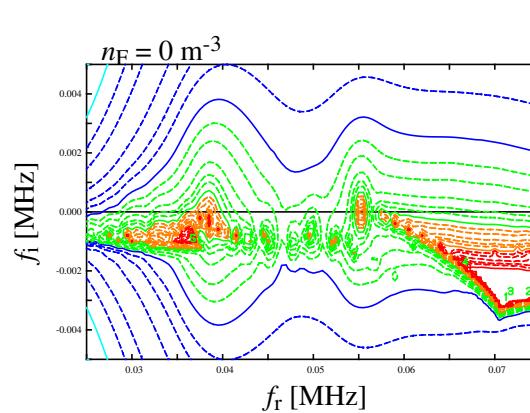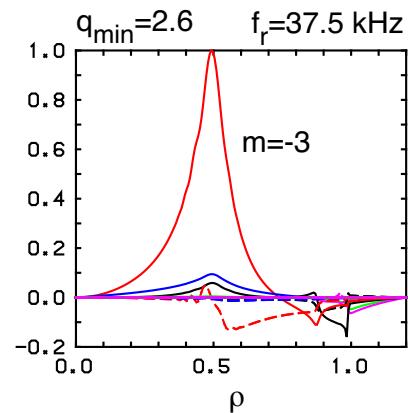
- With EP

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

  $360\,\mathrm{keV}$

  $0.5\,\mathrm{m}$
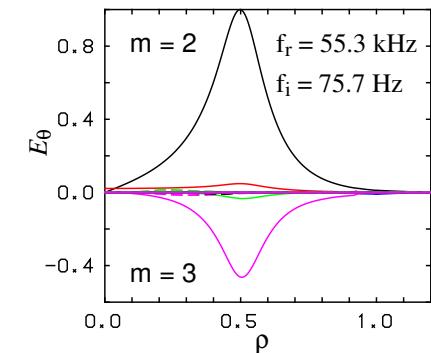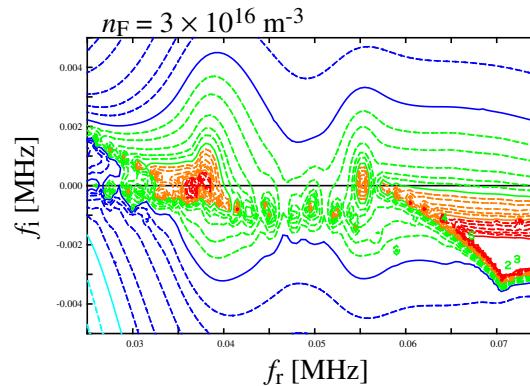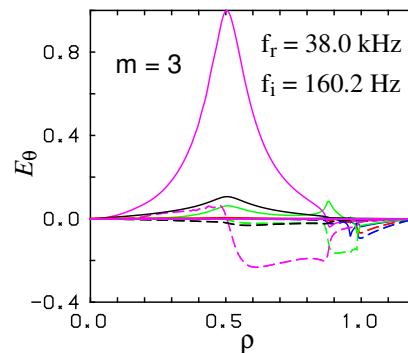
- With EP

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

  $360\,\mathrm{keV}$

  $0.5\,\mathrm{m}$

-          **TAE**

                RSAE

- **RSAE**   **GAE**

- **RSAE** $\ell + 0.5 \lesssim q_{\min} \lesssim \ell + 0.7$

-

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  -         **RSAE**

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