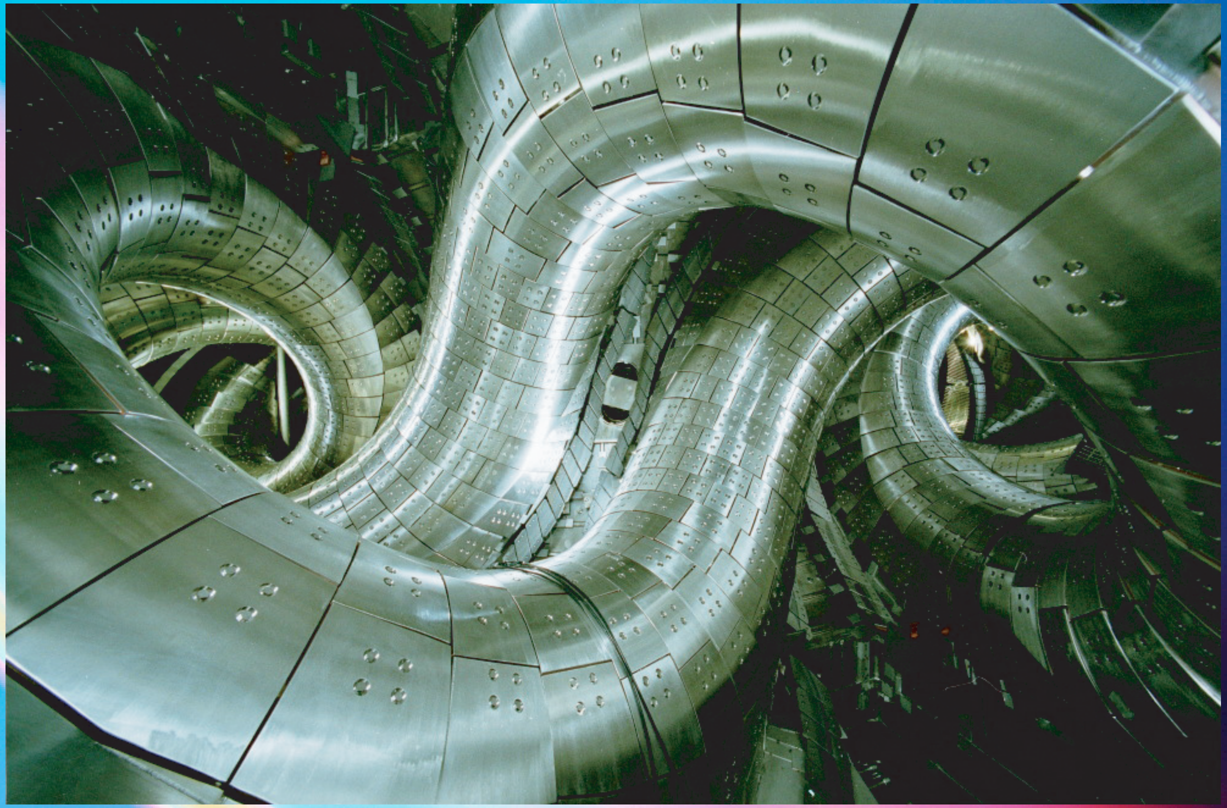
Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas

S. Yamamoto
Institute of Advanced Energy, Kyoto University

K. Toi, N. Nakajima, S. Ohdachi,
S. Sakakibara, K.Y. Watanabe, M. Osakabe
and LHD Experimental Group
National Institute for Fusion Science

C. Nührenberg
Max-Planck-Institut für Plasmaphysik,
IPP-Euratom Association

S. Murakami
Graduate School of Engineering, Kyoto University



第７回 若手科学者によるプラズマ研究会 「燃焼プラズマに向けた研究の現状と展望」
平成16年3月17−19日　日本原子力研究所　那珂研究所

Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas
- content -

Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas
- content -

Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas
- Introduction -

In a certain condition, α particles resonate with the MHD modes existing in the plasma

↓

MHD modes with the large amplitude of B, E are excited

↓

MHD mode would enhance the α particle loss

↓

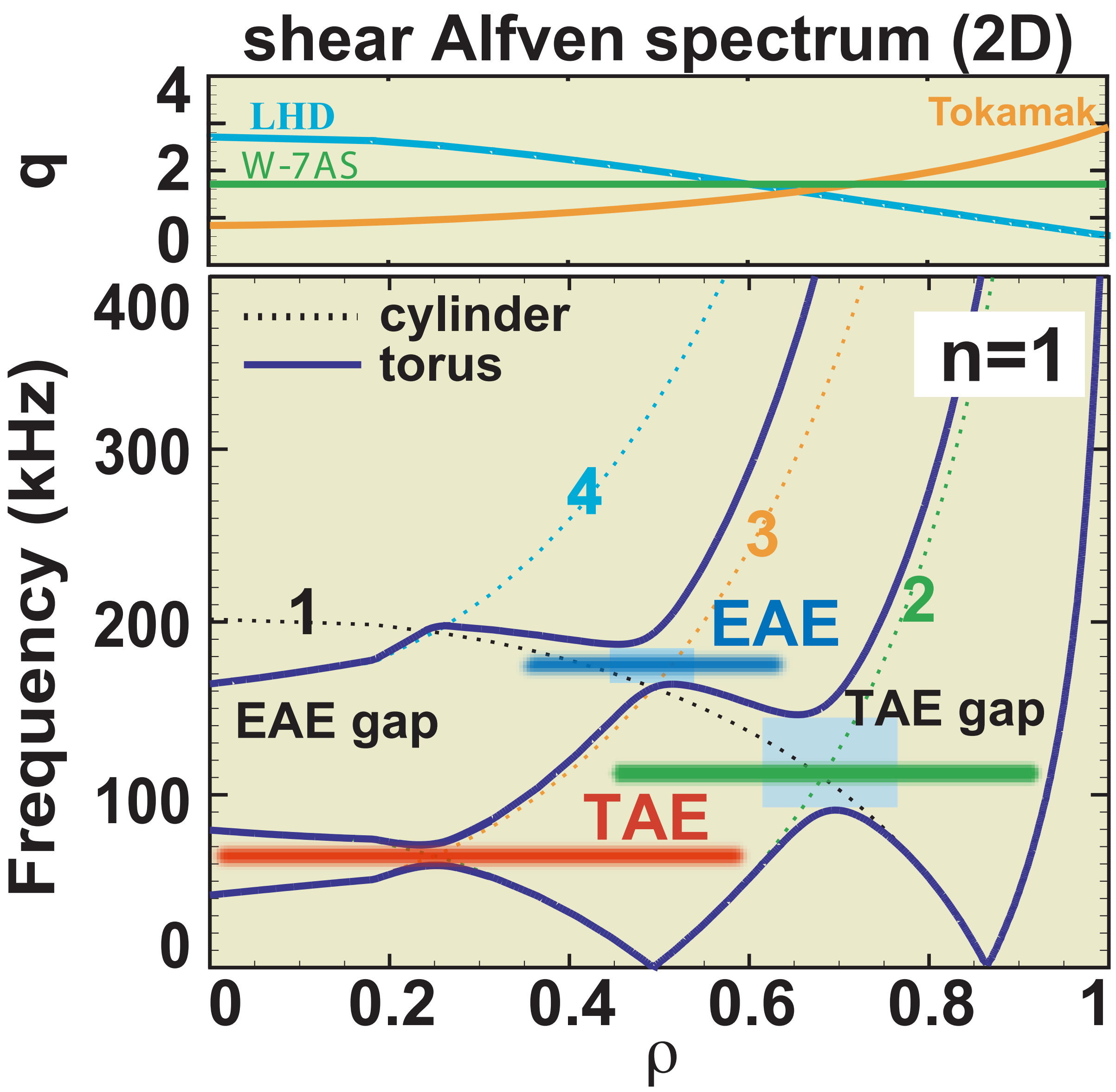
This would quench fusion burn and ejected α particles might lead to significant damage of the first wall of a fusion device

Energetic-ion-driven MHD instabilities such as Alfvén eigenmode (AE) are extensively studied in many toroidal device

- The energetic-ion-driven Alfvén eigenmodes (AEs) such as
  - toroidicity-induced AEs (TAEs)
  - helicity-induced AEs (HAEs)

  are observed in the NBI-heated LHD plasmas.
- It is important to clarify the stability and effects of energetic-ion-driven AEs because these mode may enhance the particle transport in the helical type fusion reactor.

Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas
- Alfvén eigenmodes and their excitation -



The **rotational transform increases toward the plasma edge** in contrast with the standard tokamak configuration.

➜ shear Alfvén spectrum exhibits different characters for those in tokamaks.

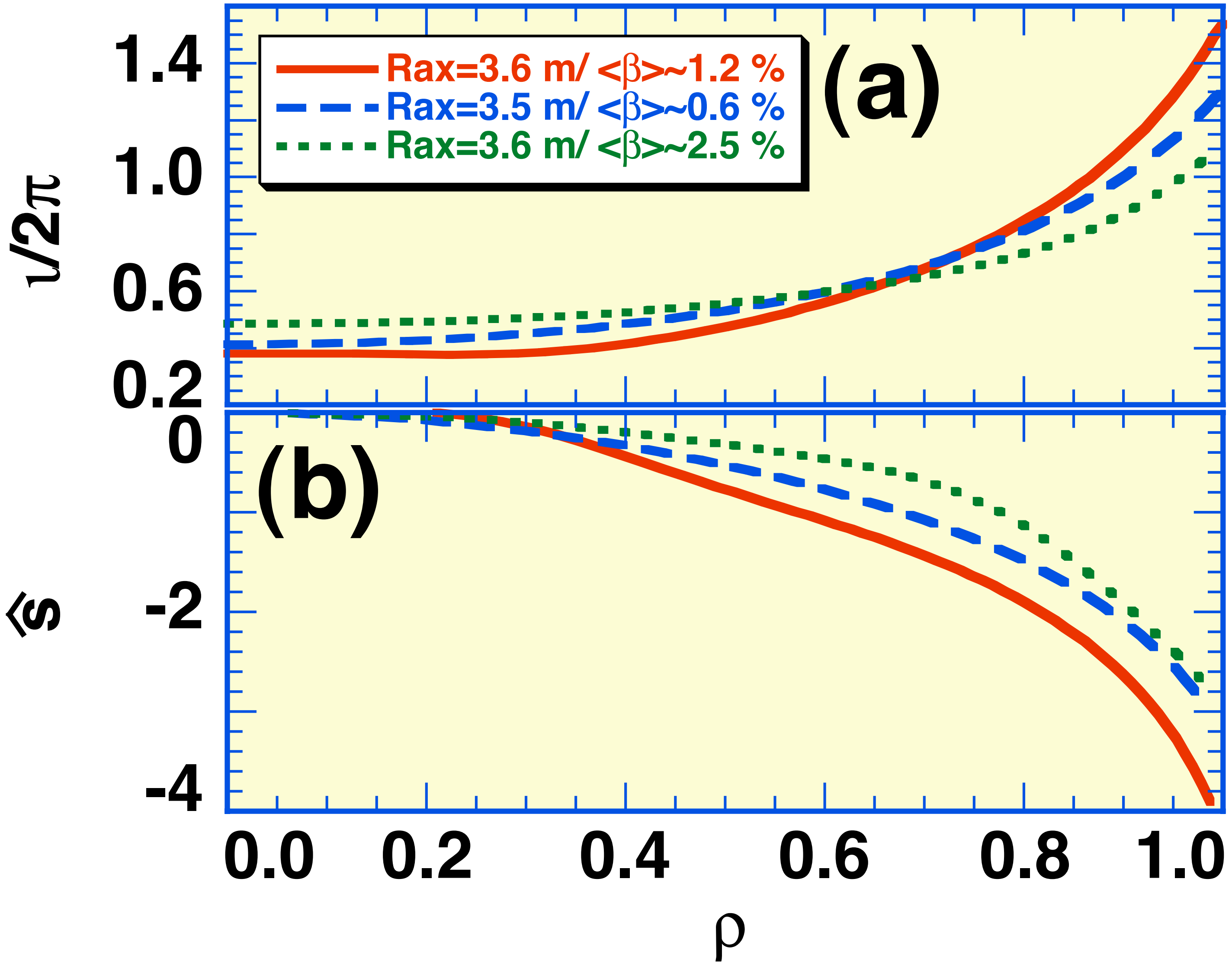
- The variation of magnetic field strength leads the mode coupling of Fourier harmonics.
  ➜ **The formation of frequency gap in the shear Alfvén spectrum**
  - TAE gap : $\varepsilon_{(1,0)}(\cos\theta)$
  - HAE gap : $\varepsilon_{(2,1)}(\cos 2\theta - 10\sin\varphi)$
- Alfvén eigenmodes can exist in these gaps.
- Driving term :
  - gradient of energetic ion density
- Damping term :
  - **continuum damping**
  - Landau damping
  - radiative damping ...
- TAE frequency: $f_{\mathrm{TAE}} = \dfrac{v_{\mathrm{A}}\iota_{\mathrm{TAE}}}{4\pi R}$
- TAE gap position: $\iota_{\mathrm{TAE}} = \dfrac{n}{m+1/2}$

Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas
- content -

1. Alfvén eigenmode and its excitation
2. **Observation of Alfvén eigenmodes**
3. Parametric studies of Alfvén eigenmodes
4. Effects on the ion transport caused by TAEs
5. Conclusion

Observation of Alfvén eigenmodes

- magnetic configuration -



I. *R*ax=3.6 m with high magnetic shear (<β>~1.4 %)

➜ typically two TAEs

II. *R*ax=3.5 m with moderate magnetic shear (<β>~0.6 %)

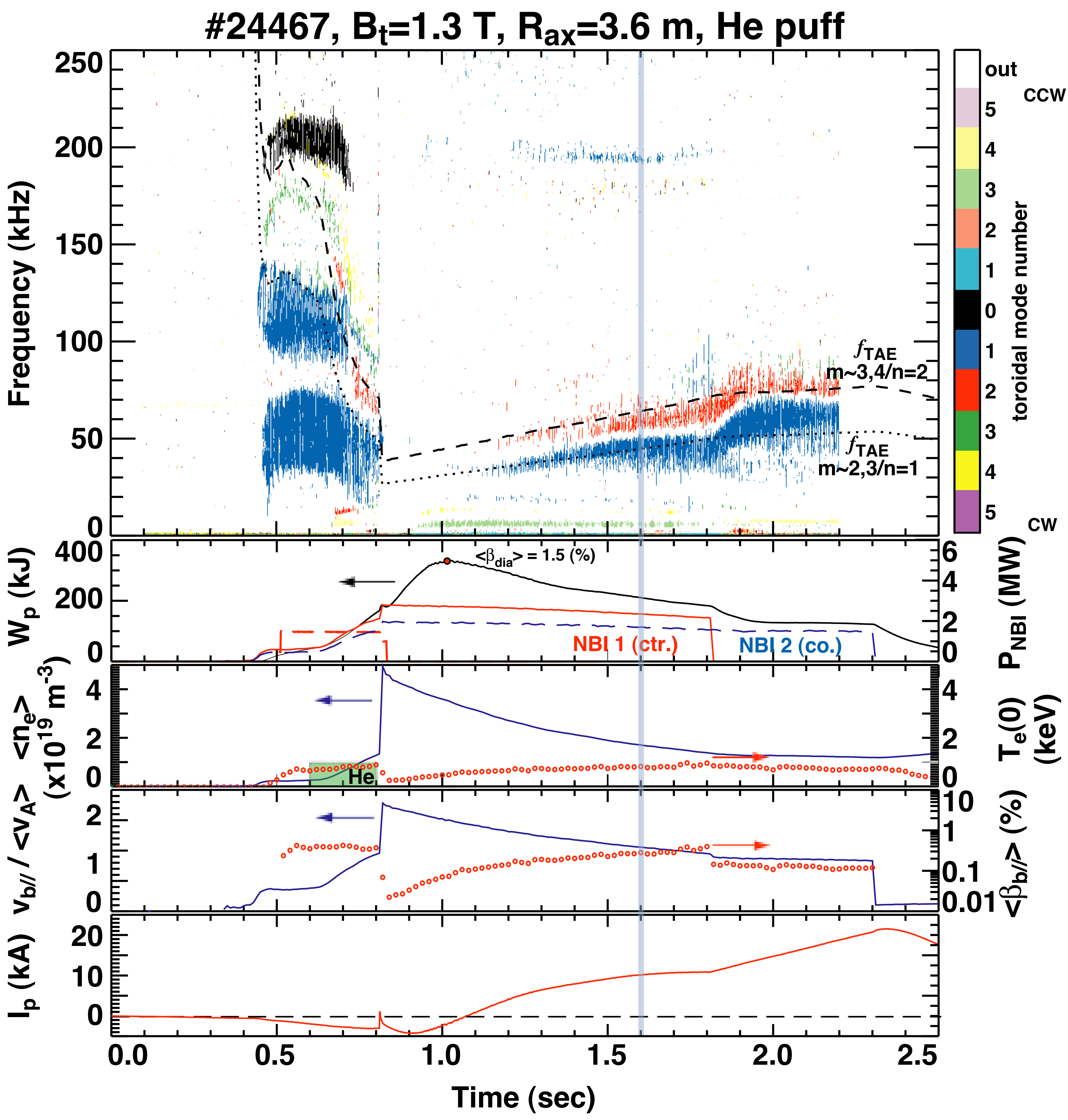
➜ a number of G-TAEs

III. High β of *R*ax=3.6 m with weak magnetic shear (<β>~2.5 %)

➜ a number of bursting G-TAEs

Observation of Alfvén eigenmodes (R_{ax}=3.6 m)

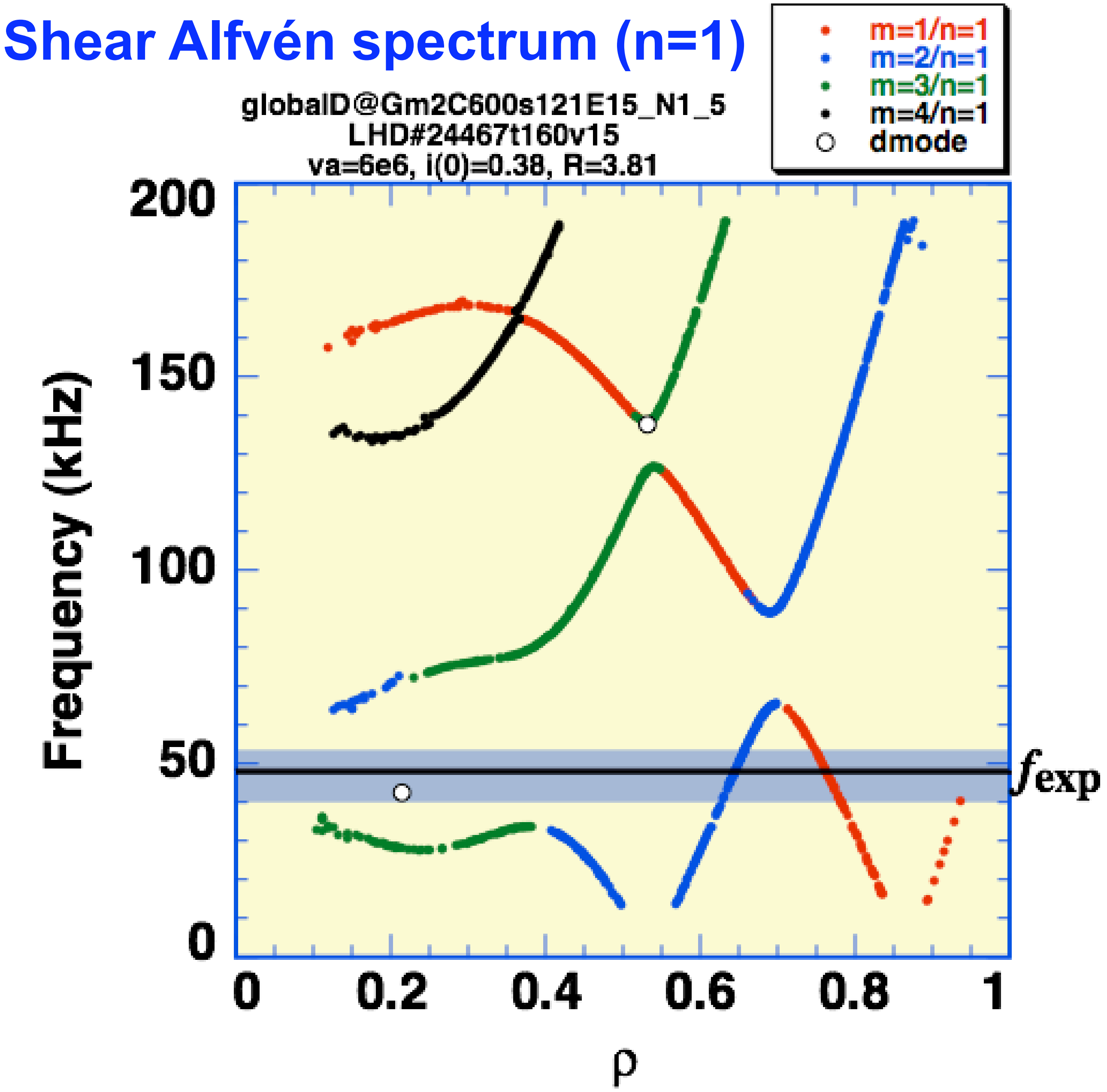
- typical result -

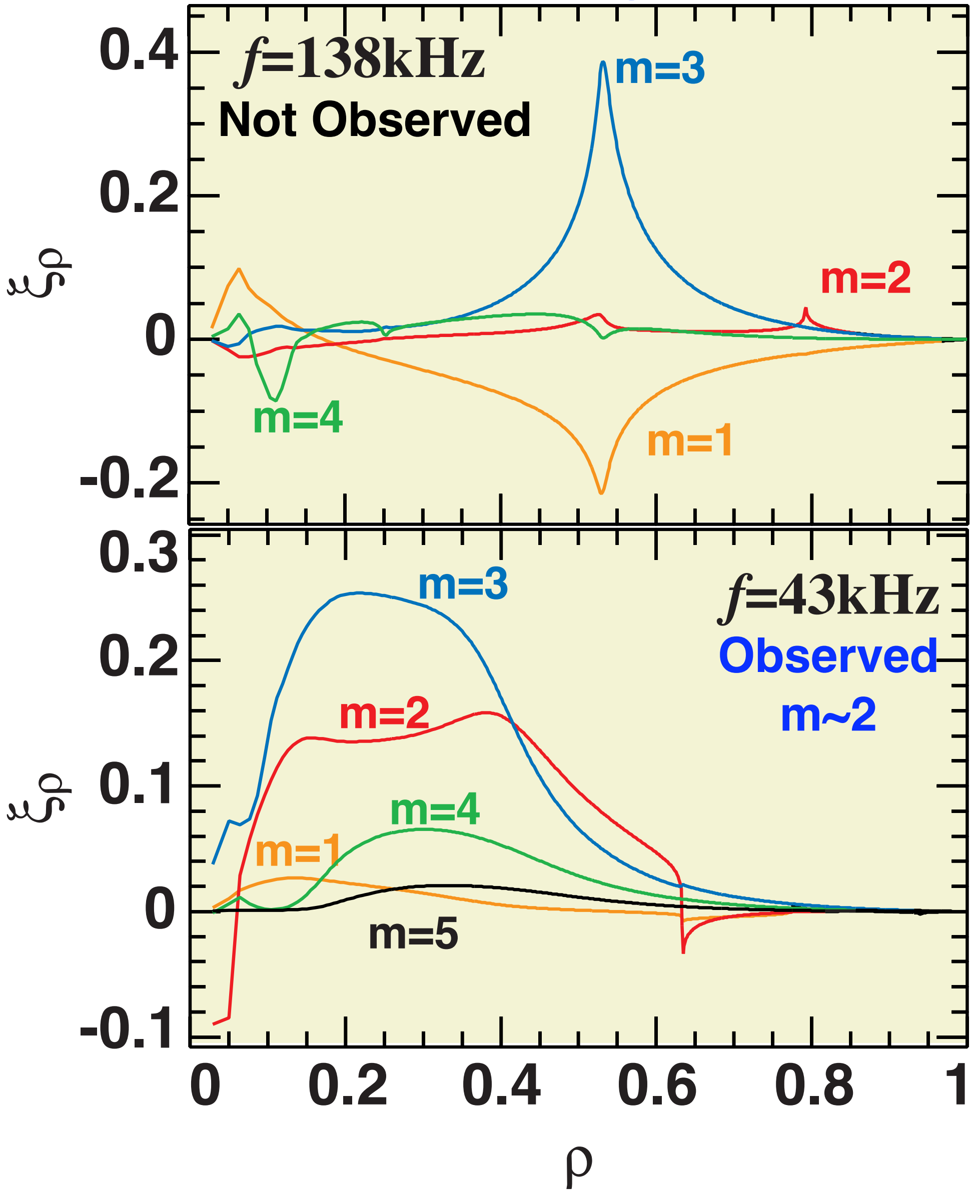


- Typical result of energetic ion driven AEs in the R_{ax} = 3.6 m plasma with high magnetic shear.
- *m*~2/*n*=1 mode
  Core-localized TAE (C-TAE)
  dotted line: f_{TAE} (m=2,3/n=1)
- *m*~3/*n*=2 mode
  Global TAE (TAE)
  broken line: f_{TAE} (m=3,4/n=2)
- Global AEs (GAEs) with n = 0 and energetic particle modes (EPMs) with n = 1 are observed before t ~ 0.8 s.
- The mode transition of *m*~2/*n*=1 C-TAE to n = 1 GAEs is observed after t ~ 1.8 s.
  → temporal change of the rotational transform across $\iota/2\pi=0.4$ (m=2,3/n=1 TAE gap)

Observation of Alfvén eigenmodes (R_{ax}=3.6 m)

- comparison between fexp and global mode analysis (Nf=1) -

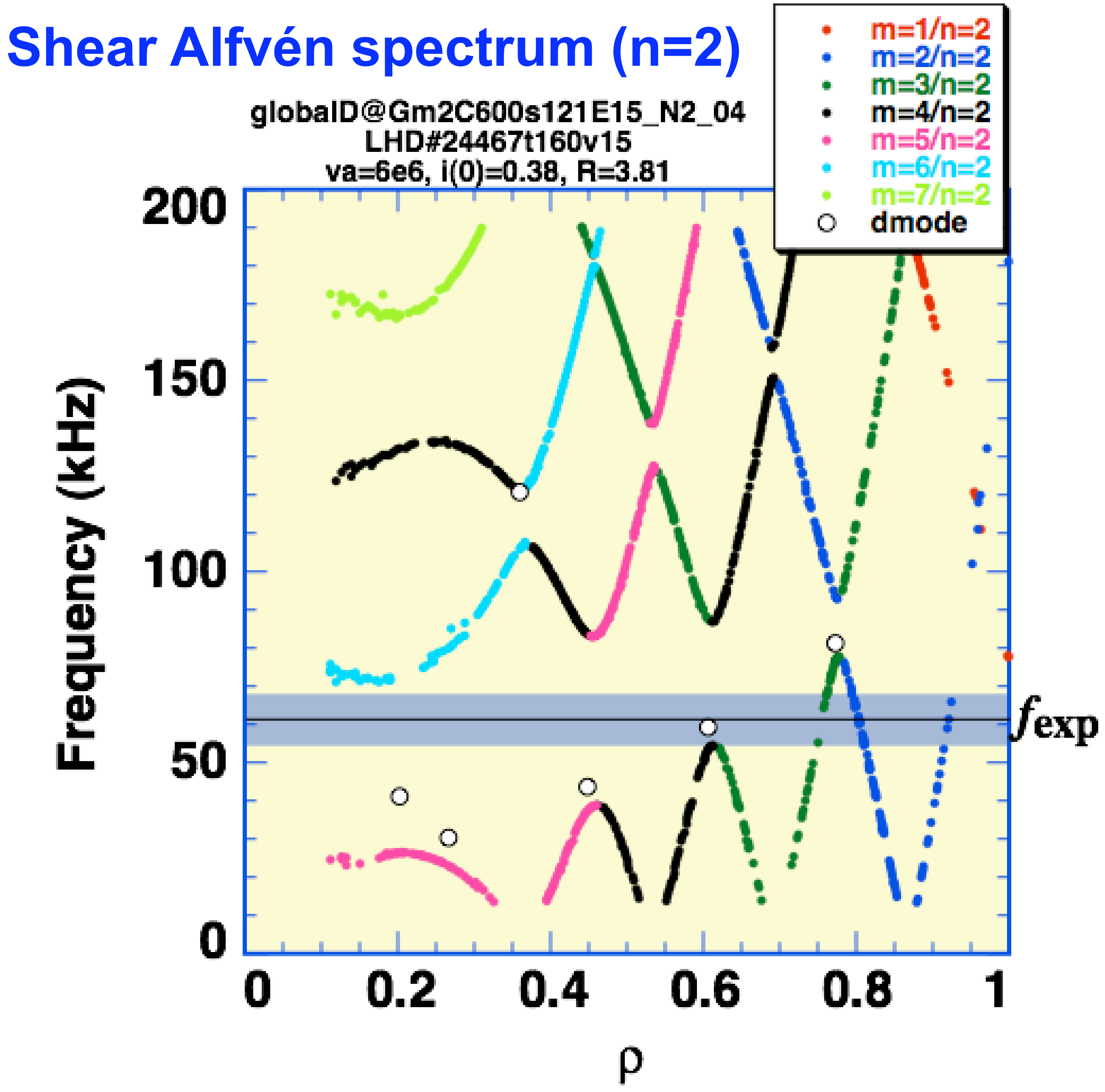

Shear Alfvén spectrum (n=1)


Profile of eigenmode

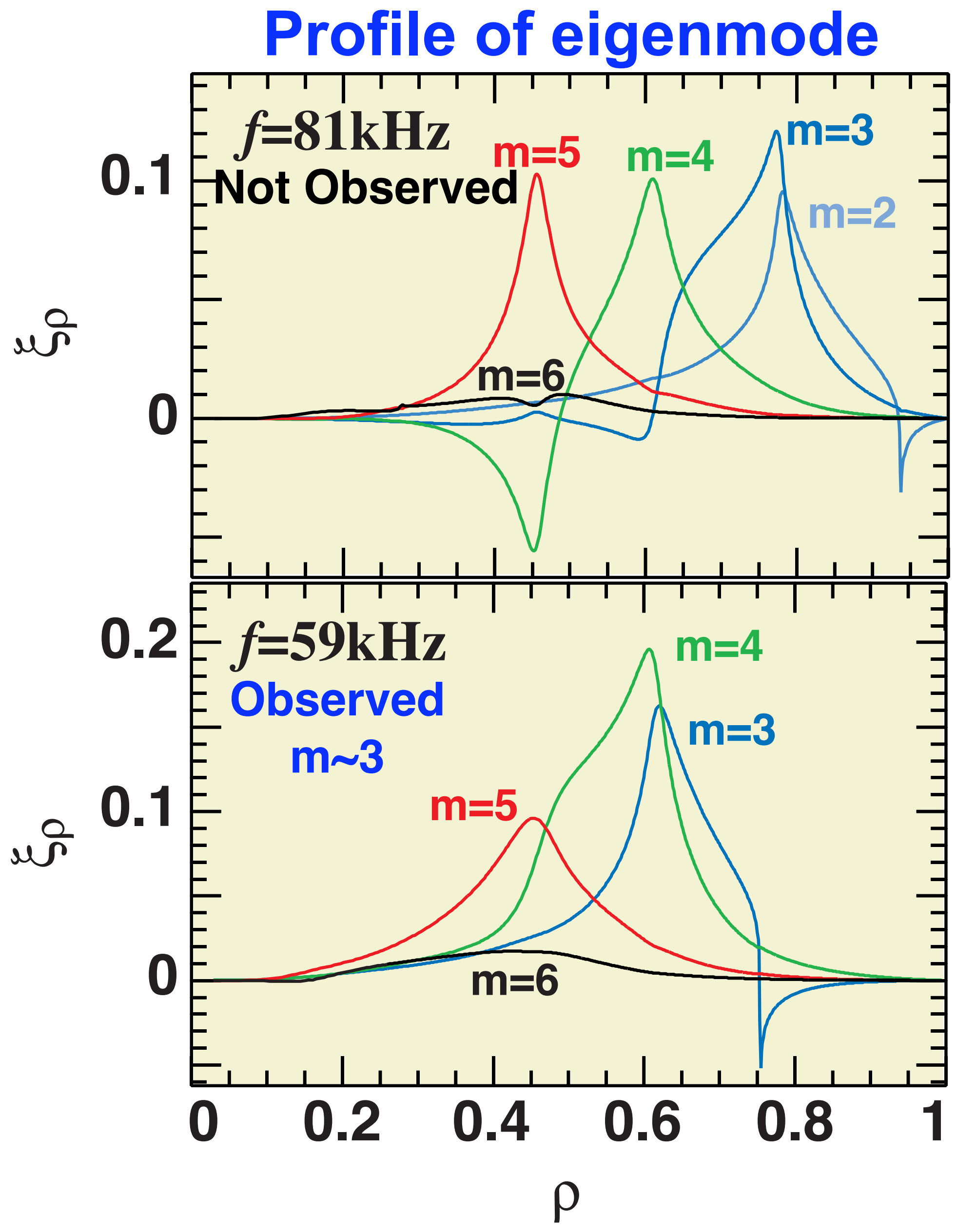
- We compared these observed frequencies at *t* ~ 1.6 s with the global mode analysis.
- The discrete mode (open circle) with even parity existing in the core plasma region with weak magnetic shear, is found.
- The frequency of discrete mode agrees with that of observed mode. → **C-TAE**

Observation of Alfvén eigenmodes (R_{ax}=3.6 m)

- comparison between fexp and global mode analysis (Nf=2) -



Shear Alfvén spectrum (n=2)

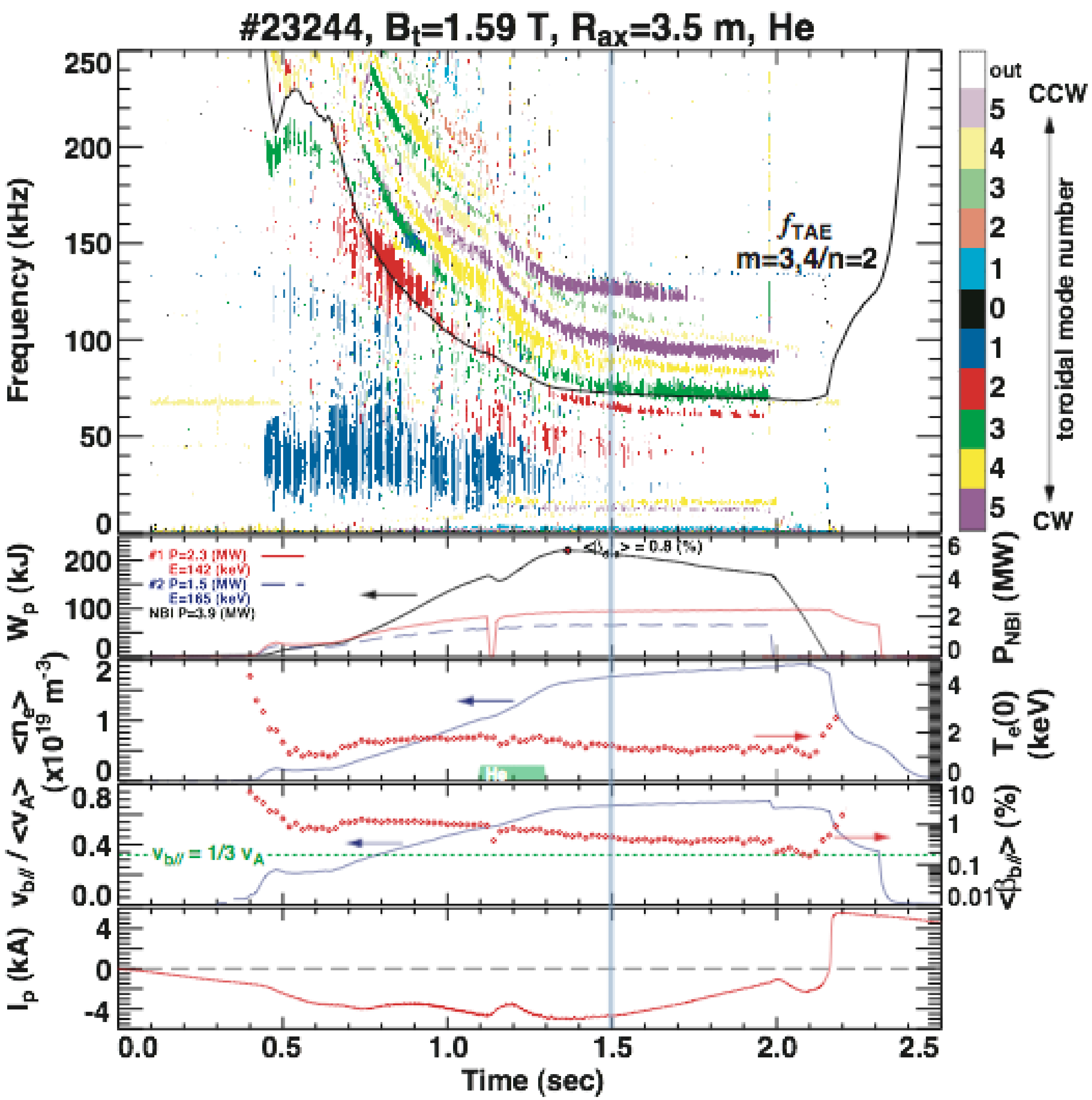


Profile of eigenmode

- A few TAEs, of which eigenfunction globally extends in whole plasma, are found in the TAE gap.
- The observed mode frequency is close to the TAE with the frequency $f_{CAS3D} \sim$ 59 kHz.

Observation of Alfvén eigenmodes (R_{ax}=3.5 m)

- typical result -



- **Typical result of energetic ion driven AEs in the *R*ax = 3.5 m plasma.**
  ➜ magnetic shear is approximately lower than that in *R*ax = 3.6 m

- **A number of the TAEs with *n* = 2~5 are simultaneously excited.**

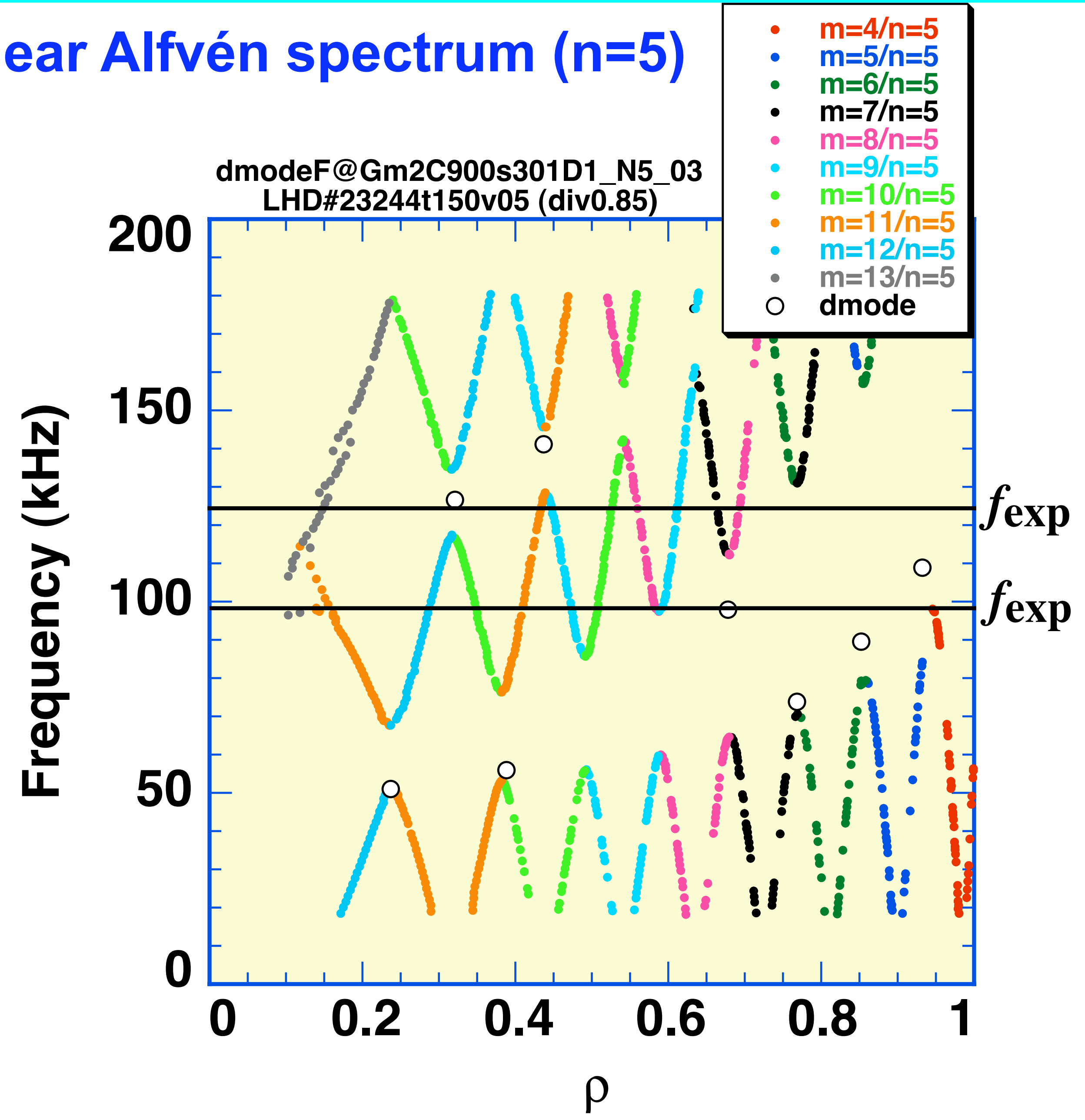
- **The frequency separation between neighboring modes**
  not by the Doppler effect,
  but by the TAE gap location.

- **The *n* = 5 mode (125 kHz at 1.5 s) is though to be ellipticity induced AE (EAE).**
  ➜ excited in the plasma core region (ρ < 0.5)

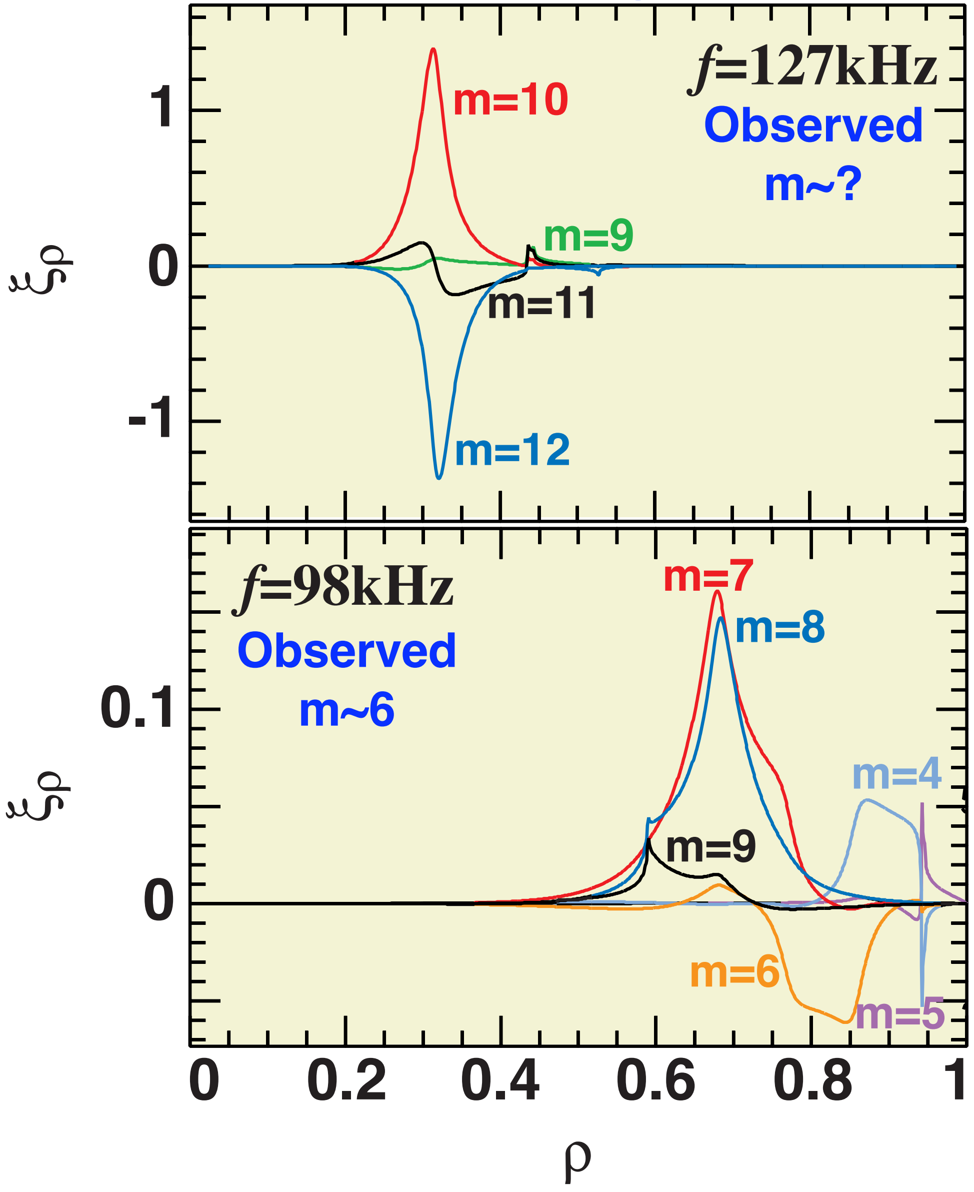
Observation of Alfvén eigenmodes (R_{ax}=3.5 m)

- comparison between fexp and global mode analysis (Nf=5) -

Shear Alfvén spectrum (n=5)



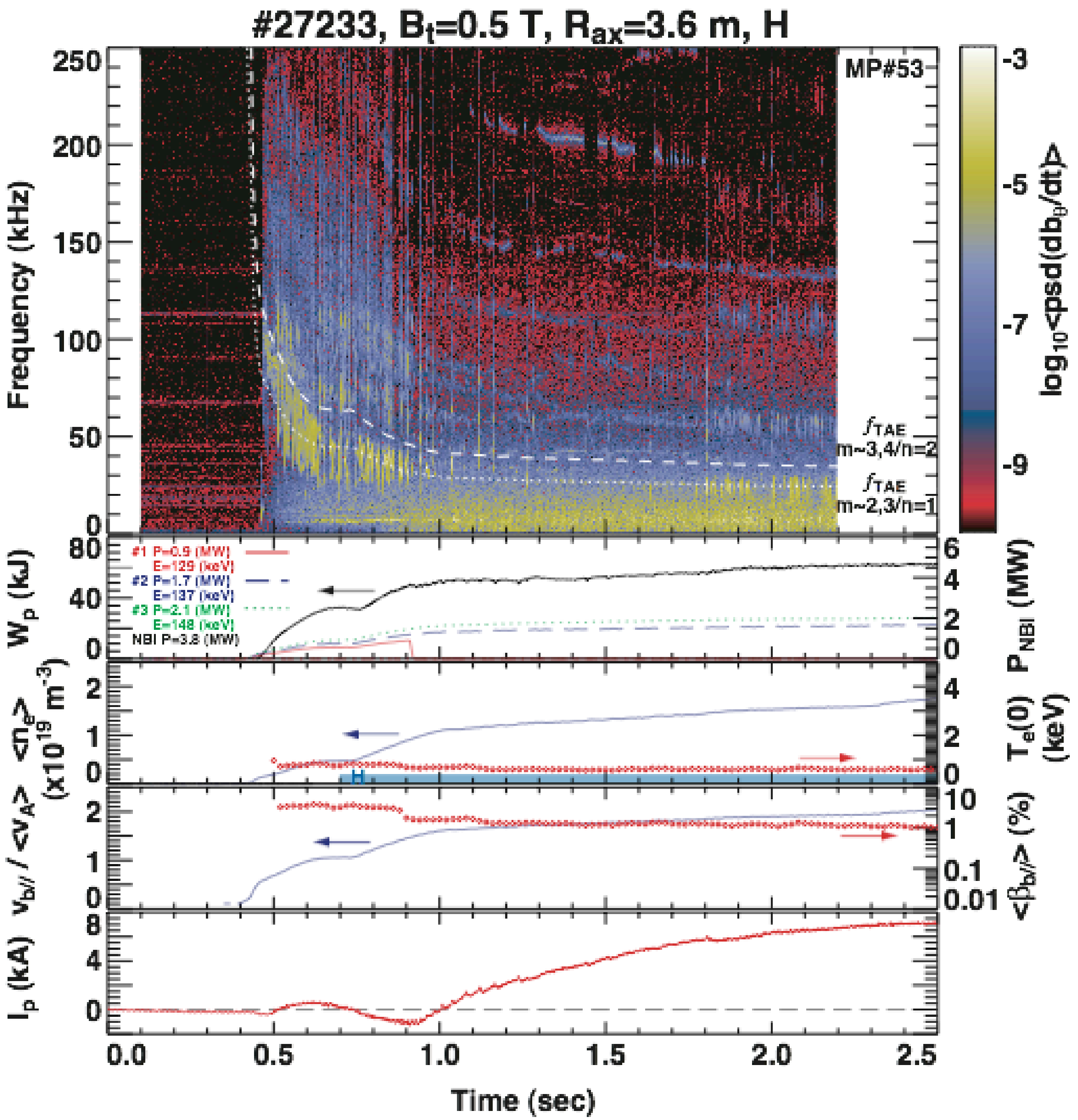
Profile of eigenmode

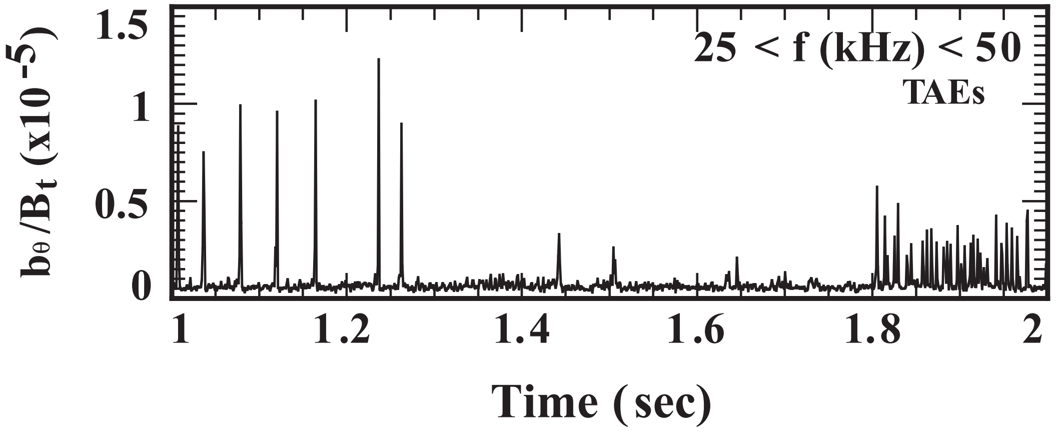


- In the case of *n*=5, the eigenfunction of TAEs localize in the gap.
  ➜ TAEs can avoid the continuum damping cause by the intersection of continuum.
- The gradient of energetic ion beta has a peak around ρ~0.6.
- Core-localized EAE with odd parity is also identified.

Observation of Alfvén eigenmodes (R_{ax}=3.6 m, β~2.5%)

- typical result -



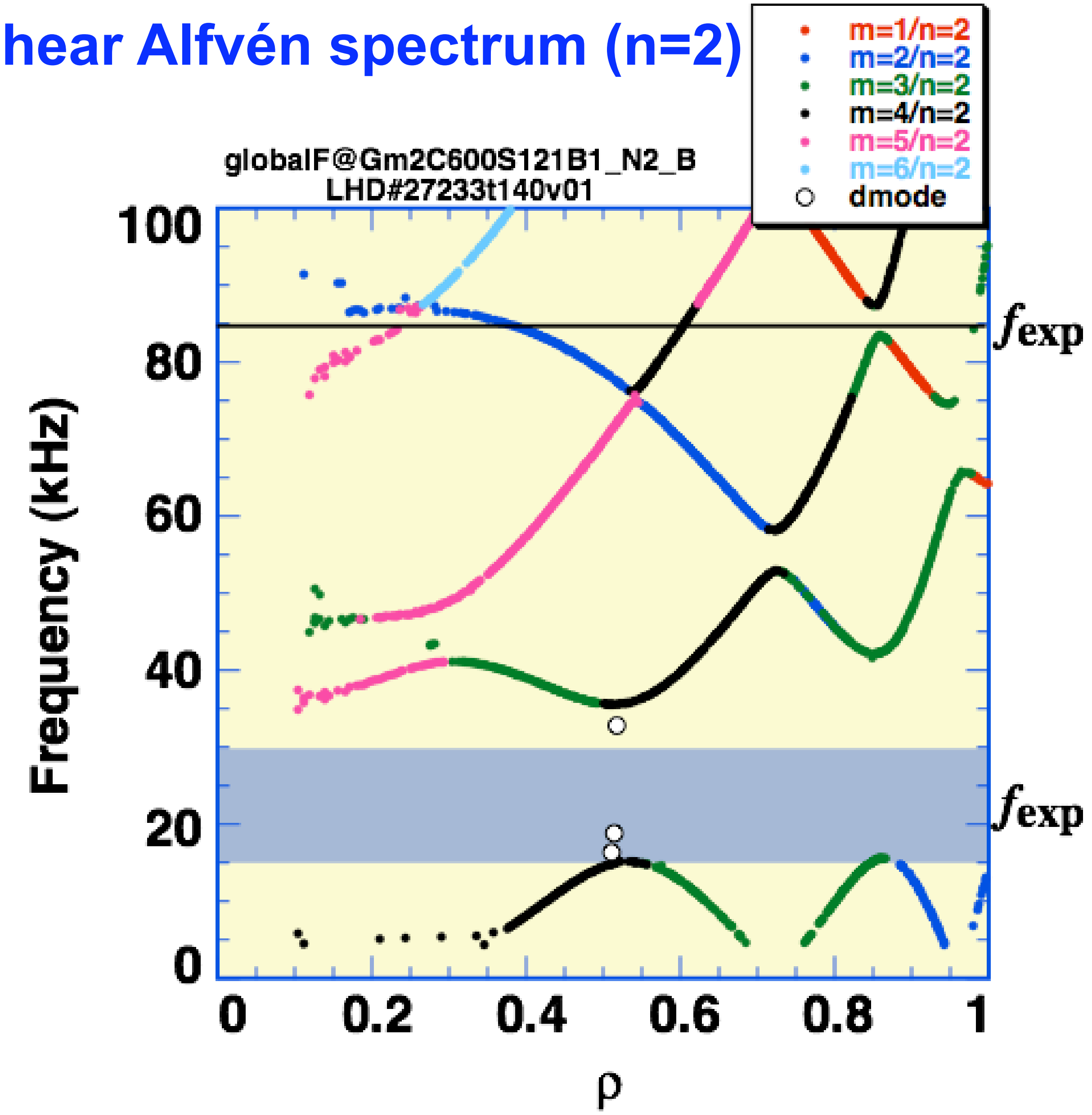


- **In the high β plasma (<β>~2.5%), a number of bursting TAEs are excited.**
- **The amplitude of magnetic fluctuation in the high β plasma is one or two order larger than that in the low β plasma.**
- **The drastic bursting TAEs may affect the energetic ion transport because some plasma parameters (e.g. Wp, NPA signals) simultaneously modulated with bursting TAEs.**

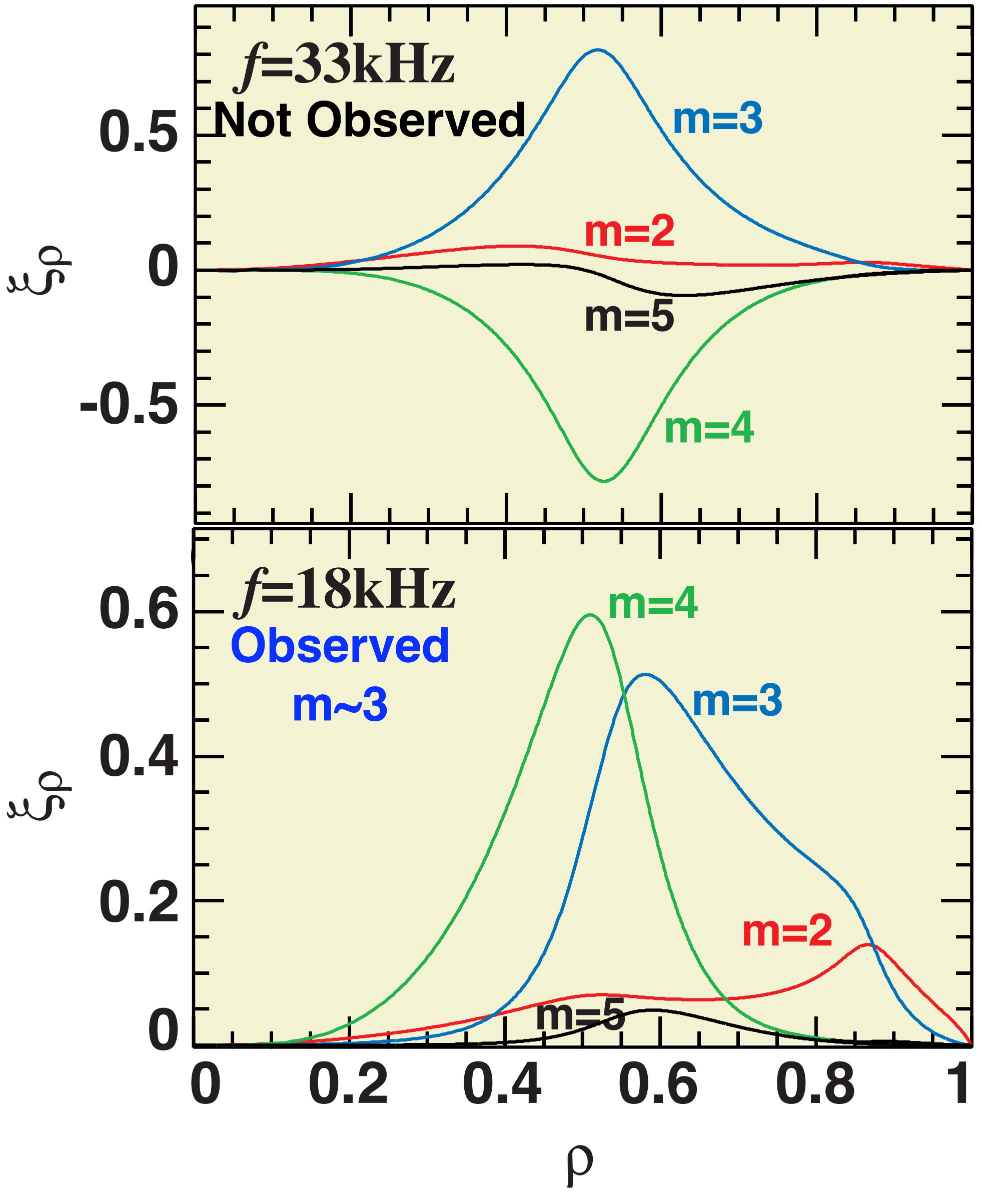
Observation of Alfvén eigenmodes (R_{ax}=3.6 m, β~2.5%)

- comparison between fexp and global mode analysis (Nf=2) -

Shear Alfvén spectrum (n=2)



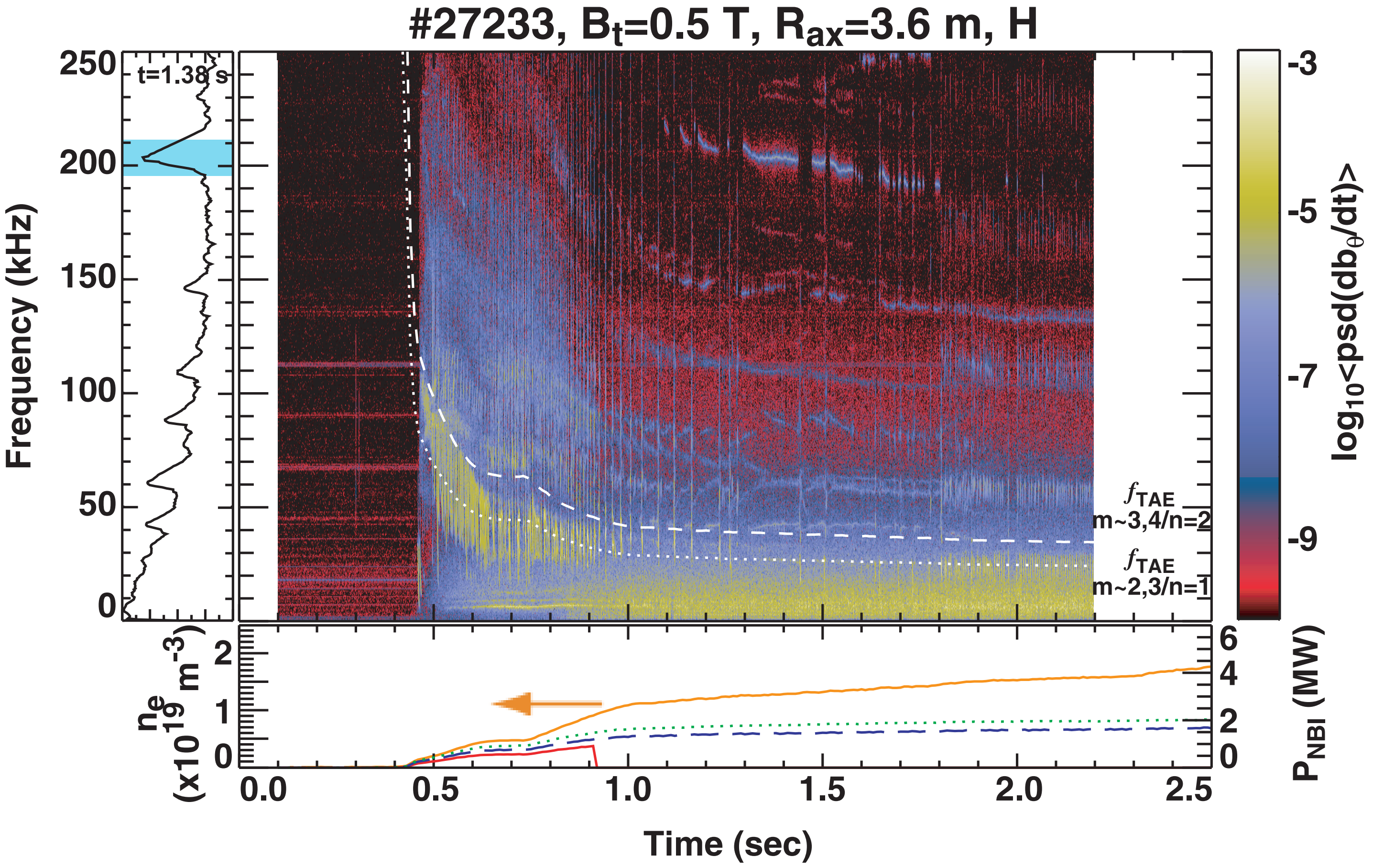
Profile of eigenmode

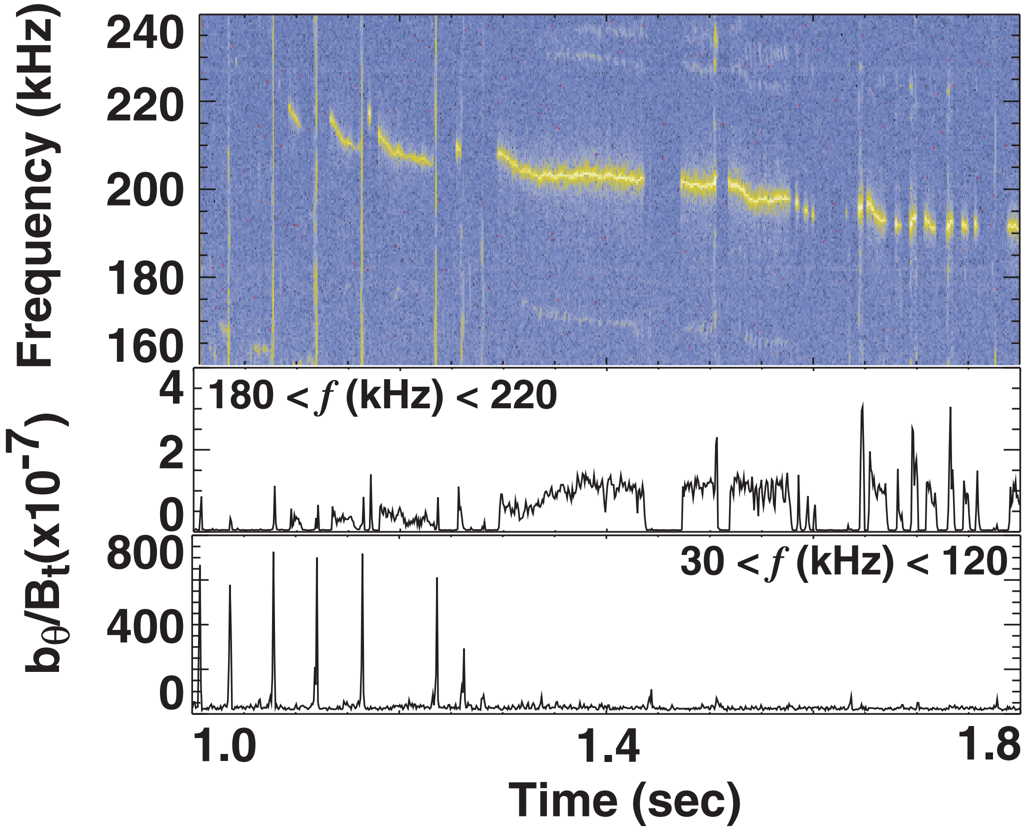


- Low magnetic shear and large Shafranov shift due to the finite β effects.
  ➜ The TAE gap is well aligned from the plasma core to the edge with fairly large gap width. (TAE gap width ~ $\varepsilon_t + d\Delta/d\rho$ [ε_t: toroidal ripple/Δ: Shafranov shift])
- The TAEs avoiding the continuum damping can exist.

Observation of helicity-induced AEs

- typical result -



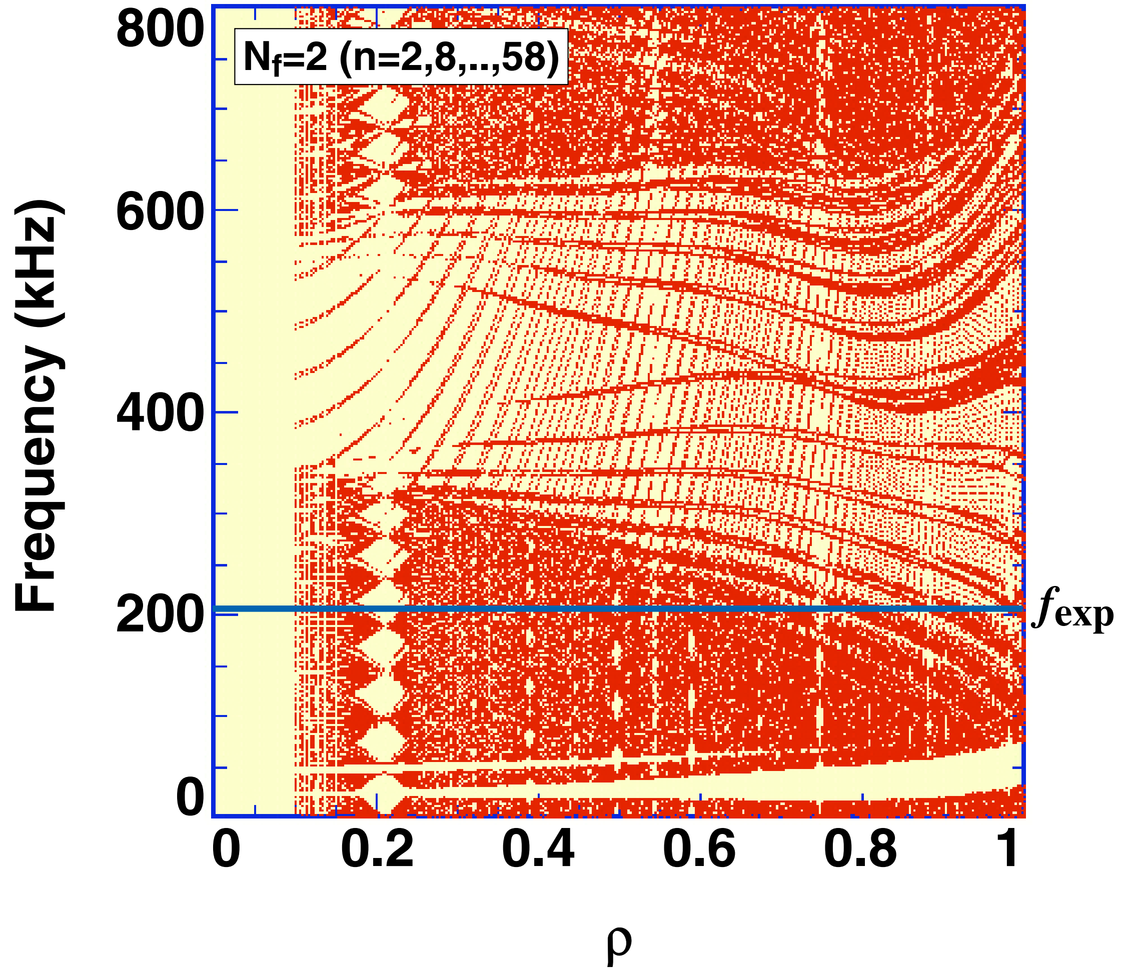


- The MHD instabilities, of which frequency is about eight times higher than that of observed TAE, are newly observed in NBI-heated plasmas of LHD at low magnetic fields ($B_t \leq 0.7$ T).
- The amplitude of magnetic fluctuation reaches $b_\theta/B_t \sim 10^{-7}$ (TAE:10^{-5}) at probe position.
- The frequencies of these modes are scaled with Alfvén velocity. → Alfvén eigenmode
- The mode suddenly disappears when the bursting TAEs are excited.

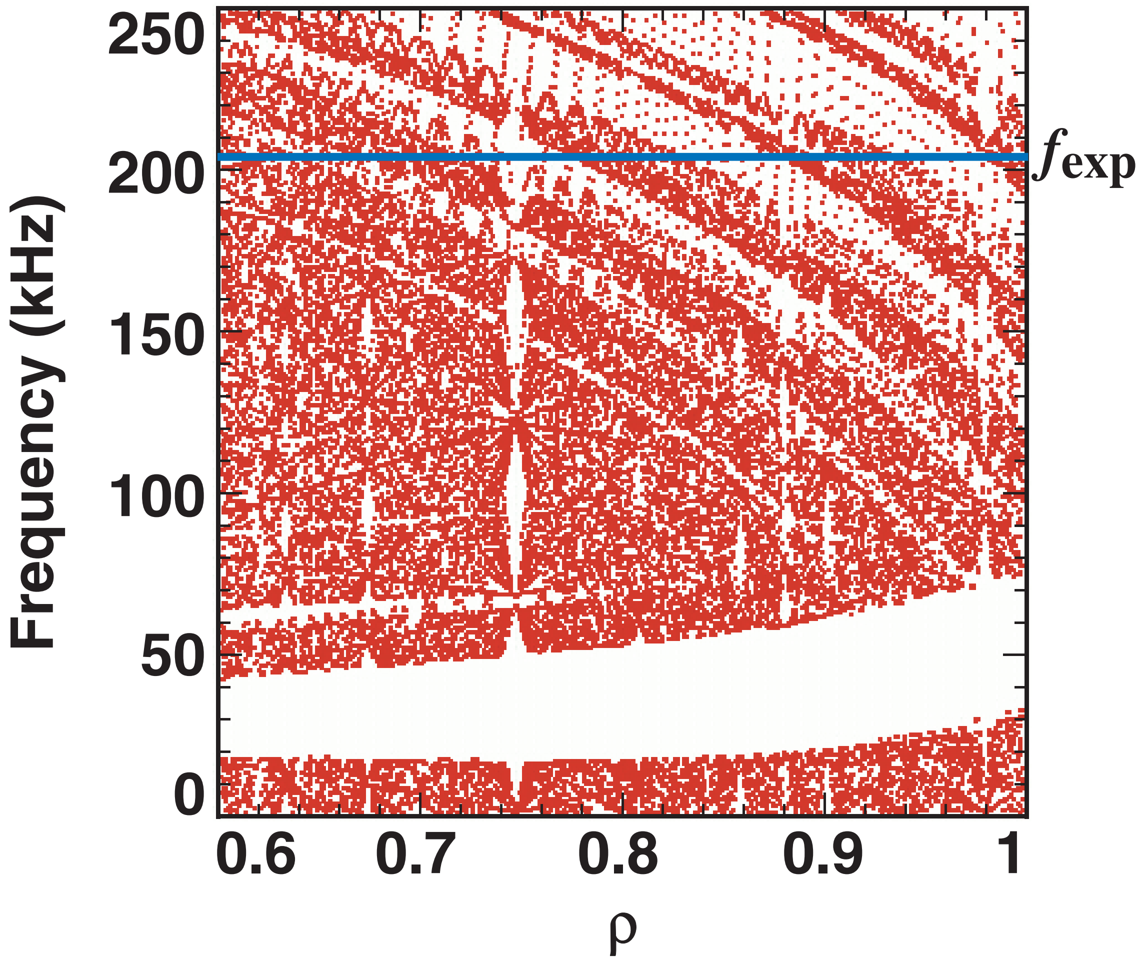
Observation of helicity-induced AEs

- comparison between fexp and shear Alfvén spectrum -

shear alfvén spectrum (Nf=2)



expanded view



- HAE gap is generated by the toroidal and poloidal mode coupling and the HAE can be excited by energetic ions in the HAE gap.

  ➜ New continua produced inside HAE gap may affect the low-n mode
- The observed frequency exists in the HAE gap at the plasma edge (ρ ~ 0.85).
- The profile of energetic ion pressure is predicted to be flat and its gradient has a peak near the plasma edge

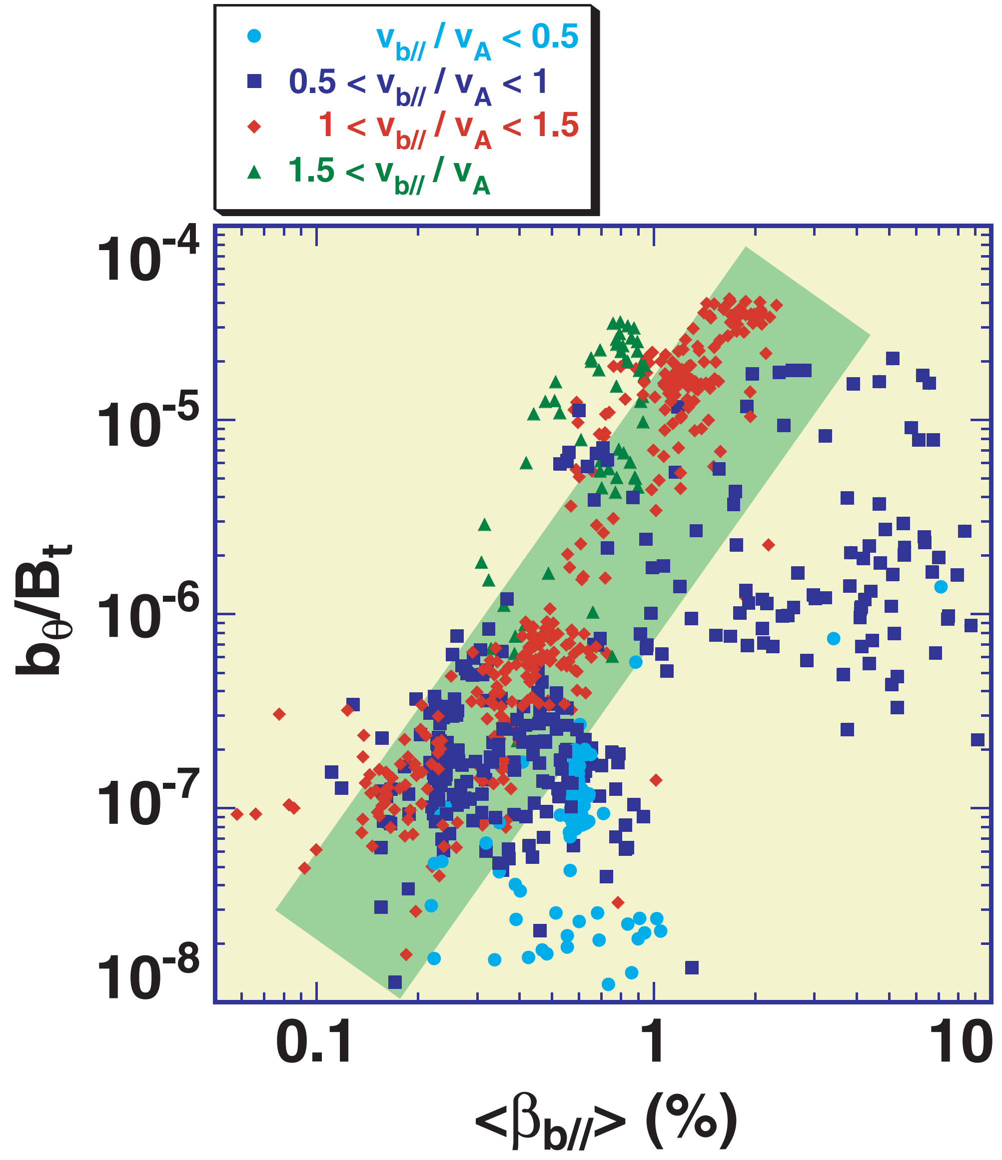
  ➜ growth rate of the mode might be large enough to overcome the damping

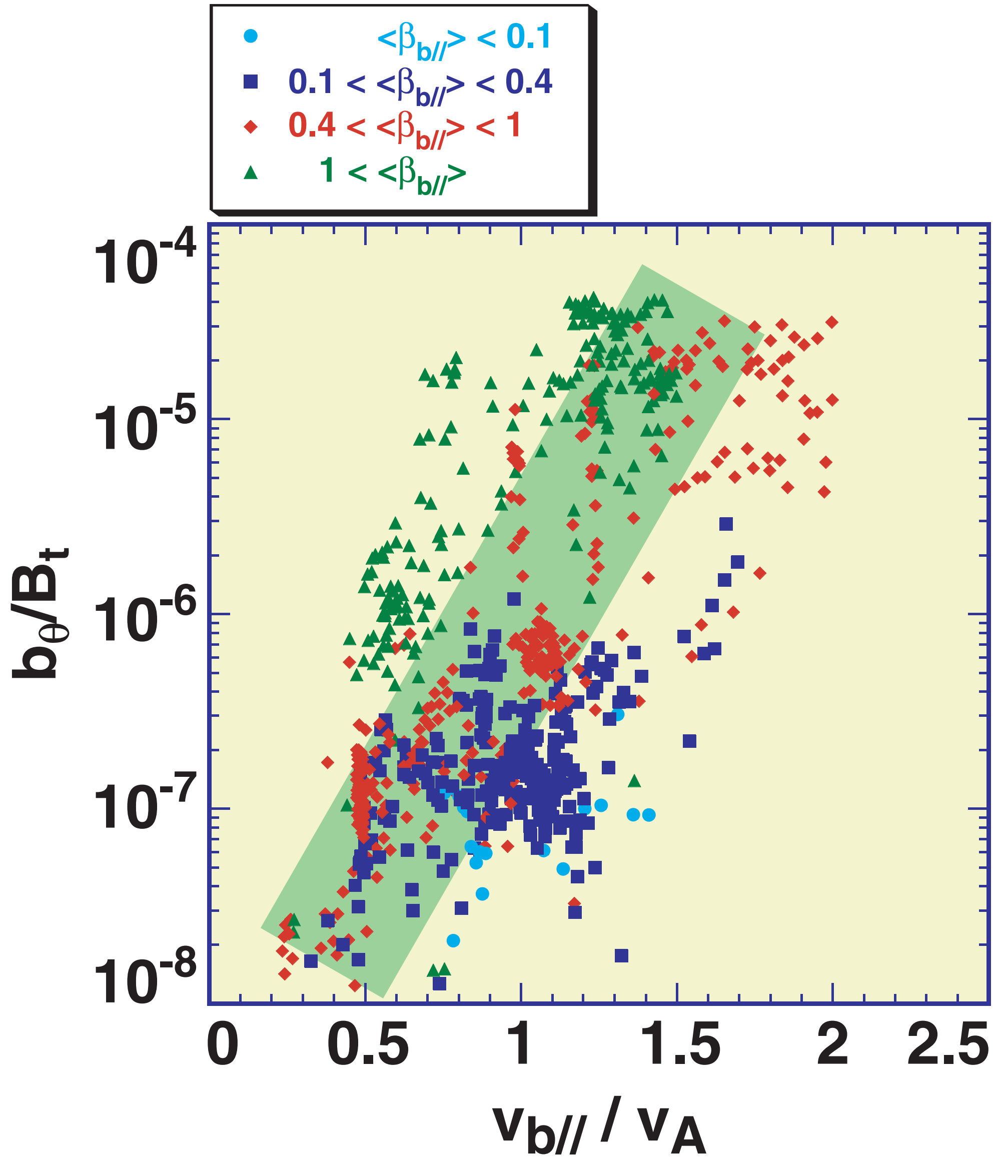
Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas
- content -

1. Alfvén eigenmode and its excitation
2. Observation of Alfvén eigenmodes
3. Parametric studies of Alfvén eigenmodes
4. Effects on the ion transport caused by TAEs
5. Conclusion

Parametric studies of Alfvén eigenmodes

- dependences of TAE fluctuation amplitude against $v_{b//}/v_A$ and $<\beta_{b//}>$ -



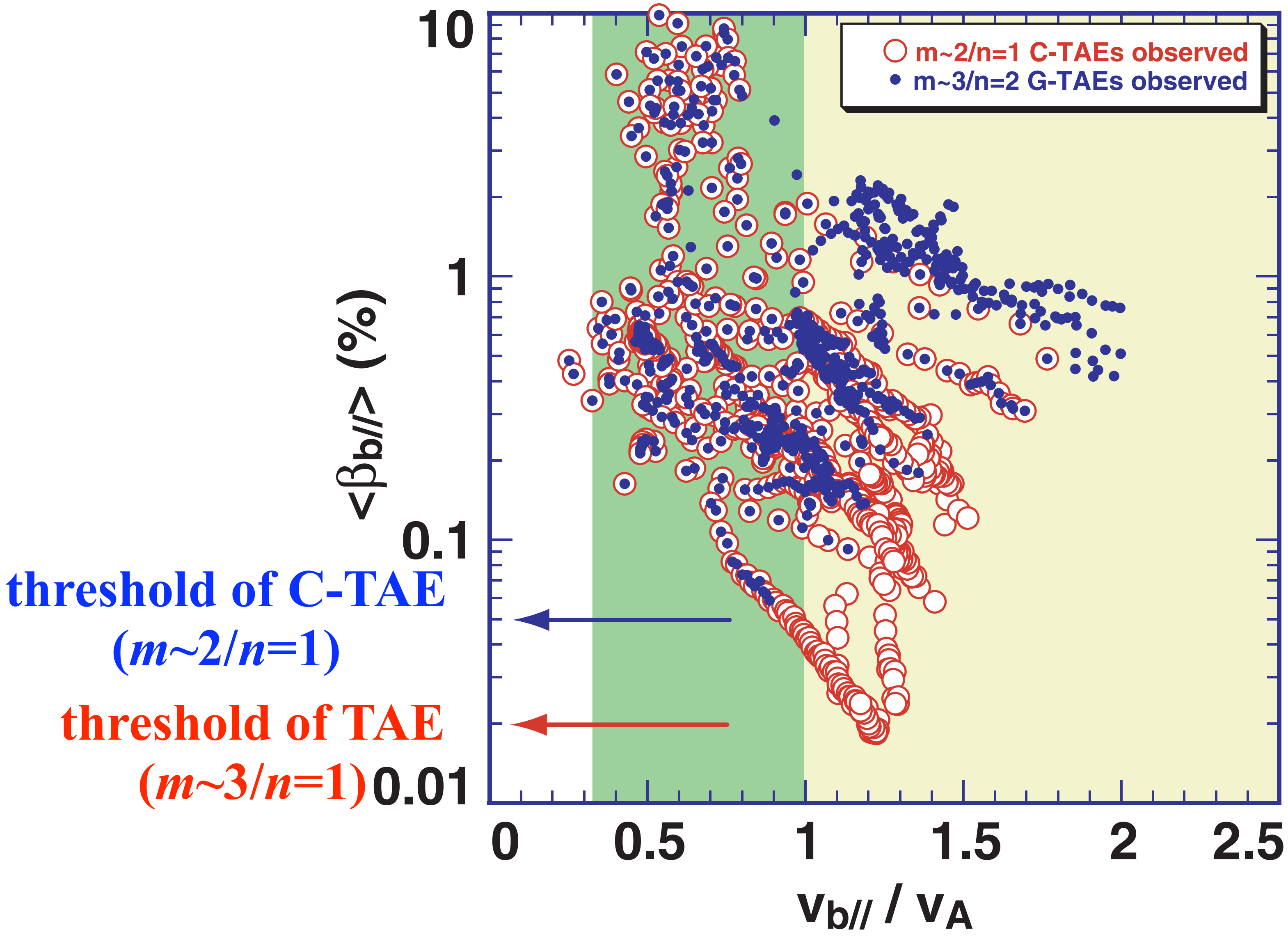


- Linear growth rate of TAE cause by energetic ions : $\gamma_L \sim \beta_{b//}(\omega_{*i}/\omega - 0.5)F(v_A/v_{b//})$

  $F(v_A/v_{b//})$ has a peak around $v_A/v_{b//} \sim 1$
- The fluctuation amplitude is rapidly increased with the increase in $<\beta_{b//}>$ and $v_{b//}/v_A$.
- The TAEs excited by the fundamental excitation ($v_{b//}/v_A >1$) are larger than sideband excitation ($0.33 < v_{b//}/v_A < 1$).

Parametric studies of Alfvén eigenmodes

- stability and resonance conditions of TAE -



threshold of C-TAE
(*m*~2/*n*=1)

threshold of TAE
(*m*~3/*n*=1)

- TAEs are observed in the region of $0.3 < v_{b//}/v_{A}/ < 2$.

  ➜ excited by the fundamental and sideband excitations.

- The thresholds with $<\beta_{b//}>$ are : *m*~2/*n*=1 core-localized TAEs : 0.02 %
  m~3/*n*=2 TAEs : 0.05 %

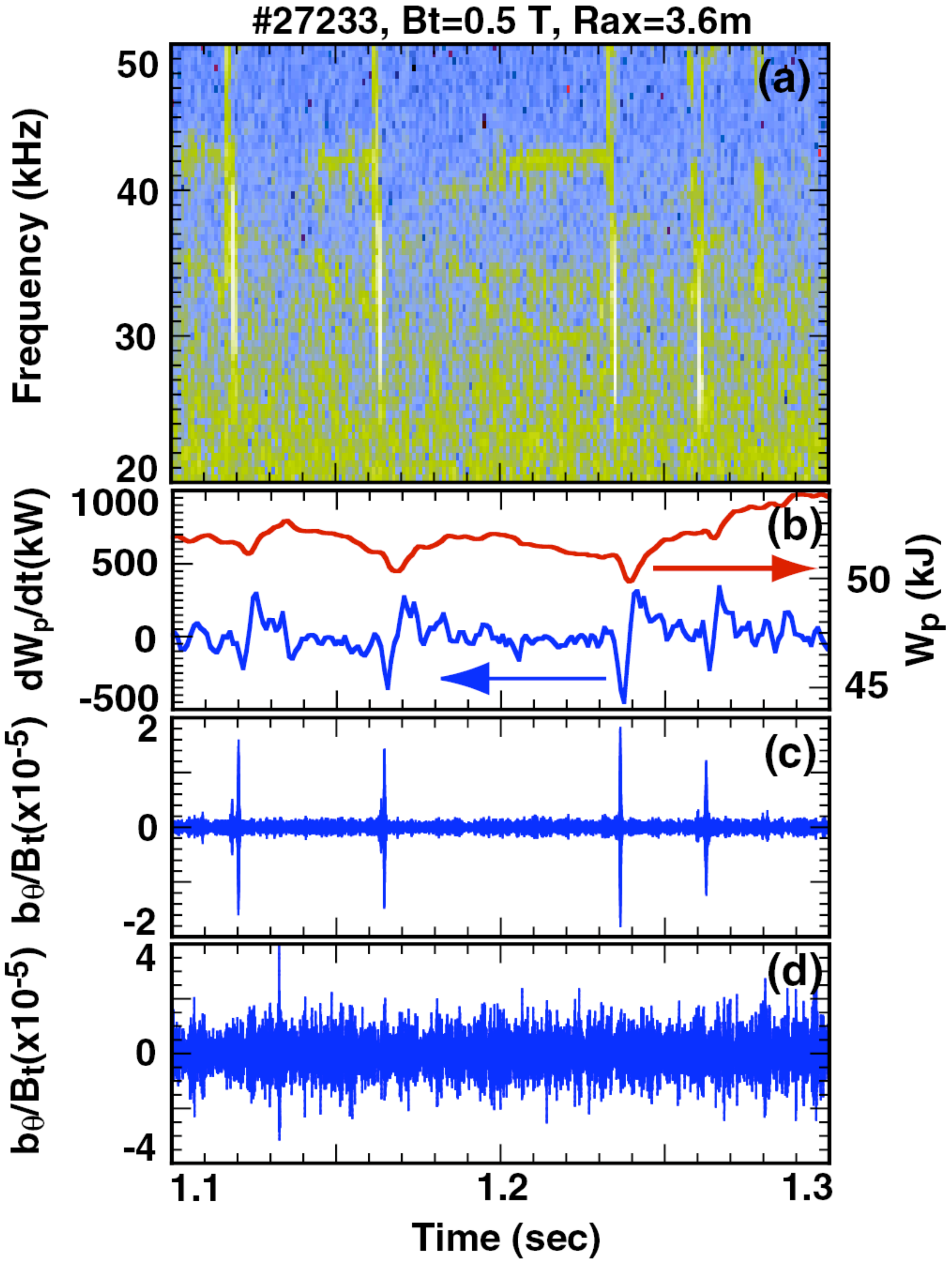
  ➜ related to the differences of the damping rate due to the continuum damping

Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas
- content -

1. Alfvén eigenmode and its excitation
2. Observation of Alfvén eigenmodes
3. Parametric studies of Alfvén eigenmodes
4. Effects on the ion transport caused by TAEs
5. Conclusion

Effects on the ion transport caused by TAEs

- typical result -



- **Some plasma parameters (e.g. Wp) simultaneously modulated with bursting TAEs.**
- **Power balance for energetic ions ($W_{b//}$) and bulk plasma energy (W_p)**

$$\frac{dW_{b//}}{dt} + \frac{W_{b//}}{\tau_s} + \frac{W_{b//}}{\tau_c} = P \qquad \frac{dW_p}{dt} + \frac{W_p}{\tau_E} = \frac{W_{b//}}{\tau_S}$$

- **The W_p and $W_{b//}$ are expressed as**

$$\frac{W_p}{W_p(0)} = \frac{\tau_*}{\tau_s} - \frac{\tau_*(\tau_s - \tau_*)}{\tau_s(\tau_E - \tau_*)}\exp\left(-\frac{t}{\tau_*}\right) + \frac{\tau_E(\tau_s - \tau_*)}{\tau_s(\tau_E - \tau_*)}\exp\left(-\frac{t}{\tau_E}\right)$$

$$\frac{W_{b//}}{W_{b//}(0)} \approx 1 - \exp\left(-\frac{t}{\tau_*}\right) \approx \frac{\tau_{MHD}}{\tau_c} \qquad \tau_* = \frac{\tau_s \tau_c}{\tau_s + \tau_c}$$

- **Time width of observed bursting TAE :**
  $\tau_{MHD} \sim$ 1 ms
- **Confinement time of energetic ions :**
  $\tau_c \sim$ 3 ms ($\tau_c \ll \tau^*$
  τ_{MHD}/τ_c = loss rate ~ 33%
- **Transient loss of energetic ions in the course of the slowing down**

Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas
- content -

Studies of Energetic-Ion-Driven Alfvén Eigenmode in LHD Plasmas
- conclusion -

- **We have studied the energetic ion driven AE in the plasma obtained in the following three types of magnetic configuration:**
  - ***R*ax=3.6 m with high magnetic shear**
  - ***R*ax=3.5 m with moderate magnetic shear**
  - **high β (> 2%) of *R*ax=3.6m plasma with weak magnetic shear.**
- **In the LHD plasma, the following Alfvén eigenmodes destabilized by the energetic ion are observed.**
  - **$n = 1$: core-localized TAEs (C-TAEs), n=2~5: global TAEs (TAEs)**
  - **$n = 5$: C-EAE**
  - **$n = 2$ and 3: HAEs**
  - **$n = 0$ and 1: GAEs and $n = 1$ EPM**
- **We have identified these mode due to the comparison with global mode analysis via CAS3D3.**
- **We have investigated the excitation conditions of TAE in the wide parameter range of the $\langle\beta_{b//}\rangle$ and $v_{b//}/v_A$.**
- **From the above mentioned results, continuum damping is the important damping mechanisms in the LHD plasma.**
- **Bursting TAEs appreciably modulate some plasma parameters. This phenomenon suggests that the energetic ions are transiently lost by TAE burst.**