Impact of Energetic-Ion-Driven Global Modes on Toroidal Plasma Confinements

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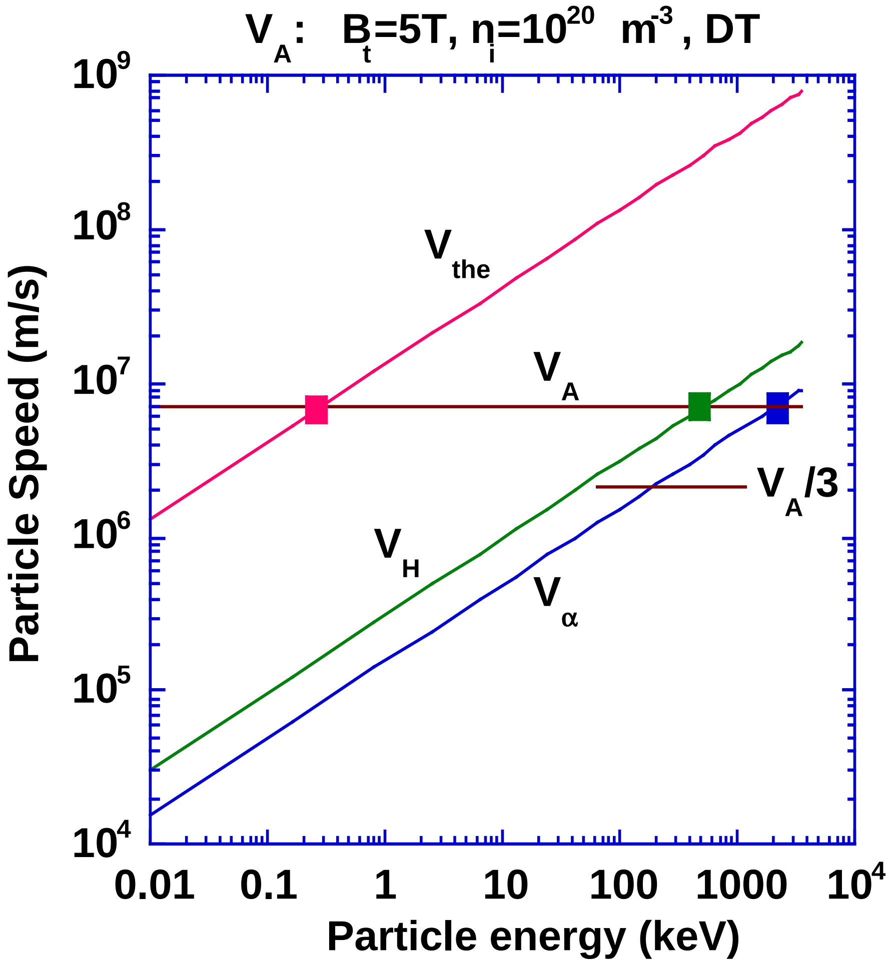
Introduction

♣ In DT burning plasmas, energetic α-particles dominantly heat electrons through slowing-down process. In the course of slowing down, the speed of α-particles will match the Alfven speed . These α-particles will resonantly interact with shear Alfven waves, and excite Alfven eigenmodes inside the shear Alfven spectral gaps.



Motivation & Objectives

- ♣ It is important to predict impacts of energetic-ion-driven MHD modes such as Alfven eigenmodes (AEs) in ITER like burning plasma.
- ♣ It is crucial to clarify the damping rate of AEs and their effect on energetic ion transport in such burning plasmas.
- ♣ In major tokamaks these subjects are intensively investigated using NBI and/or ICRF heating, and alpha particles generated in DT plasmas.
- ♣ In helical devices, that is, W7-AS, CHS and LHD, these studies are also performed.

In this presentation, we summarize experimental results on energetic ion driven AEs from CHS and LHD, comparing with those in tokamaks and W7-AS.

Excitation of AEs by energetic ions such as α-particles

- Shear Alfven spectral gaps in toroidal plasmas

magnetic field strength: N(field period number)=10 in LHD

$$B/B_O=1+\sum_{\mu,\nu}\varepsilon_B^{\mu,\nu}(\psi)\cos(\mu\theta-\nu N\phi)$$

- two cylindrical Alfven branches intersect and

generate gaps: $\omega = k_{//m,n}V_A = -\,k_{//m+\mu,n+\nu N}V_A$

μ=1,ν=0: TAE μ=2,ν=0: EAE μ=3,ν=0: NAE ,…

μ=2,ν=1: HAE21 μ=1,ν=1: HAE11 μ=2,ν=2: HAE22 ,…

gap frequency : $f^{(\mu,\nu)} = |N\nu q^* - \mu| V_A / (4\pi R q^*)$

gap position : $q^*=(2m+\mu)/(2n+\nu N)$

gap half-width : $\Delta f \sim |\varepsilon^{(\mu\nu)}{}_B - \varepsilon^{(\mu\nu)}{}_g/2|\, f^{(\mu,\nu)}$

resonance condition : $V_{b//}/V_A=1/[1\pm 2/(\nu N q^*-\mu)]$

Experimental conditions for energetic ion experiments

- **Parameter space for studies of energetic driven MHD modes**

@Resonant condition

@Energetic ion drive

$$\gamma/\omega_o = 9/4\beta_{hot}\,[f^*_{hot}/f_o - 0.5\,]F(V_A/V_{hot})$$

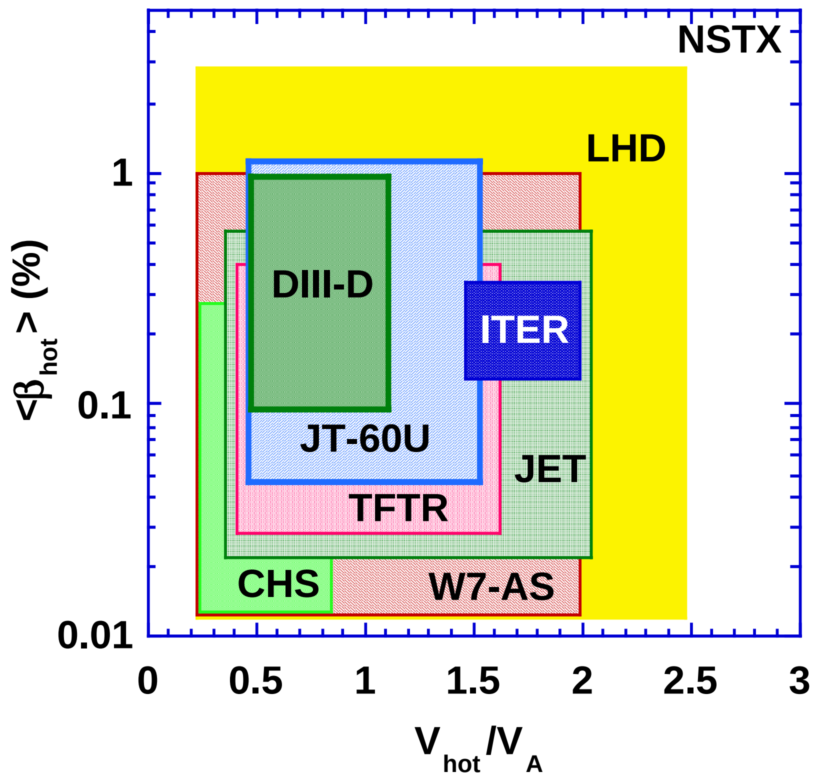
@Damping mechanisms

*Electron Landau damping

*Continuum damping

*Radiative damping

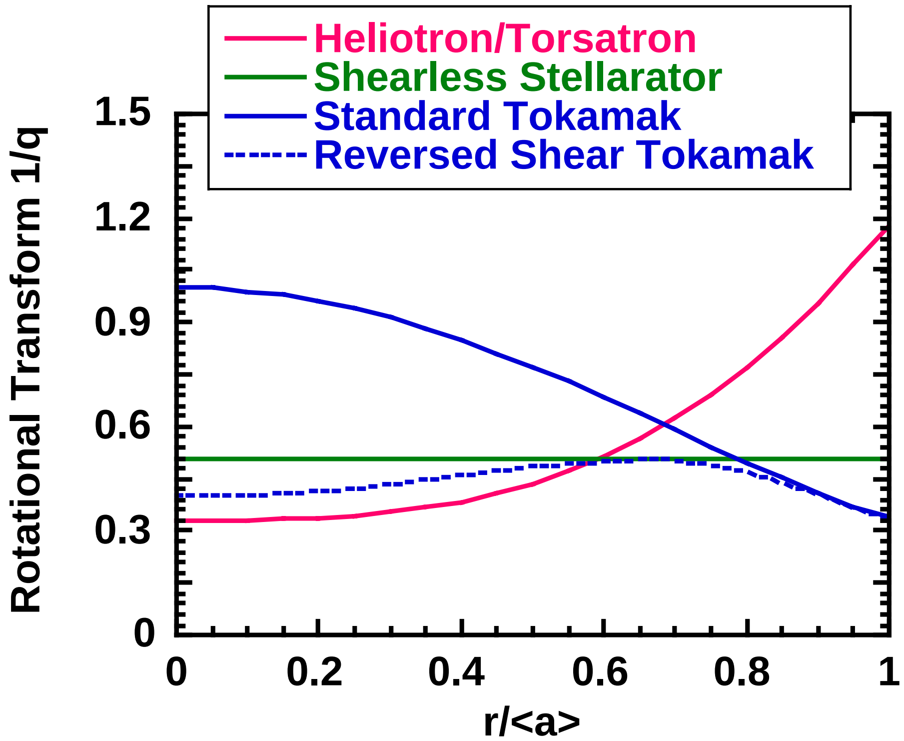
*Ion Landau damping



$<\beta_{hot}>$, V_{hot}/V_A, f^*_{hot} : important parameters

Radial profile of rotational transform in major helical devices

- **Helical devices have different 1/q-profile for tokamaks.**
- **3D-configuration**
- **Non-uniformity of magnetic field can be introduced by various Fourier components.**

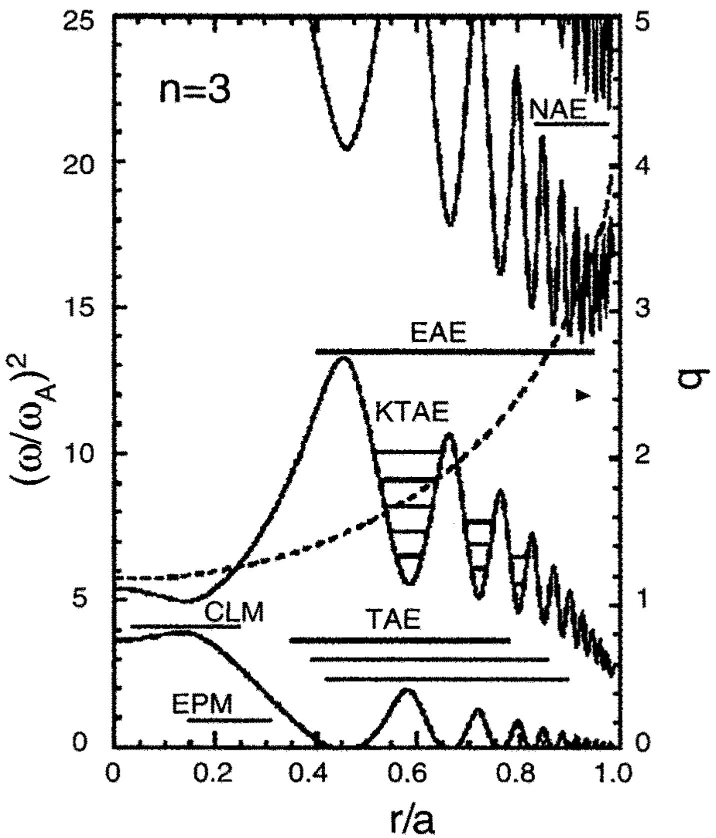


Shearless stellarator (W7-AS) : GAEs, TAEs, EPMs
Heliotron/torsatron (CHS, LHD) : TAEs, EPM, n=0 GAE, ...

Excitation of Alfven Eigenmodes by Energetic Ions

Various AEs driven by energetic ions in a tokamak plasma

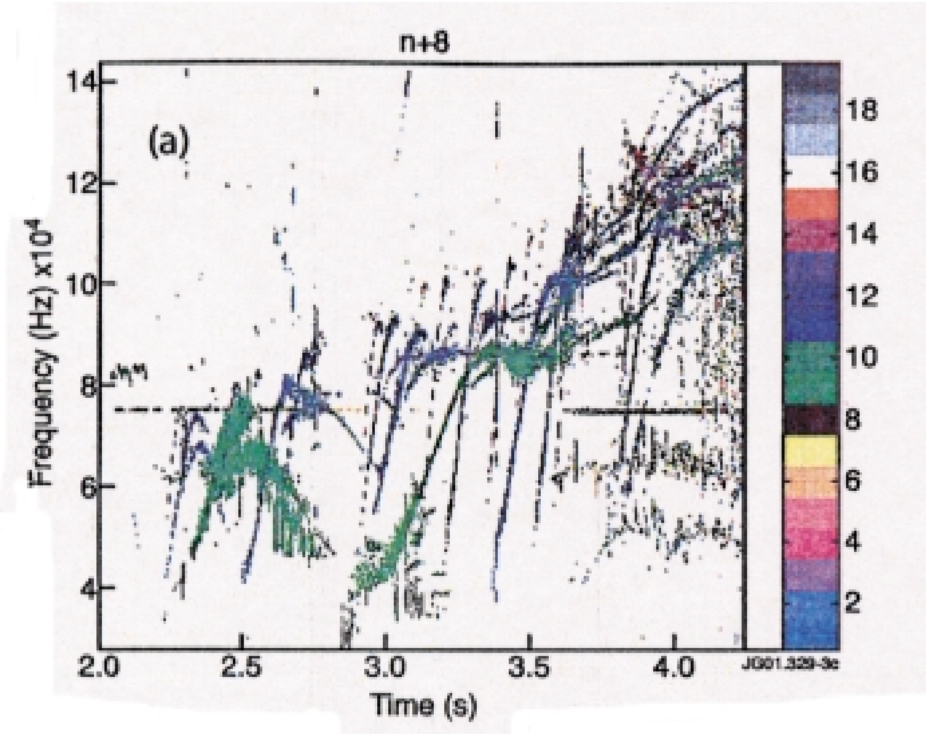
- ♣ Toroidicity-induced AE (TAE) and core-localized TAE (CLM)
- ♣ Kinetic TAE (KTAE)
- ♣ Ellipticity induced AE (EAE)
- ♣ Triangularity induced AE (NAE)
- ♣ Energetic paricle (continuum) mode (EPM) or resonant TAE(R-TAE)



ITER Phys. Basis, NF (1999)

Typical example of AEs observed in reversed shear plasmas of JET

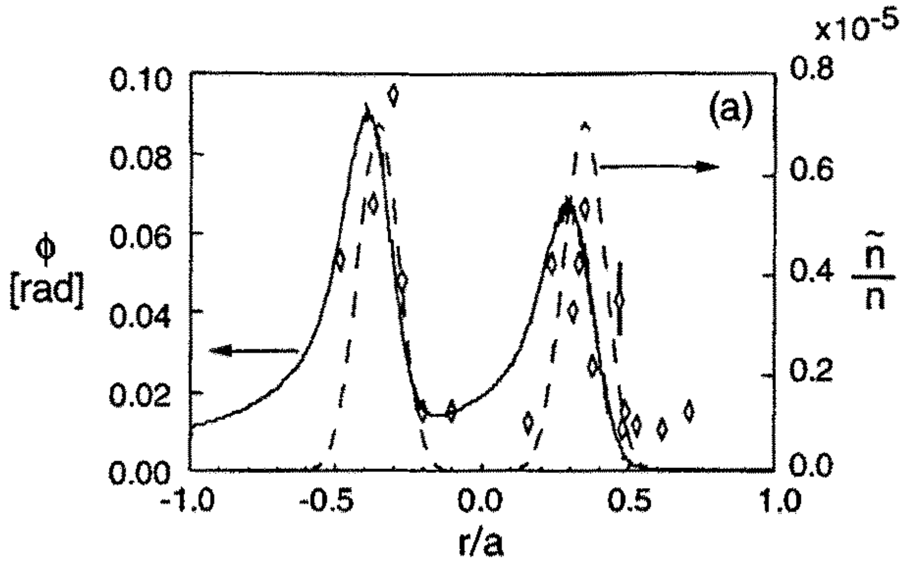
- Alfven spectra exhibit quasi-periodic pattern with mainly upward frequency sweeping (Alfven cascade).
- Time evolution of frequency clearly reflects that of q_{min}. Alfven cascade phenomena can be used for a diagnostic tool of q_{min} in the reversed shear configuration.
- The similar observation was done in ICRF plasma of JT-60U.



H.L. Berk et al., PRL (2001)

Measurement of internal structure of AEs

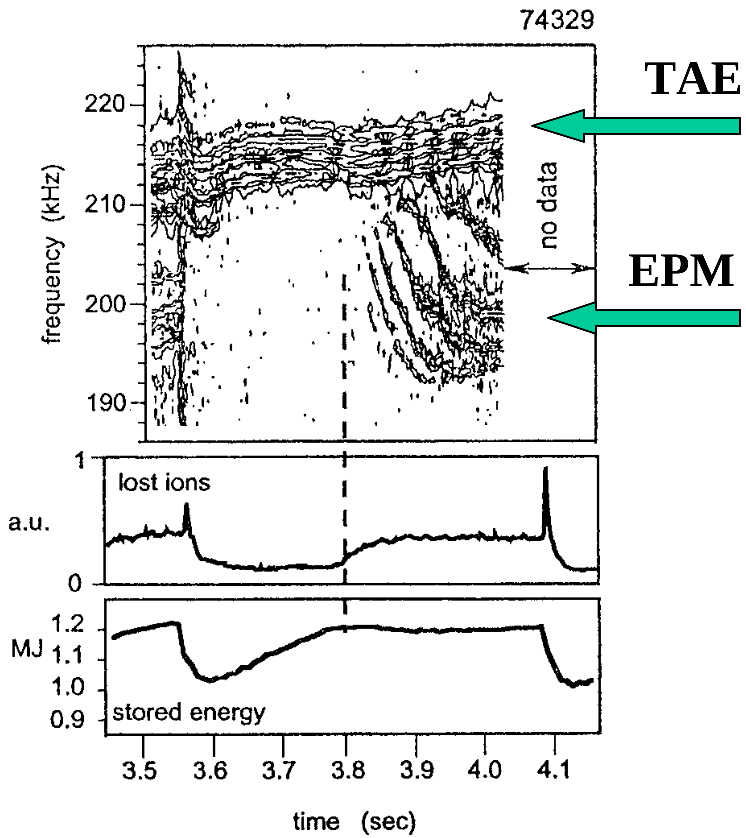
- Information about internal structure of TAEs is important to identify them, comparing theoretical results.
- Internal structure of TAEs was measured by reflectometer in TFTR and other tokamaks.
- The data clearly indicated a core-localized type of TAEs.



R. Nazikian et al., PoP, 1998

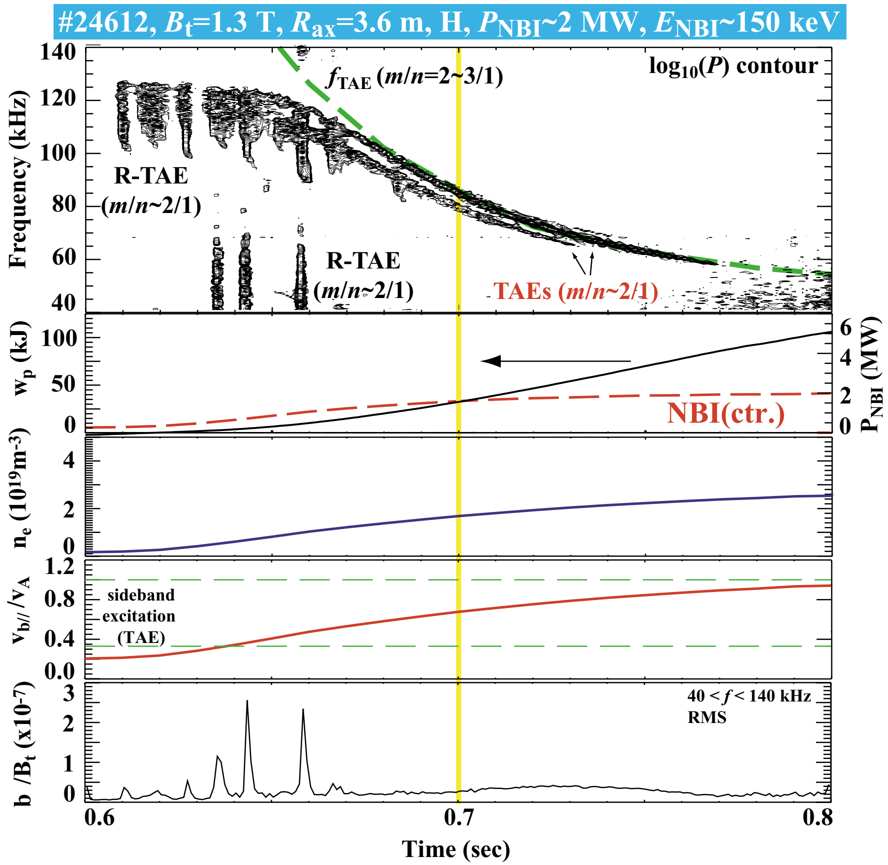
Excitation of EPM in tokamaks

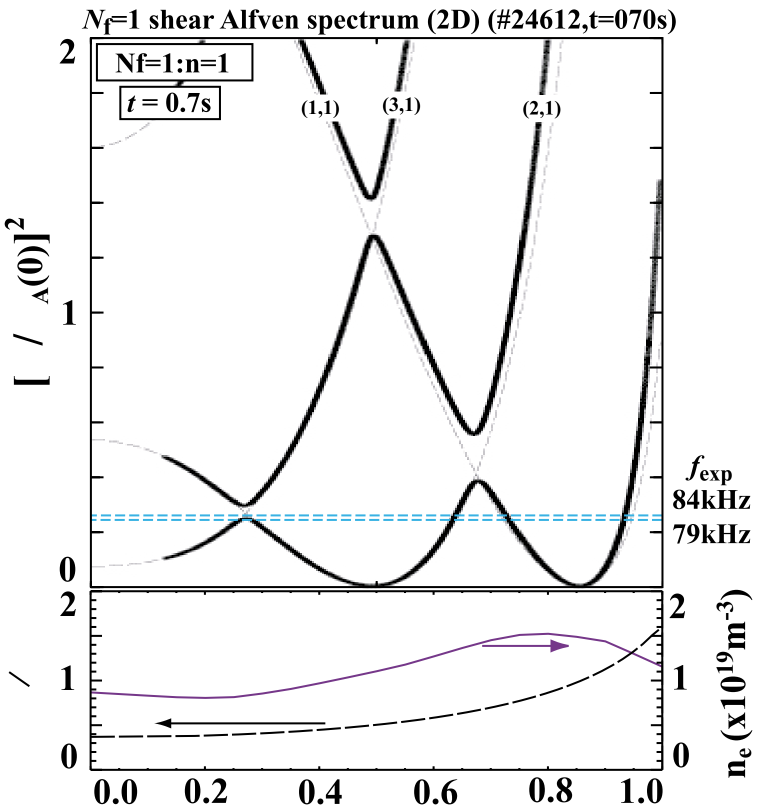
- EPMs are also observed in many tokamaks when instability drive is trong enough.
- EPM and TAEs often couple each other.
  In TFTR, TAE can be excited by the radial transport of energetic ions by EPM.
- EPM often play a key role in enhanced enegetic-ion loss.



S. Bernabei et al., PoP (1999)

TAEs & EPMs in tangential NBI heated plasmas of LHD

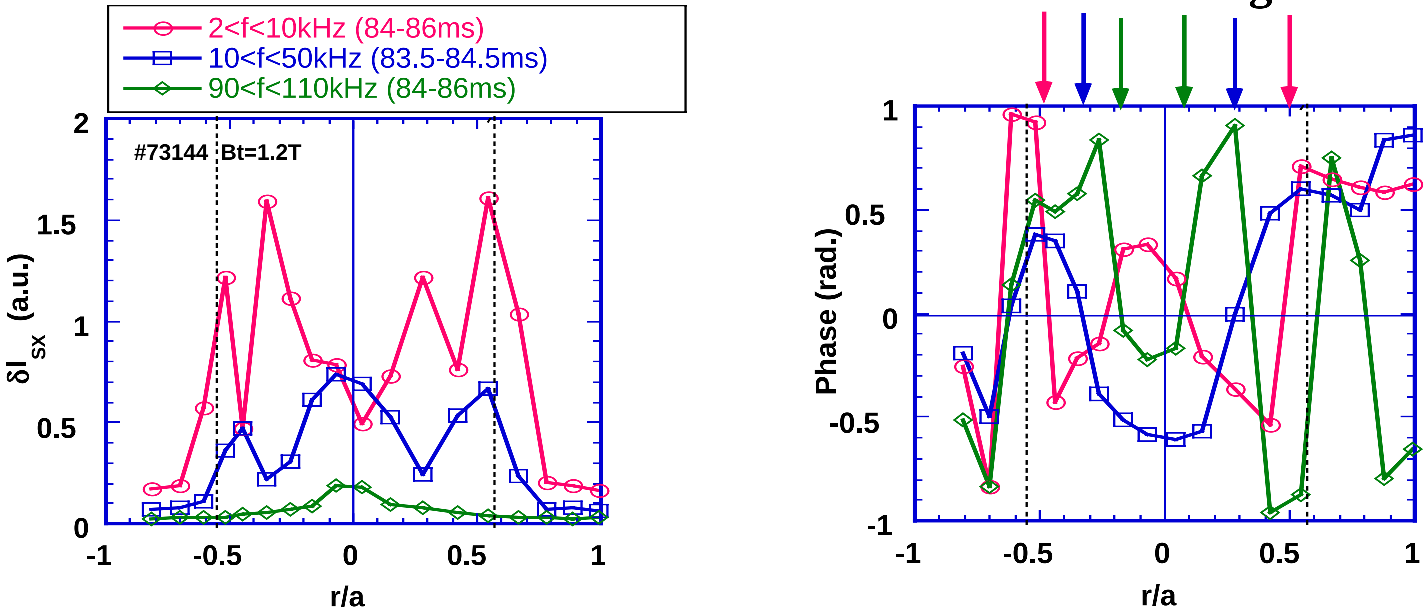




In LHD or CHS, TAE gap frequency increases toward the plasma edge. This TAE may be a core-localized type TAE.

Internal structure of TAE & EPM in CHS

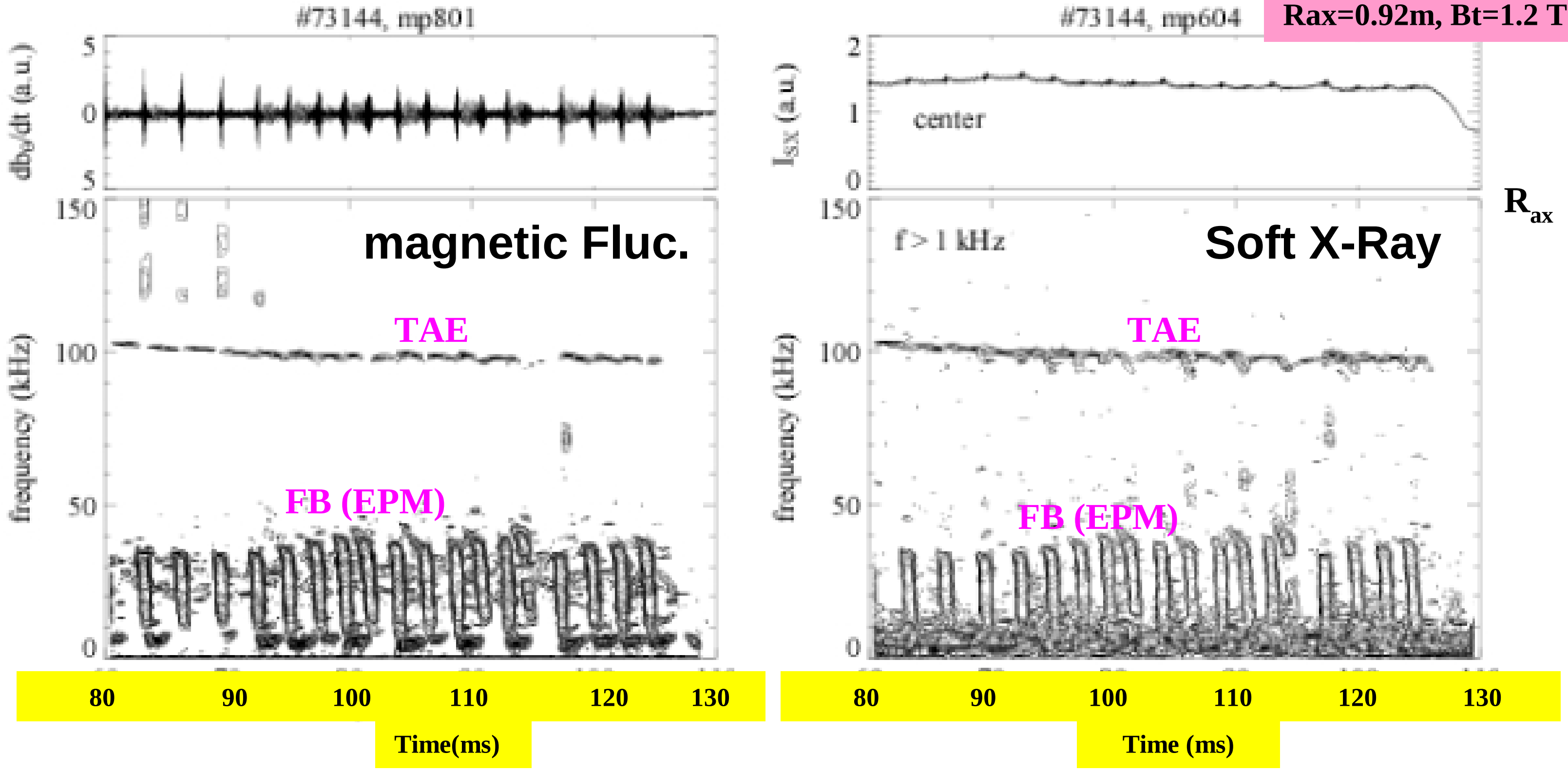
SX fluctuation diagnostics



- EPM is localized inside the q=2 rational surface.
- TAE is localized near the plasma center. ---> Core localized type TAE
- LF has a peak near the q=2 surface, indicating interchange mode.
- EPM as well as TAE exist near the innermost TAE gap.
- m~3/n=2 EPM has a similar internal structure to that of m~2/n=1 EPM.

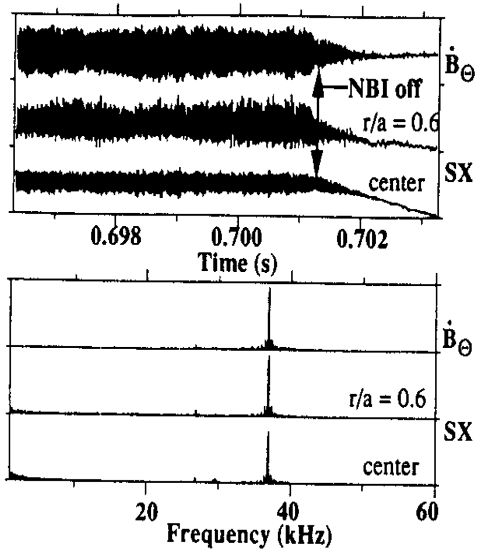
Excitation of EPM & TAE in CHS

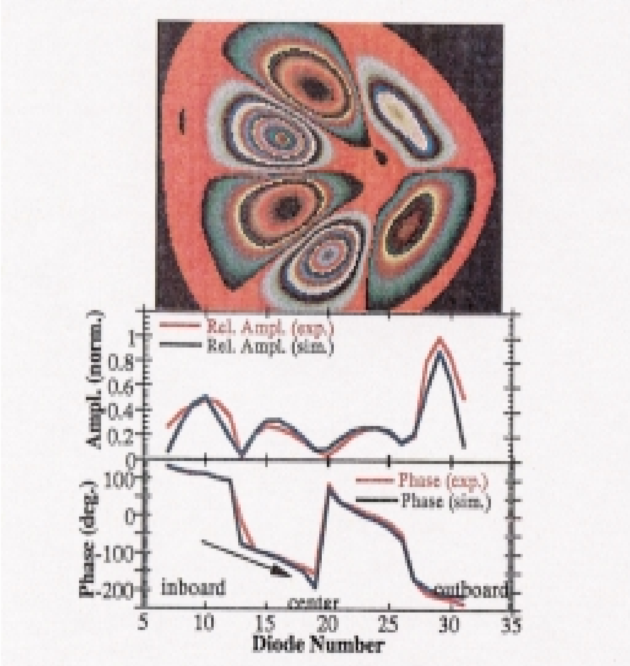
Rax=0.92m, Bt=1.2 T

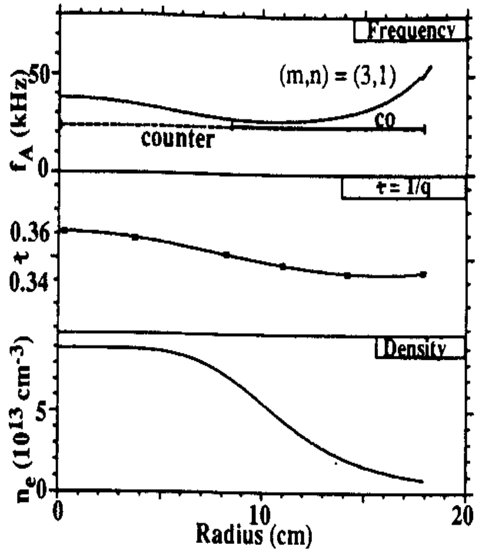


* Fishbone-like burst modes FB (EPM): strong frequency chirping
* n=1TAE is interrupted by m~2/n=1 EPM.
* Time evolution of amplitudes of FBs and TAEs can be explained by the temporal change in P_{fasti} or ∇P_{fasti}.

GAEs in low shear plasmas of W7-AS





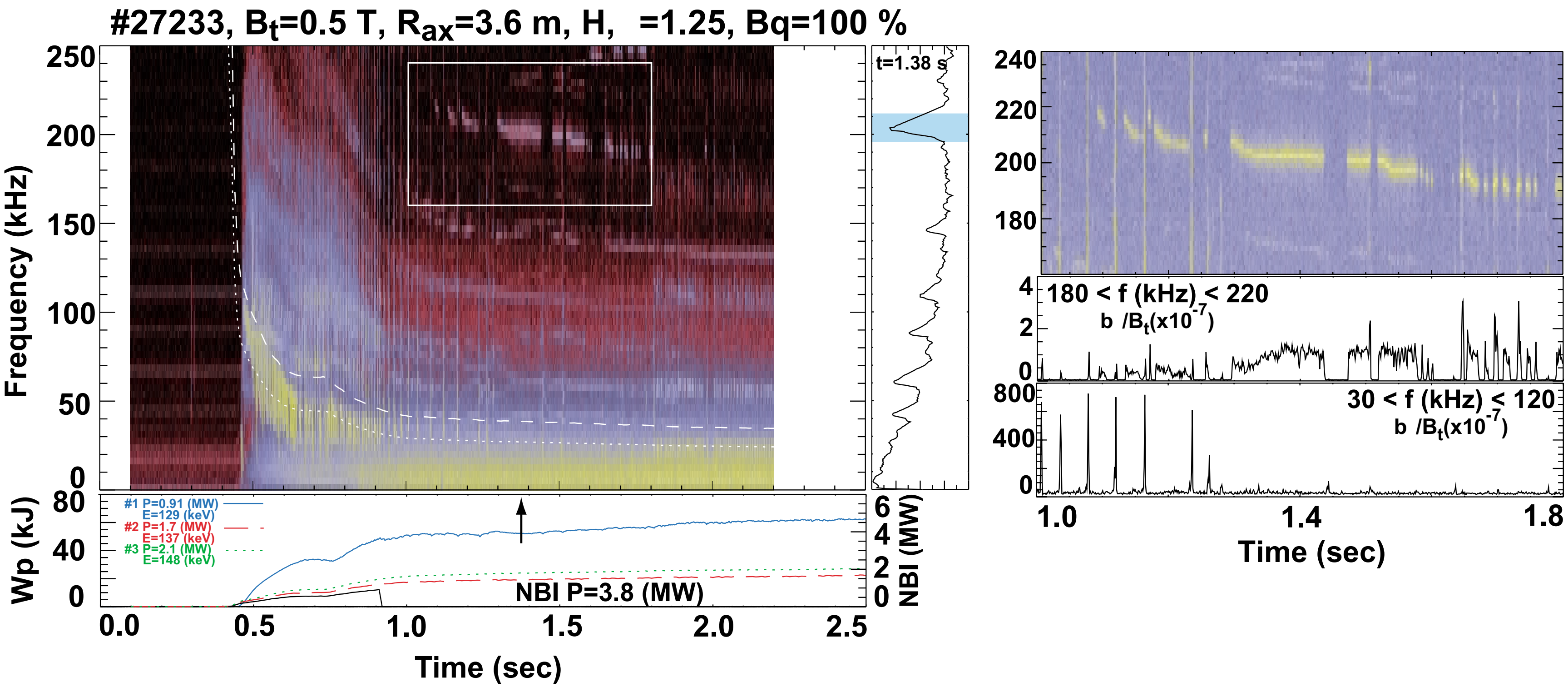


Due to low magnetic shear, low n GAEs can be destabilized at the fairly low beam velocity due to side-band excitation.

The small shear enables the exciation of TAEs in W7-AS.

A. Weller et al., PRL (1994).

Variety of various AEs observed at low Bt in LHD



Helicity induced Alfven eigenmode (HAE) has a frequency by about Nq-times higher than TAE-frequency.

At low Bt<0.7T, f_{HAE}< 500 kHz in LHD.

Observed fluctuations may be HAE.

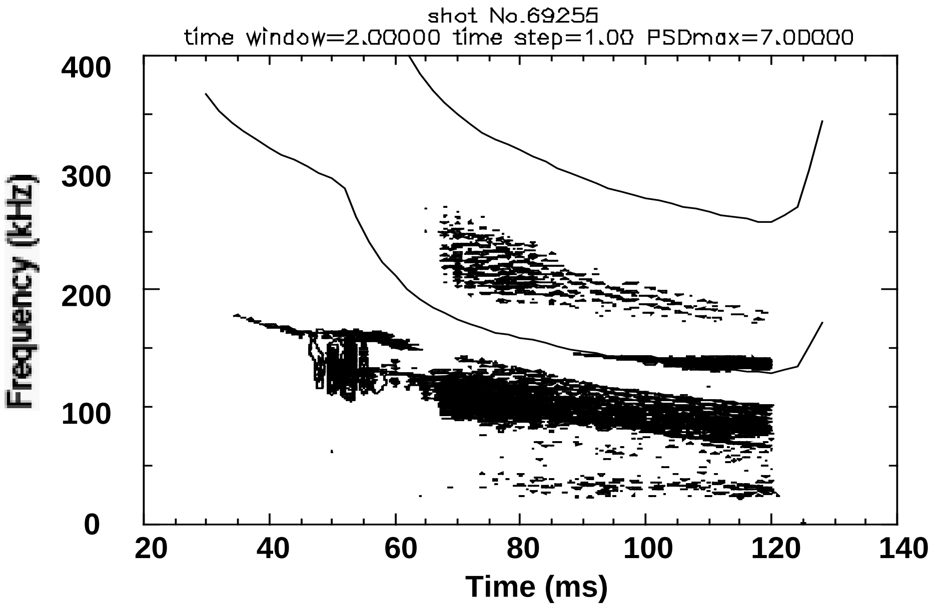
Nonlinear effects of energetic ion driven AEs

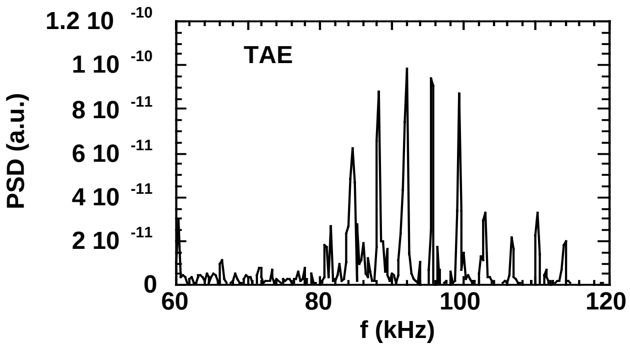
(1) **Bursting amplitude modulation: TAEs, EPMs in CHS, LHD, ...**

(2) **Fast frequency chirping: TAEs, EPMs in CHS, LHD, ...**

(3) **Frequency spectrum splitting: in CHS (similar to that in JET)**

These nnonlinear phenomena closely link to energetic ion transport.

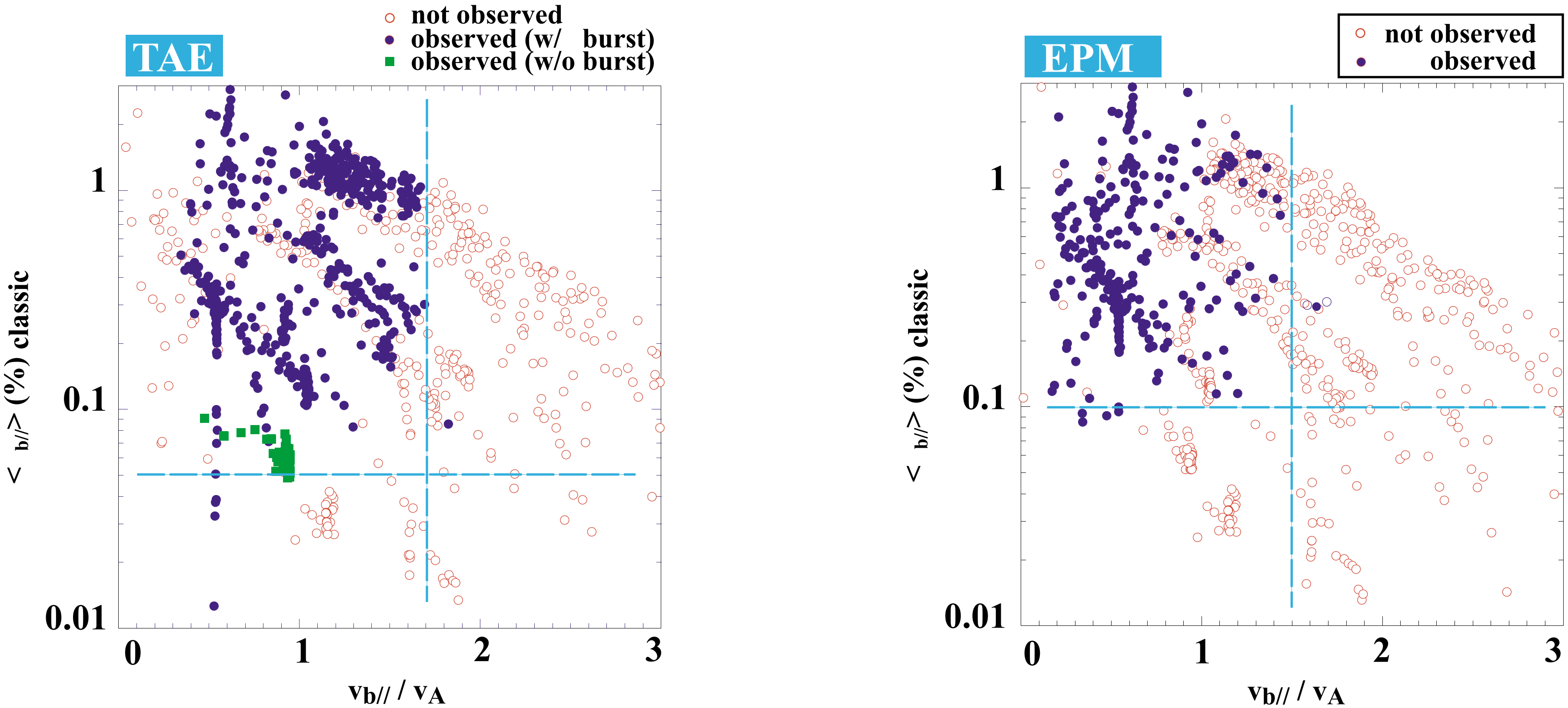




Spectrum Splitting in CHS

K. Toi et al., Nucl. Fusion (2000)

Summary of excitation condition of TAEs and EPMs in LHD



TAEs: $0.01 < \langle\beta_{b//}\rangle < 3$ %, $0.3 < V_{b//}/V_A < 1.7$;

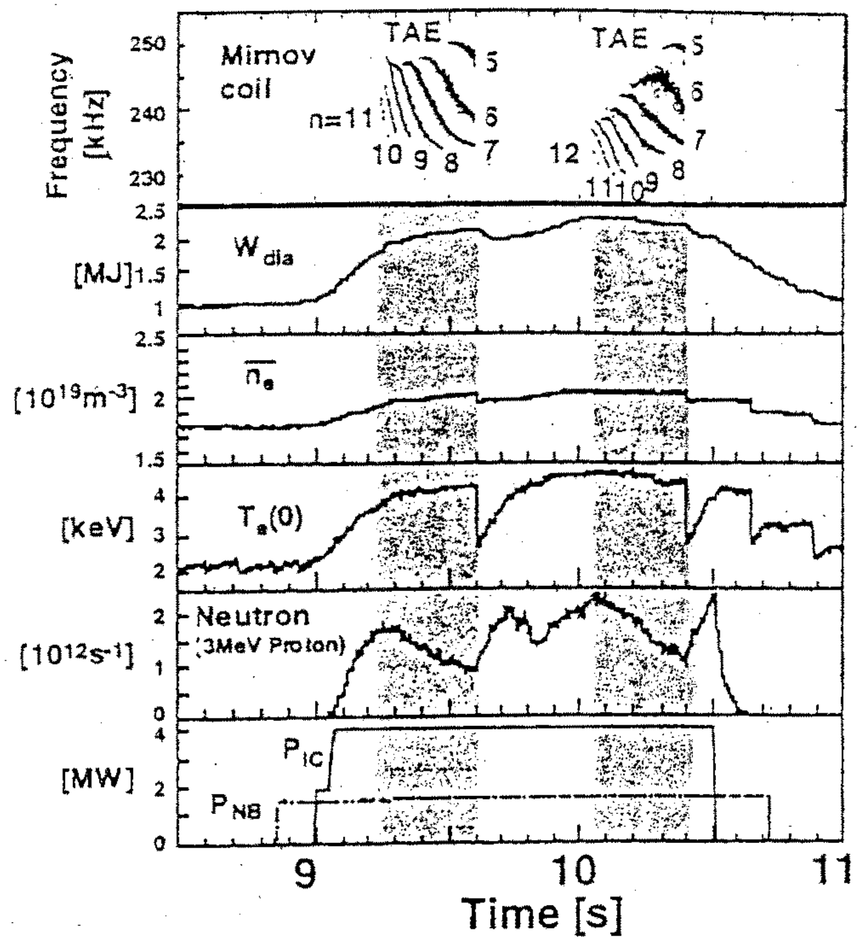
At higher $\langle\beta_{b//}\rangle$, TAE becomes bursting.

EPMs: $0.08 < \langle\beta_{b//}\rangle < 3$ %, $0.1 < V_{b//}/V_A < 1.6$; EPM is usually bursting

Effects of energfetic ion driven AEs on energetic ion transport

Typical example of energetic ion loss in tokamak plasmas

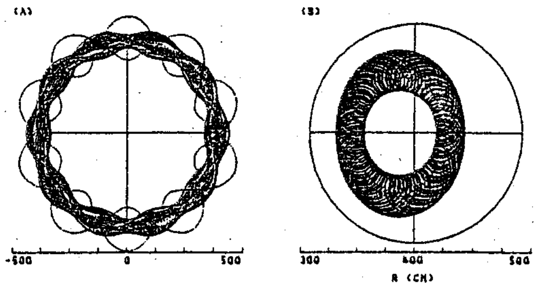
- **TAEs sometimes enhance loss of energetic ions, or redistribution of energetic ion profiles.**
- **Multiple TAEs , bursting TAE and EPMs often enhance radial transport of energetic ions.**



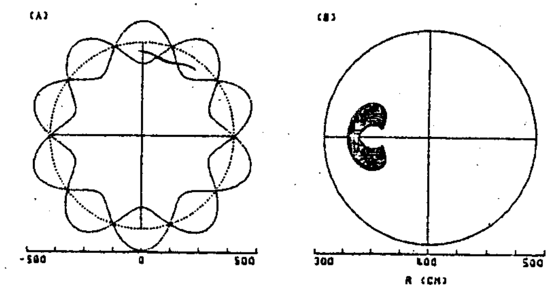
H. Kimura et al.Nucl. Fusion (1998)

Particle Orbit Classes in CHS (LHD)

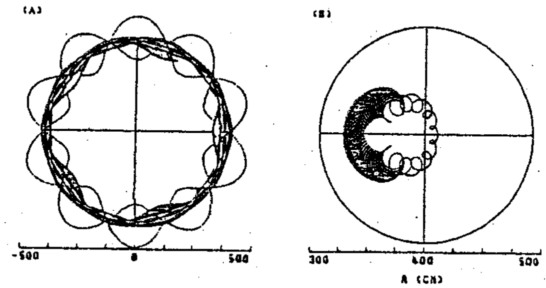
(1) Circulating Particles
χ = 57°
E = 50 keV



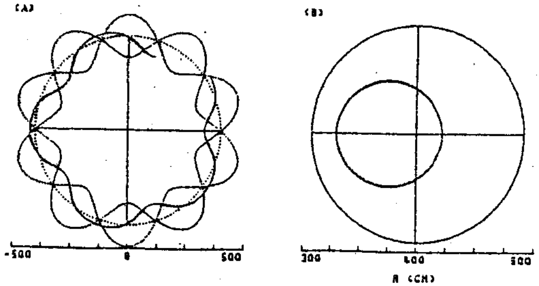
(2) Particles Trapped in Helical Field Ripple (Localized Particles)
χ = 59°
E = 50 keV



(3) Transition Particles (Transition between Localized and Blocked States without Coulomb Collisions)
χ = 65°
E = 50 keV



(3) Helical Mirror Trapped Particles
χ = 85°
E = 50 keV



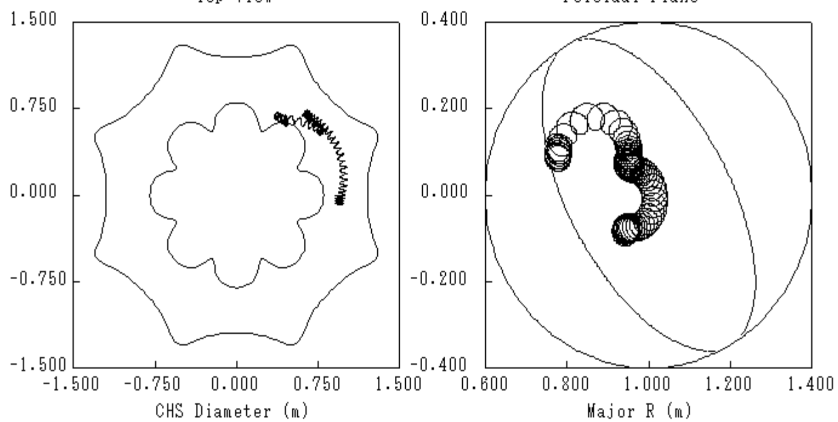
Guiding center orbit

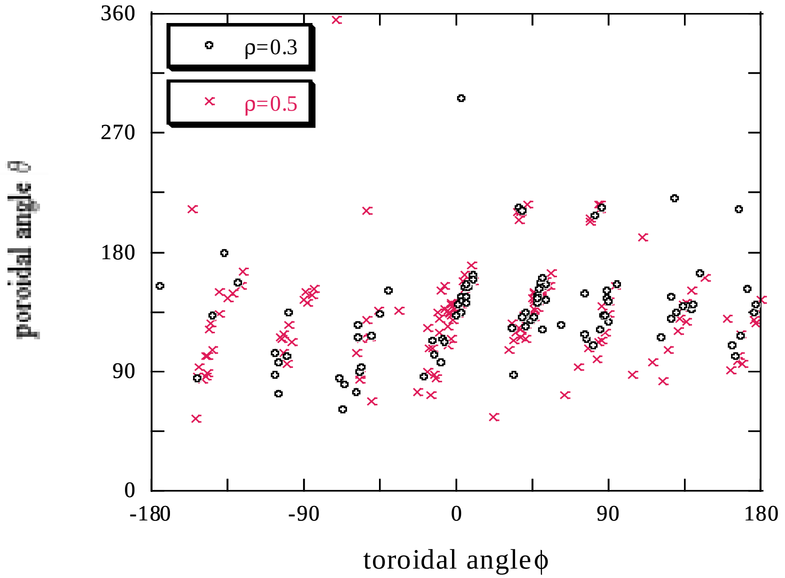
- **Banana orbit in a tokamak does not exist in CHS (LHD) configuration. Usual fishbones observed in tokamaks would not be excited.**
- **In CHS (LHD), the initial pitch angle of most ions will be in the range of χ=20-50° because of tangential injection.**

Hit Points of Lost Energetic Ions on the Vacuum Vessel Surface in CHS

- **Transient loss of fast ions was detected only in the outward-shifted plasmas.**
- **Orbit calculations have revealed that energetic ions are lost in poloidally and toroidally localized zone for both inward and outward shifted configurations.**
- **Detectors of lost ions should be placed at this narrow zone where lost fast ions would arrive.**

R_{ax}=0.92 m; ρ_{start}=0.3 & 0.5; E=40 keV





Dependence of energetic ion loss flux on fluctuation amplitude (CHS)

- **Relation between ion loss flux and fluctuation level:**

  $\delta\Gamma_i \propto (b_{fluc})^s$

  s=1: Resonant convec. loss

  s=2: Diffusive transport

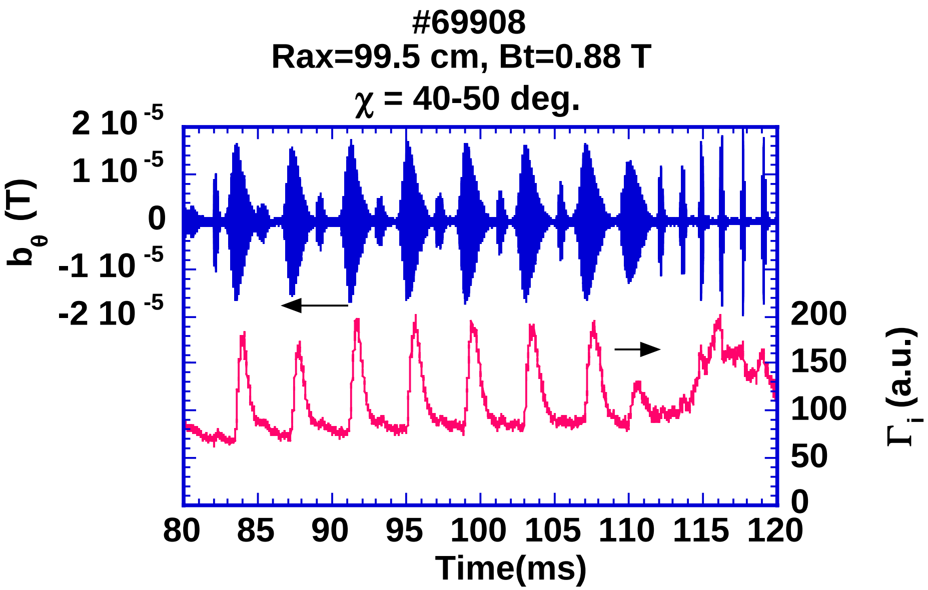
  s>2: Destruction of magnetic surface

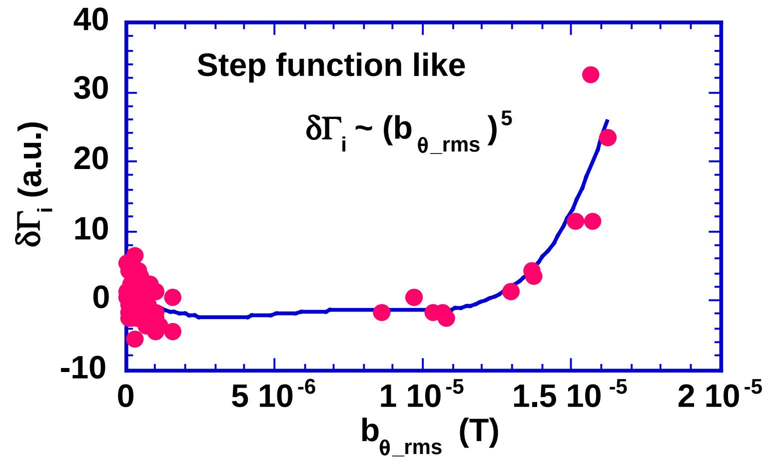
- **For fast ions in χ=40-50 deg.**

  s > 5 or

  $\delta\Gamma_i \propto u(b_\theta - b_{crit})$: threshold

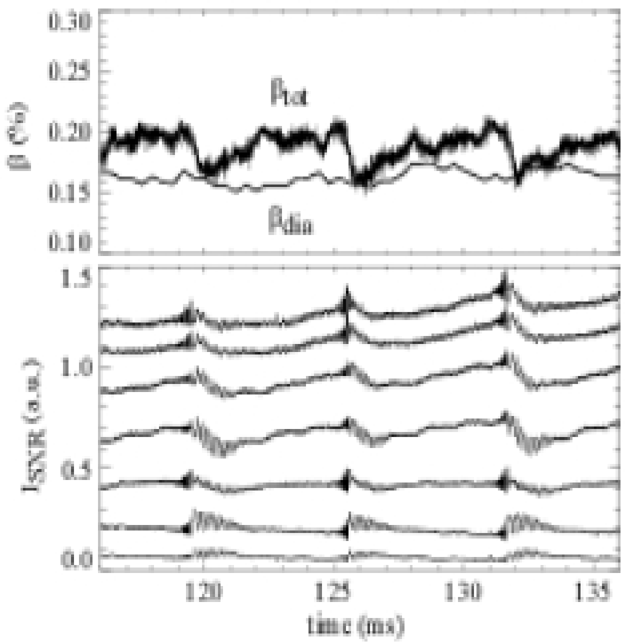
  This may link to loss cone.





Transient Decrease in Shafranov Shift due to m~2/n=1 EPM (CHS)

- **Magnetic axis position derived from SX-emission profile is transiently changed by each fishbone burst.**
- **The transient decrease of the Shafranov shift may be attributed to the flattening of the energetic ion profile, because of no change in $<b_{bulk}>$.**



Shafranof shift $\propto \beta_{b//}(0)+\beta_{dia}(0)$

S. Takagi et al., Rev. Sci. Instrum. 2001

Energetic ion loss due to bursting TAEs in LHD

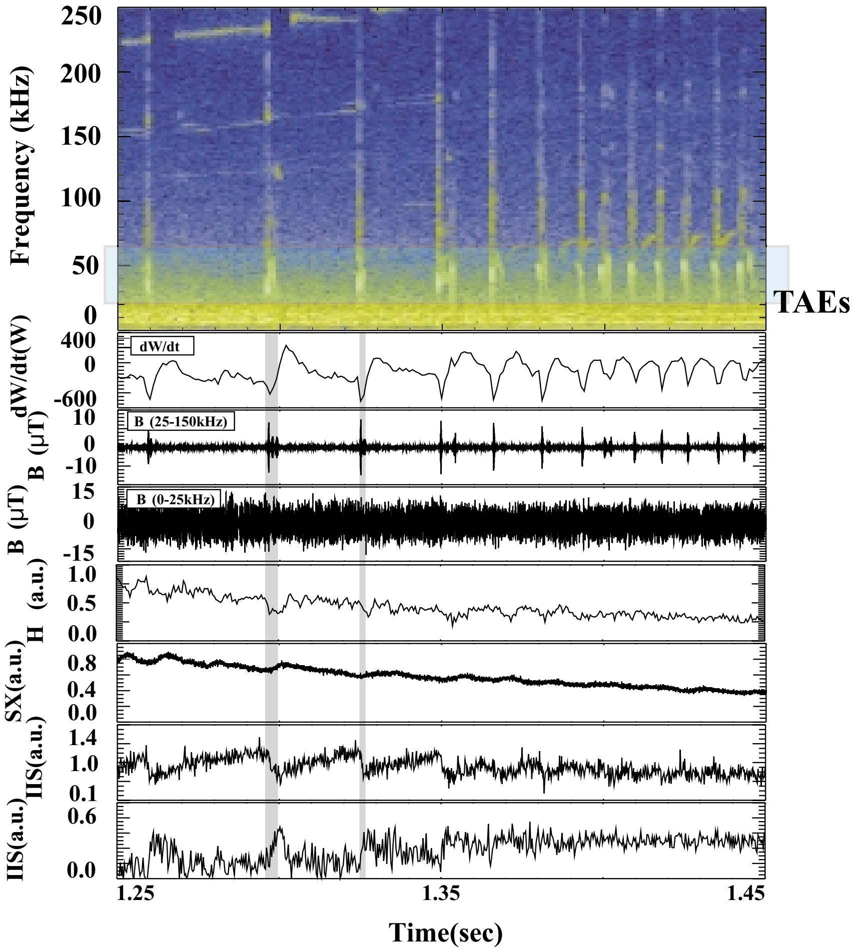
*** Strong bursting TAEs (n=1 + n=2) transiently reduce W_p (i.e., $dW_p/dt<0$), which suggests enhanced loss of energetic ions.**

~ 15 % loss of P_{NBI}

*** Note:**

Just after the each burst, W_p is increased beyond the previous level, reducing Ha-light and increasing ne & SX-emission.

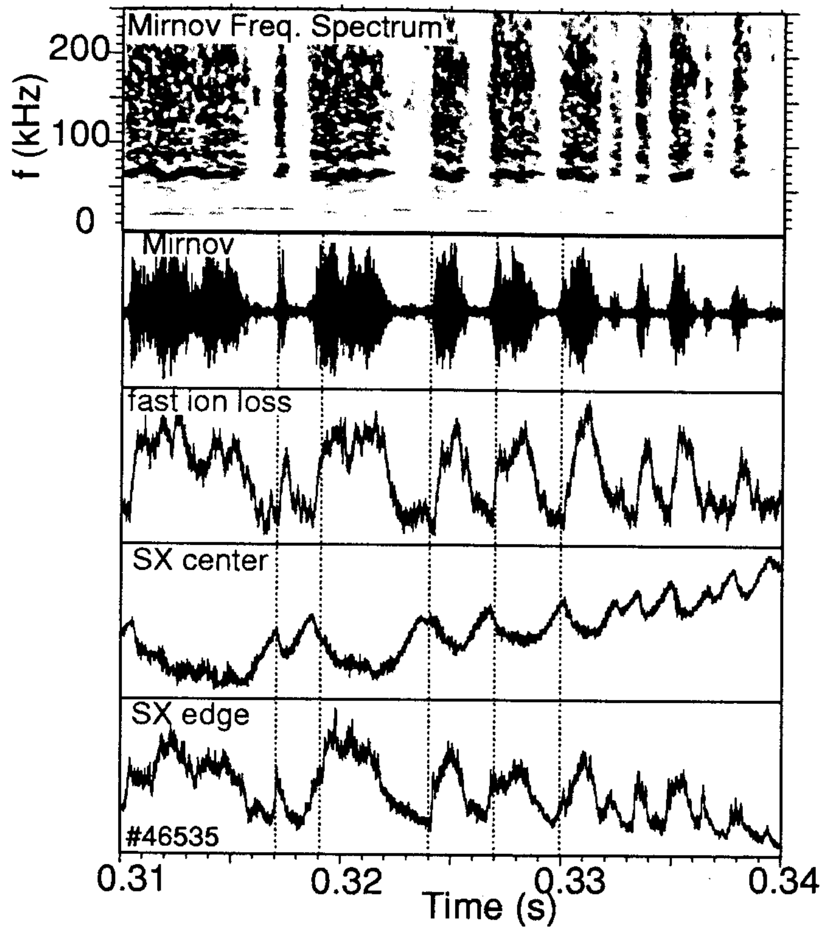
#25950, B_t=0.6T, R_{ax}=3.6 m, H, P_{NBI}~3 MW, E_{NBI}~150 keV



S. Yamamoto et al., this conf.

Energetic ion loss in W7-AS plasma

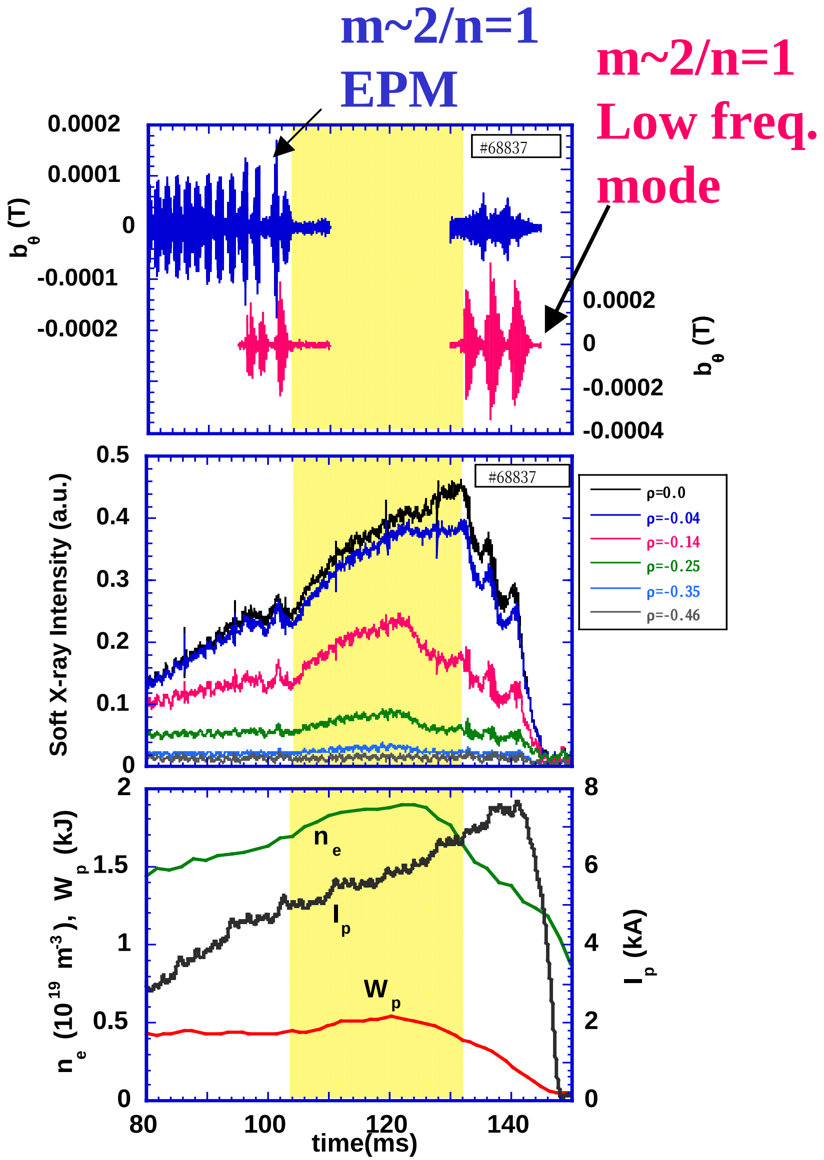
- **Bursting AEs enhance energetic ion loss, of which modes are m=3/n=1 GAE or EPM.**
- **High freq. bursting modes (TAE?) also enhance the loss.**
- **These modes reduce the bulk plasma energy too.**



A. Weller et al.,PoP (2001)

Impact of EPM on Bulk Conf. (CHS)

- Bulk plasma confinement is appreciably affected by m~2/n=1 EPM.
- The suppression of the EPM leads to the increase in Wp & n_e by ~20 %.
- The suppression of EPM as well as low frequency(LF) modes is not due to the removal of q=2 surface by the rise of I_p.
- The suppression occurs in the certain range of $\langle\beta_{b//}\rangle$ (=0.25 - 0.35%). This phenomenon does not always take place.
- Suppression mechanism is still unclear and under investigation.



Summary and Future Plan

- ♣ **Studies on energetic ion induced MHD modes such as Alfven eigenmodes have intensively been performed in three helical devices LHD, CHS and W7-AS as well as in major tokamaks.**
- ♣ **A lot of information about Alfven eigenmodes excited by energetic ions are obtained, that is, TAEs, EAEs, EPMs and so on were identified, as are predicted by MHD theories including energetic ions.**

  However, quantitative comparison between experiments and theories is still preliminary.
- ♣ **In helical devices such as CHS and LHD, very wide parameter range can be explored without suffering current disruptions. These researches can contribute to improved understanding of Alfven eigenmode in toroidal plasmas, as well as need for physics design of a helical device reactor.**
- ♣ **As future studies in CHS and LHD,**

  to experimentally obtain shear Alfven spectra through Alfven spectroscopy.

  to clarify physics related to interaction between MHD modes and energetic ions.