19th NEXT Workshop
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Overview of Experimental Research on Energetic-Particle-Driven Modes in 2D and 3D Plasmas

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NIFS, Professor Emeritus

Outline

- **Motivation and Objectives**
- **Basis of Experiments on EP Driven Instabilities**
- **Recent topics**
- **Summary and Future Prospect**

Motivation and Objectives

Significances of Researches on Energetic Particle-MHD Wave Interactions

Self sustainment of D-T burning plasma

$_1D^2 + {}_1T^3 \rightarrow {}_2He^4$ (α: 3.5 MeV)+ $_0n^1$(neutron: 14.1 MeV)

➔Demonstration in ITER(~2026）

DT burning plasma: bulk plasma(~10-20 keV) + minority energetic ions (0. 2-3.5 MeV) in ITER （$n_{hot} << n_{bulk}$ ）

Self-organized plasma with less external control nobs

Fusion energy gain

$Q = P_{fusion}/P_{heat} = 5P_\alpha/P_{heat}$

Alpha heating fraction

$f_\alpha = P_\alpha/(P_\alpha + P_{heat})$

$= Q/(Q+5)$

Q=1 f_α =17 %

Q=5 f_α =50%

Q=10 f_α =67 % (ITER)

Parameter ranges in experiments on

Tokamaks : JET, JT-60U, TFTR, DIII-D, AUG, C-Mod, KSTAR, EAST, HL-IIA …)

Spherical tori (NSTX, MAST)

Helical/Stellarators (LHD, CHS, W7-AS, W7-X)

ITER

$T_{i,e}$ = 0.2 – 20 keV, B=0.1 – 10 T

q=1 – 10; 1<R/a < 8, E_f = 0.05 – 1 MeV,

$\upsilon_{Ti} << \upsilon_f \sim \upsilon_A << \upsilon_{Te}$, $\beta_f \lesssim \beta_{bulk}$

DT Burning Plasmas in Tokamak and Stellarator/Helical Reactors

Tokamak type
(2D configuration
+3D perturbations)

ITER :
$<\beta_\alpha> \approx 0.2\%,$
$\beta_\alpha(0) \approx 0.7\%$
$(T_o = 20\text{keV},$
$n_e = 2\text{x}10^{20}\text{m}^{-3})$
$\tau_s \sim 0.8\text{s}$

A. Fasoli et al., Nucl. Fusion (2007)

Good α-confinement
Confinement degradation
in high n_e regime
=>High T & low n_e plasma

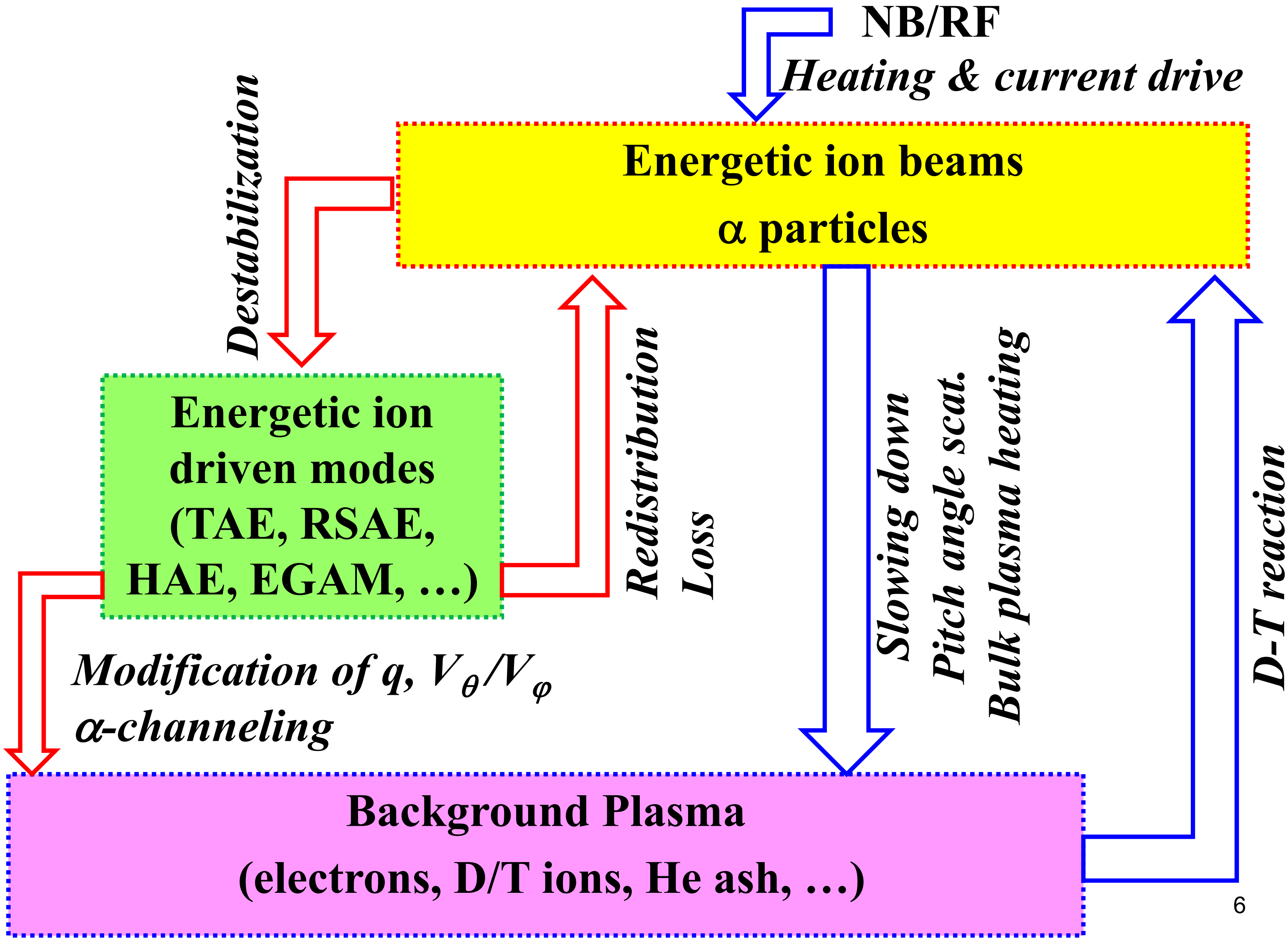
Stellarator/Helical type (3D config. or quasi-symmetric)

ARIES – CS Reactor :
$<\beta_\alpha> \sim 0.1\%,$
$\beta_\alpha(0) \sim 0.4\%$
$(T_o = 10\text{keV}, n_e = 5\text{x}10^{20}\text{m}^{-3};$
$\tau_s \leq 0.1\text{s}$ (*short*!)

Degraded α-confinement
due to field ripple
Good confinement
in high n_e regime
⇒ Low T & high n_e plasma
⇒ Reduced $P_\alpha \tau_s$

L.P. Ku et al., Fusion Sci. Technol. (2008)

Effects of Energetic Ions in Burning Plasma



Basis of Experiments on EP Driven Instabilities

Fast Ion Orbits in 2D Plasma (Ideal Tokamak)

- **Adiabatic invariants of guiding center motion : E , μ_B**

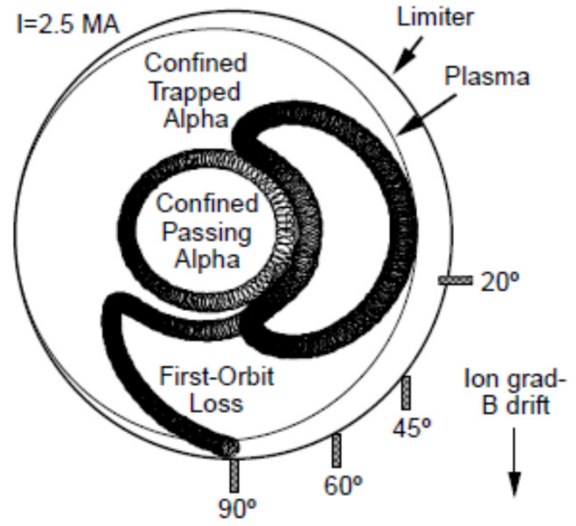
- **in 2D axisymmetric tori: $P_\varphi = m_j R v_\varphi - e_j \psi$**

  $E-(n/\omega)P_\varphi$ is also conserved

  => $\Delta E = (n/\omega)\Delta P_\varphi$

  Change in E leads to the change of ψ

  => Particle transport across magnetic surfaces



Alpha particle orbit in TFTR at Bt=5T and Ip=2.5MA
Zweben: NF NF (2000)

3D perturbation in actual tokamak plasma(=> 2D plasma+3D perturbations)

@ Finite number of TF coils & feritic steels＝＞Edge magnetic ripple

(toroidicity in 2D plasma=> not 3D effect => passing/trapped orbits)

@ Resonant magnetic perturbations for ELM control

@ 3D deformation of plasma by large scale helical instabilities such as RWM and snake

Particle Orbits in Stellarator/Helical Devices with large N

In 3D plamas (non-axisymmetric tori):

P_φ **is not an adiabatic invariant.**

For specific 3D configurations having the following characters

1. **Small ι/2π per the toroidal field period :**

$$\frac{\iota/2\pi}{N} \ll 1$$

2. **Field variation due to toroidicity is smaller than that due to helical ripple:**

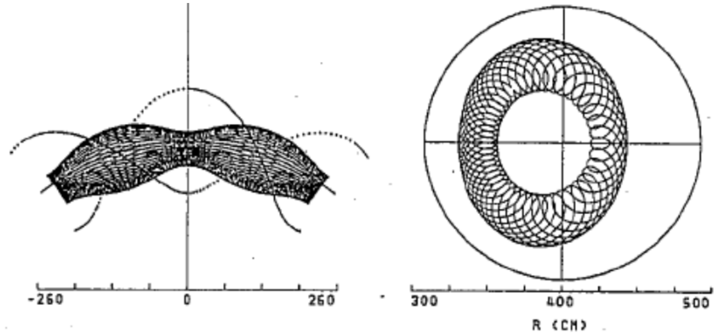
$$\frac{\varepsilon_t}{\varepsilon_h}\frac{\iota/2\pi}{N} \ll 1$$

=> For passing particles with small λ, P_φ is nearly conserved.

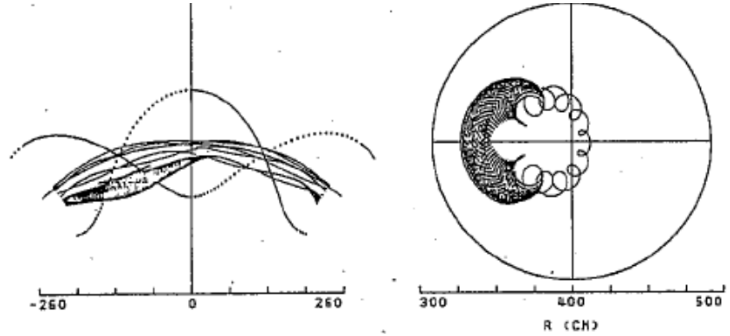
Typical particle orbits for various pitch-angle in LHD configuration

Guiding center orbits on LHD

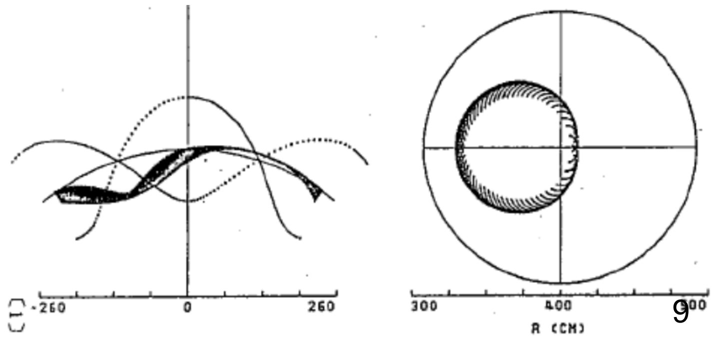
Passing particles (λ=54 deg.)



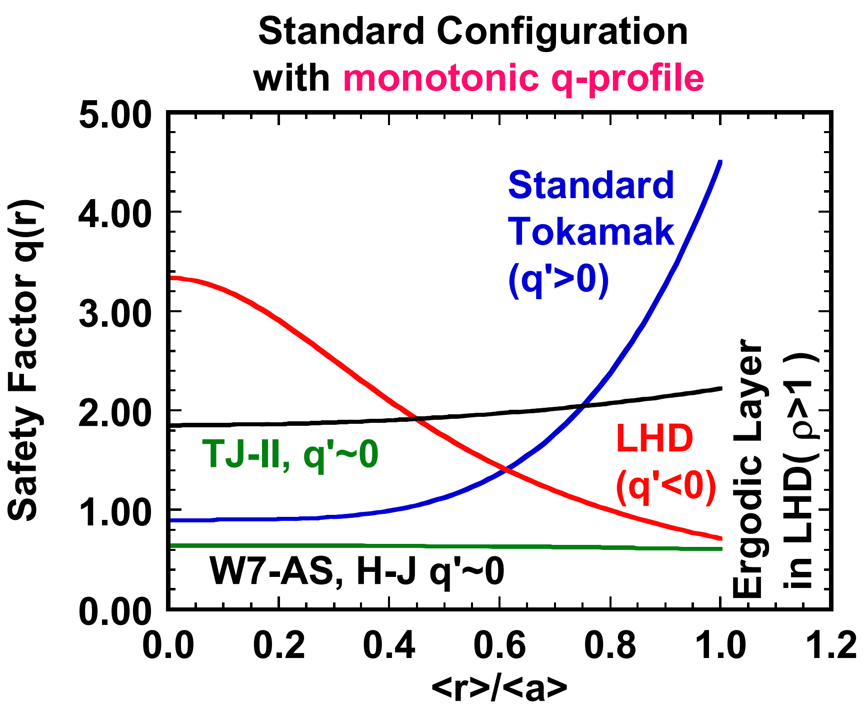
Transition particles (λ=65 deg.)

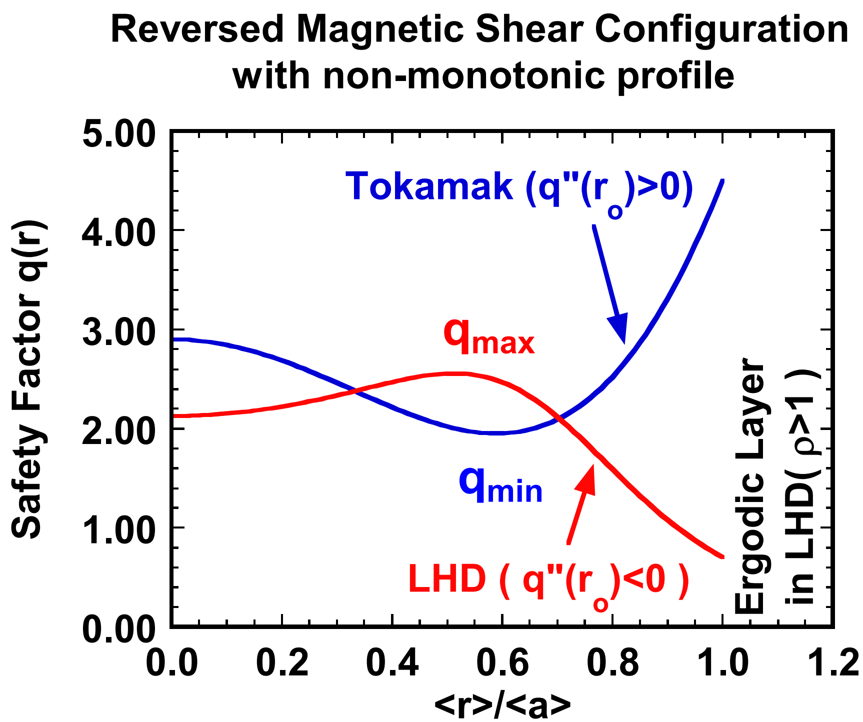


Helical-ripple trapped particles (λ=75 deg.)



AEs in Monotonic and Reversed Magnetic Shear Plasmas in 2D & 3D Plasmas





2D tori : tokamaks
w/o 3D perturbations
3D tori : LHD, W7-AS, TJ-II

RS configurations with positive and negative $q''(r_o)$
Time evolution of q_{min} and q_{max}
=> Characteristic sweeping of RSAE frequency

$\iota(r)/2\pi = 1/q(r)$

Shear Alfven Spectral Gaps in 2D Torus

Cylindrical plasma: shear Alfven continua $\omega = k_{//} \upsilon_A$

Tokamak plasma : Coupling of m and m±1 continua

$$k_{//m} \upsilon_A = -k_{//m+1} \upsilon_A$$

=> TAE gap

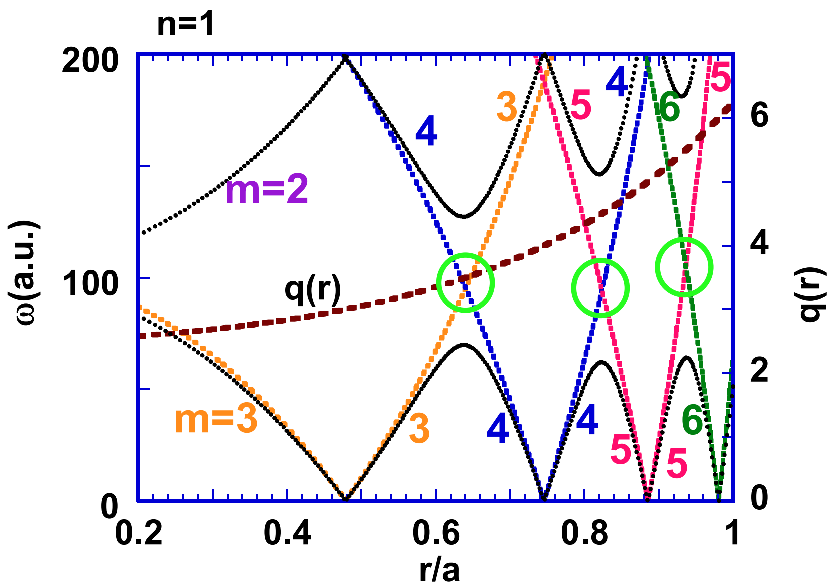
TAE gap frequency : ($1/n_e^{0.5}$-dependence)

$$f_{TAE} = \frac{\upsilon_A}{4\pi R q^*} \quad \text{where } q^* = \frac{2m+1}{2n}$$

Coupling of m and m+2 continua => EAE gap

$f_{EAE} \sim 2 f_{TAE}$

Note: **No or inverse density dependence in GAE or RSAE *frequency***
$f = (k_{//} \upsilon_A)_{min\ or\ max} / (2\pi)$
depends on q profile evoltion

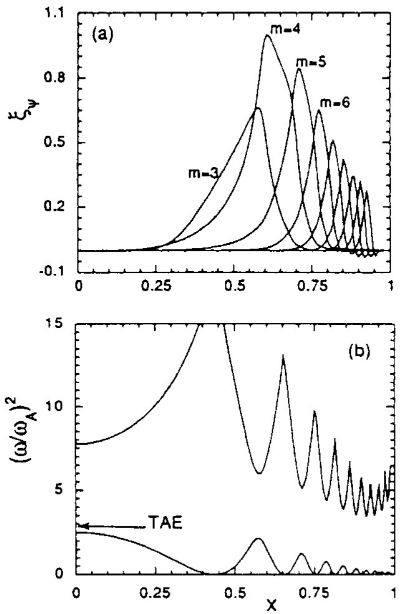


Typical Example of TAEs in Tokamak Plasmas

TAES observed in TFTR

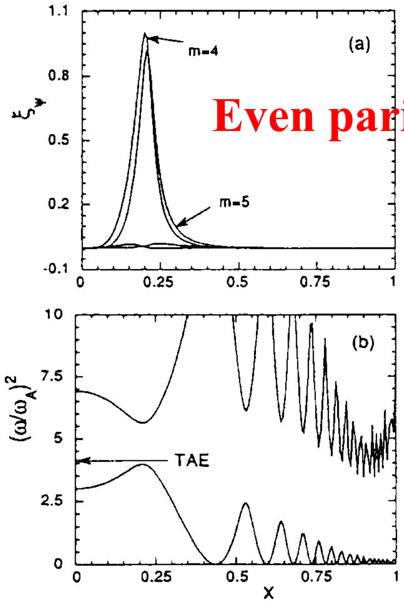
(a)

Global TAE



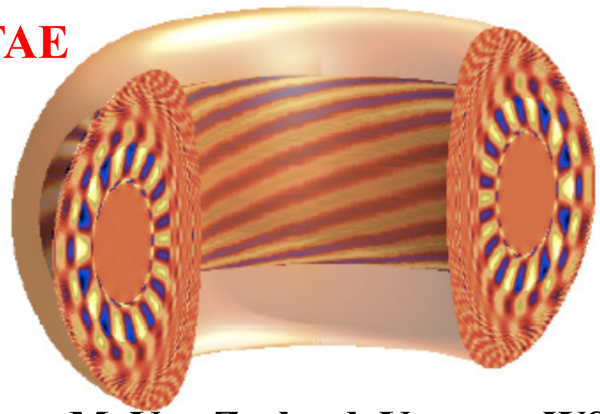
(b)

Core-localized TAE



Even parity C-TAE

(c) **Te fluctuation pattern by n=10 TAE on ITER**



M. Van Zeeland, Varenna WS on Plasma Diagnostics (2007)

G.Y. Fu et al., PoP (1996)

2 types of TAEs in a tokamak plasma with monotonic q(r)-profile (positive shear)

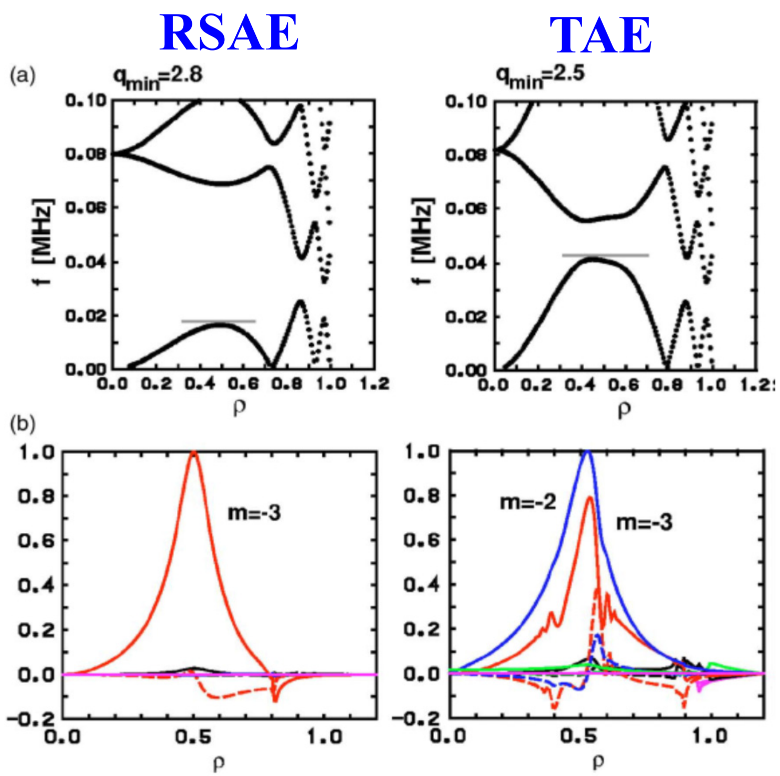
(a) Global type TAE (G-TAE) with multi-m Fourier components

(b) Core-localized TAE (C-TAE) with two dominant m components, in low shear plasma core region

even parity C-TAE(ballooning)、odd-parity C-TAE(anti-ballooning)

RSAE in RS Plasmas on JT-60U

GAE: just below shear Alfven continua or above the continua (NGAE)
RSAE: just below or above the continua in a RS plasma
GAE and RSAE composed by a single dominant Fourier mode



JT-60U (calculated by TASK/WM code)
Shear Alfven spectra in the cases of q_{min}=2.8 and 2.5 of JT-60U RS plasma

q_{min}=2.8: RSAE with one dominant Fourier mode
q_{min}=2.5: TAE with multi-Fourier modes

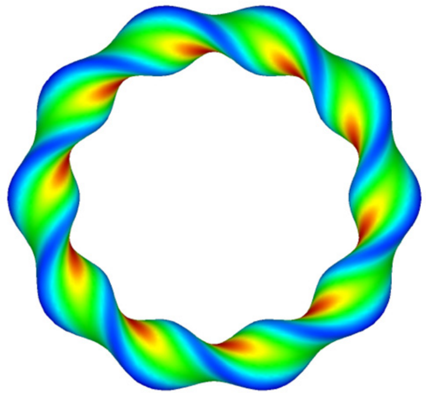
Fukuyama et al., 6th IAEA TM on Energetic Particles in Magnetic Confinement Systems, Naka, 1999.
M. Takechi et al., PoP (2005)

Shear Alfven Gaps in 3D Plasma

Fourier spectra of equilibrium field strength（$|B|/B_o$) and geometrical structure (metric tensor of magnetic coordinates)

|B| expressed by Boozer magnetic coordinates(ψ, θ, φ)

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



|B| contour at r/a=0.5 on LHD

Coupling of counter propagating shear Alfven waves
=> Gap

$$k_{//m,n}\upsilon_A = -k_{//m+\mu,n+\nu N}\upsilon_A$$

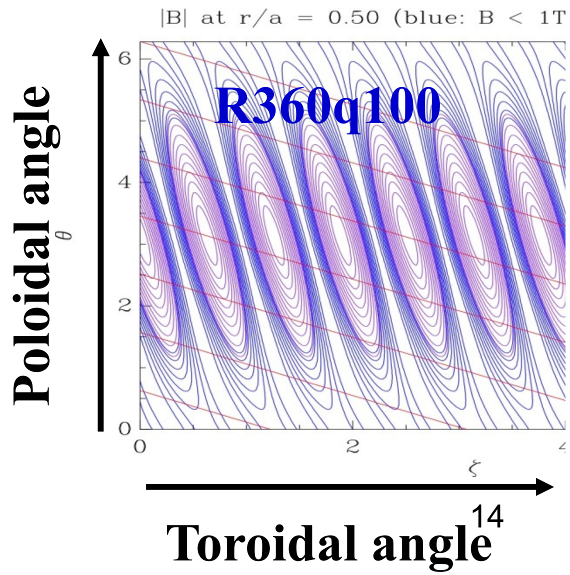
ギャップ位置とギャップ周波数:

$$q^* = \frac{2m+\mu}{2n+\nu N}$$

$$f_{gap}^{(m,n)} = \frac{|\nu q^* N - \mu|\upsilon_A}{4\pi R q^*}$$

ギャップ幅:

$$\Delta\omega^2/\omega^2 \propto \left|\varepsilon_B^{2,1} - \varepsilon_g^{2,1}\right|/2$$



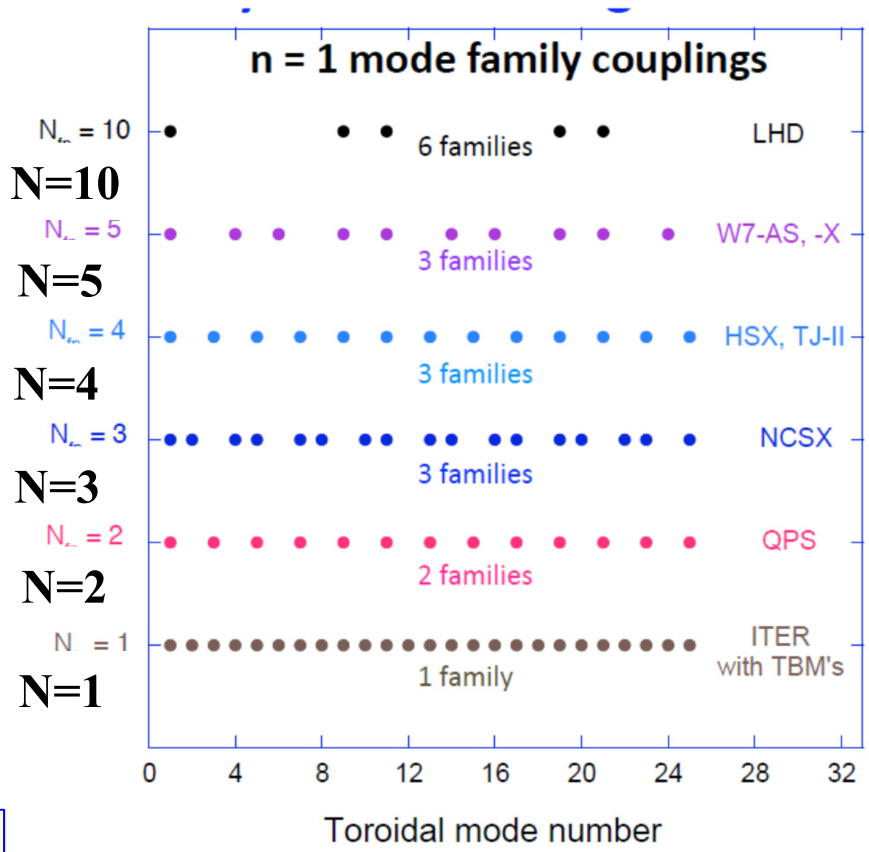
(μ=1, ν=0) ➔ TAE gap,
(μ=2, ν=1) ➔ HAE$_{21}$ gap $f_{HAE} \sim N f_{TAE}$ **(wide gap)**

Importance of Toroidal Mode Coupling in 3D Plasms

Toroidal mode coupling takes place in a 3D toroidal plasma with toroidal period number N.

Toroidal mode coupling of n and n’ modes on the condition of n’±n=kN where k=0, 1, 2, ….。

Number of the mode family
= 1+N/2 (C. Schwab, PFB5(1993))



n’ modes that can couple with n=1 mode in various 3D tori

Weak toroidal mode coupling in 3D configuration with large N such as LHD

=> Essential for HAE gap formation

=> Weak effects on TAE (~2D plasmas)

D.A. Spong et al., 21the IAEA FEC, Geneva, 2008, paper No. TH-3/4.

Typical Example of Helicity-Induced AE(HAE) in an LHD (3D) Plasma

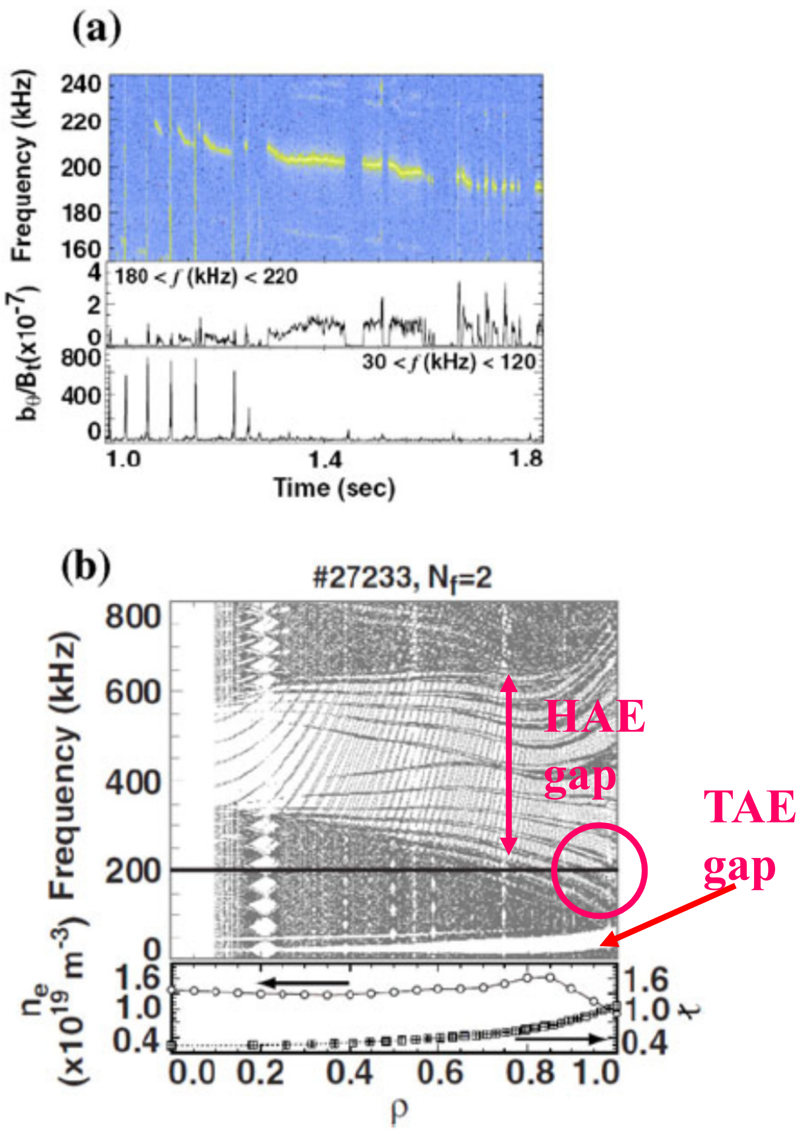
Observation of HAEs in LHD

weak toroidal mode coupling, essential for HAE gap formation

The AE spectra are calculated including toroidal mode coupling with n=2, 8,12, …, 48 and 52 modes (included 919 Fourier modes)

S. Yamamoto et al., PRL (2003)

Density fluctuations of HAE are observed in the HAE gap near the plasma edge. K. Toi et al., PPCF (2010)



Resonant Wave-Particle Interactions

Energy exchange rate ***dW/dt*** :

$$\frac{dW}{dt} \approx eZ_h \mathbf{\upsilon}_d \cdot \mathbf{E}_\perp$$

$$\frac{dW}{dt} \sim \sum_{m,n,\mu,\nu} C^{\mu,\nu} \exp[-i\omega t + i(m+\mu)\omega_\theta t - i(n+\nu N)\omega_\varphi t]$$

Resonance condition for efficient energy exchange between wave and partcles:

$$\omega - (m+\mu)\omega_\theta + (n+\nu N)\omega_\varphi = 0$$

For large aspect ratio tokamak, $\mu = \pm l, \nu = 0$

$$\frac{\upsilon_{//}}{\upsilon_A} = \frac{l}{\pm 2 - l}$$

l=1 ➔ **TAE**➔ **$|\upsilon_{//}/\ \upsilon_{A}|$=1, 1/3**

l=2 ➔ **EAE**➔ **|υ/// υA|=1/2**

Linear Growth Rate of EP Drive Modes

Adiabatic invariants in 2D plasmas: E, μ and P_φ

➔ $E-(n/\omega)P_\varphi$ **is conserved**

➔ **AE growth rate by EPs:**

$$\gamma_\alpha \propto \frac{\partial f_{\alpha o}}{\partial E} - \frac{\lambda}{E}\frac{\partial f_{\alpha o}}{\partial \lambda} - \frac{n}{\omega}\frac{\partial f_{\alpha o}}{\partial P_\varphi}$$

Destabilization of $n\neq0$ AE modes by the 3rd term

(due to spatial non-uniformity of EP density)

Destabilization of n=0 mode (EP driven GAM, n=0 GAE)

by gradients for E and λ in velocity space (Velocity space instabilities)

In 3D plasmas, P_φ is conserved for passing EPs with small λ

=> This idea is applicable for passing EPs on LHD

Various Fluctuations Induced by EP Driven Modes

Magnetic fluctuations perpendicular to **B** by shear Alfven eigenmodes: $b_\perp$

Incompressible waves: $\nabla \cdot \boldsymbol{\xi} = 0$

Various fluctuations by AEs:

Fluctuations of magnetic, density, electron temperature, plasma potential, lost ion flux, and so on

Plasma fluctuation diagnostics:

- Magnetic probes (b_r, b_θ, b_φ)
- Millimeter wave reflectometer,
- ECE /ECE imaging (ECEI),
- Beam emission spectroscopy (BES),
- Lost ion probe/fast ion loss detector,
- Heavy ion beam probe (HIBP),
- ….

Ideal MHD plasma

$$\mathbf{b} = \nabla \times (\xi \times \mathbf{B})$$

$$\frac{\delta\rho}{\rho} = -\nabla \cdot \boldsymbol{\xi} - \frac{\boldsymbol{\xi} \cdot \nabla\rho}{\rho}$$

$$\frac{\delta p}{p} = -\gamma\nabla \cdot \boldsymbol{\xi} - \frac{\boldsymbol{\xi} \cdot \nabla p}{p}$$

$$\frac{\delta n_e}{n_e} = -\nabla \cdot \boldsymbol{\xi} - \frac{\boldsymbol{\xi} \cdot \nabla n_e}{n_e}$$

$$\frac{\delta T_e}{T_e} = -(\gamma - 1)\nabla \cdot \boldsymbol{\xi} - \frac{\boldsymbol{\xi} \cdot \nabla T_e}{T_e}$$

For shear Alfven waves: $\nabla \cdot \boldsymbol{\xi} = 0$

However, toroidal effect leads to

$$\nabla \cdot \boldsymbol{\xi} \approx -\frac{2}{R}(\boldsymbol{\xi} \cdot \mathbf{R}) \neq 0$$

Even for a flat profile,

$$\delta n_e \neq 0 \text{ and } \delta T_e \neq 0$$

Effects of Plasma Rotation on Mode Frequency

Correction of Doppler effect due to plasma rotation:

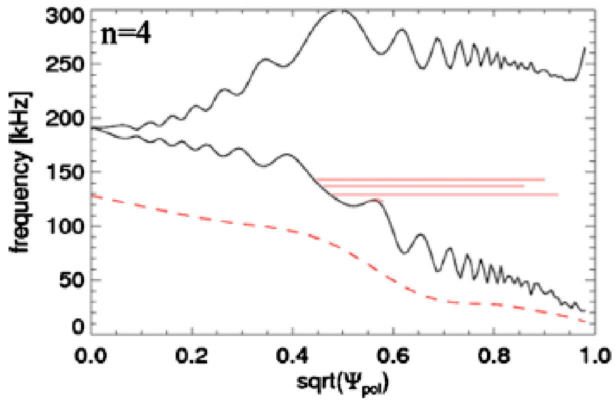
$$\omega_{laboratory\ frame} = \omega_{plasma\ frame} + \boldsymbol{k} \cdot \boldsymbol{v}$$

If the mode is convected with purely toroidal flow => $f_{obs} \approx f_{AE} + nf_{\varphi}(r)$
(E.J. Strait et al., PPCF 1994)

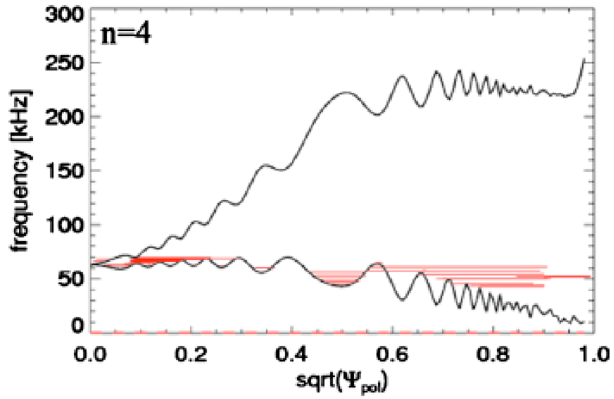
Shear Alfven spectra with and without the correction of sheared toroidal rotation in NSTX

M. Podesta et al., PoP (2010)

w/ Doppler effect correction



w/o Doppler effect correction



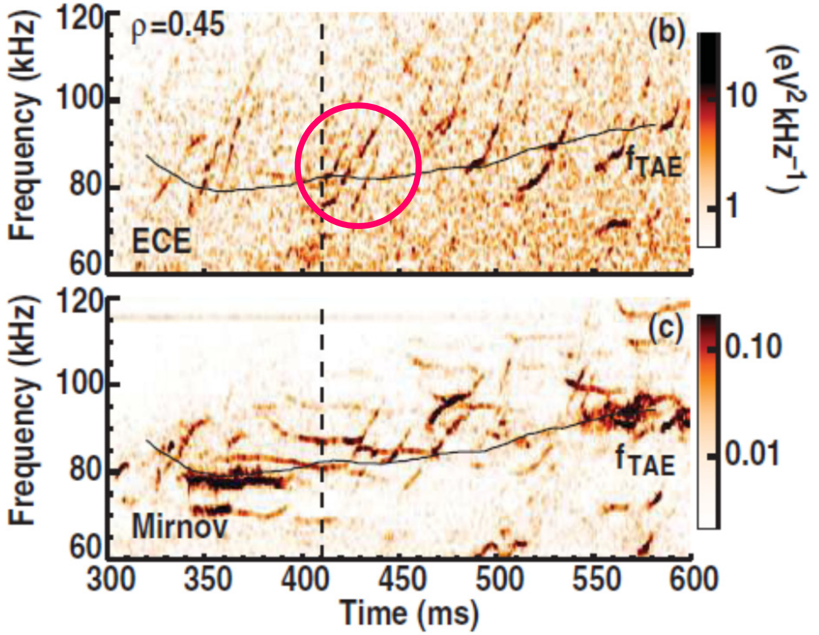
Doppler effect on AE frequencies is important for large *n* AEs in tokamaks and ST plasmas heated by tangential NBI.

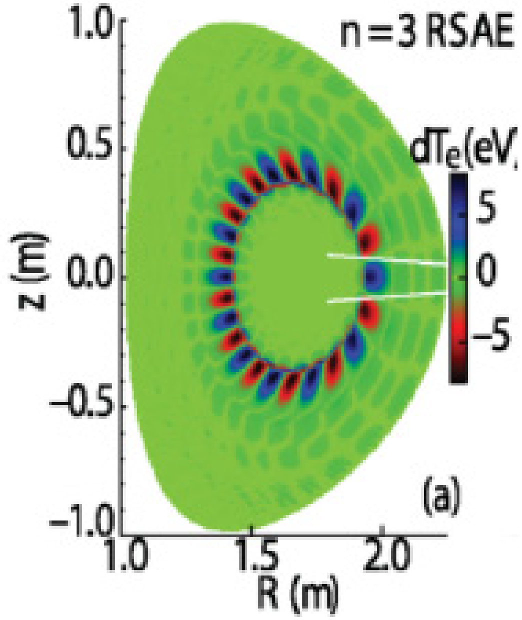
In LHD, only low *n* AEs are excited on the condition of low toroidal rotation speed < 30 km/s , where *R*~3.6m-3.9m.
=> Doppler effect can be neglected, because $f_{Doppler} \sim n$ (kHz).

Some Recent Topics

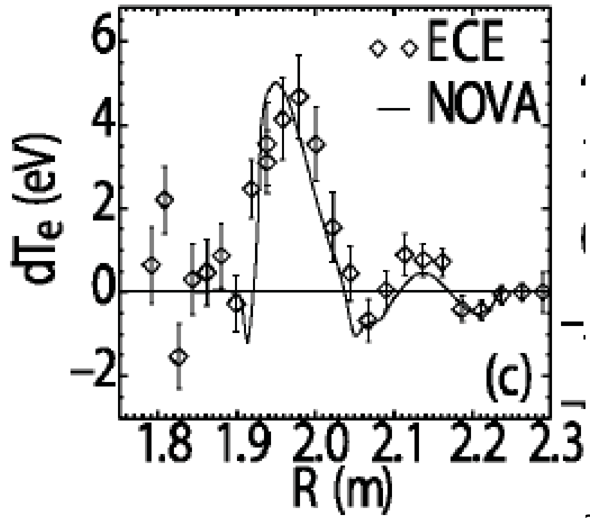
1D Structure of RSAE Measured by ECE

DIII-D





$$\frac{\tilde{T}_e}{T_e} = -(\gamma-1)\nabla\cdot\xi - \xi\cdot\nabla T_e / T_e$$



Internal structure of RSAE measured by high spatial resolution ECE:

Excellent agreement with NOVA (ideal MHD code)

M.A. Van Zeeland et al., PRL(2006).

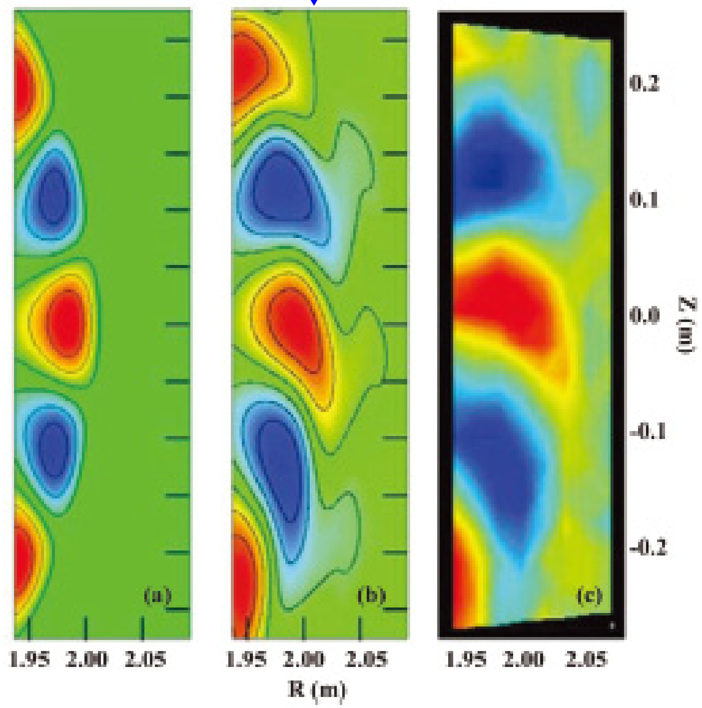
2D Structure of AEs Measured by ECEI

DIII-D

Calculated RSAE by ideal MHD(NOVA)

Calculated by TAEFL

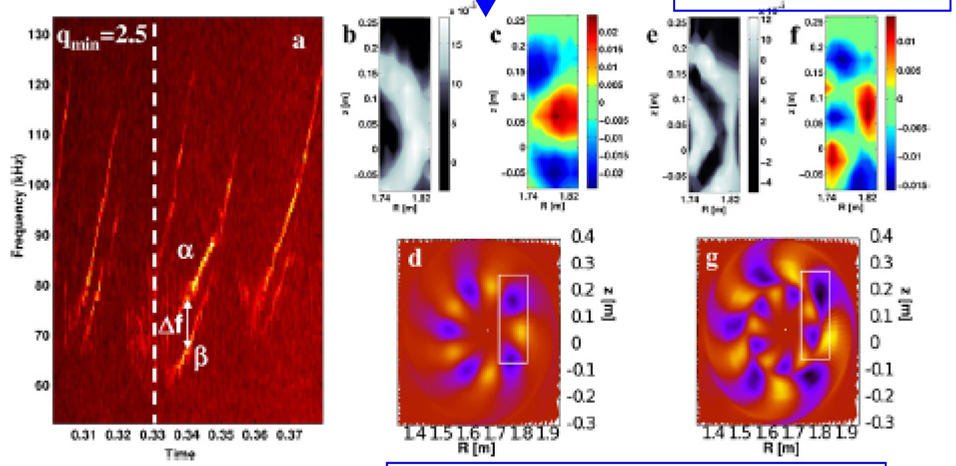
Experimental data by ECEI



AUG

p=0 RSAE measured By ECEI

p=1 RSAE by ECEI



Calculated by LIGKA

Poloidally twisted structure of RSAE due to energetic ion effects

⇒ Good agreement with a gyro-fluid code TAEFL

B.J. Tobias et al., PRL & PoP (2011)

2D structures of RSAE with *p*=0 and *p*=1 due to low magnetic shear

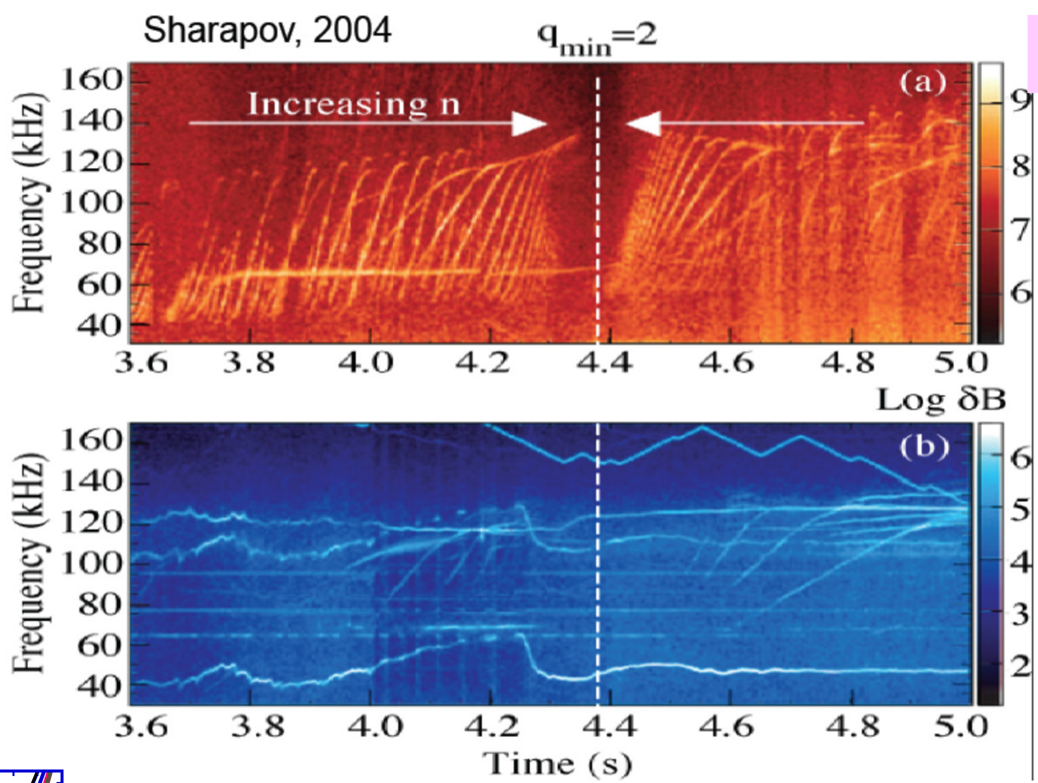
⇒ Good agreement with a linear gyro-kinetic code LIGKA

I.G.J. Glassen et al., PPCF(2011)

Characteristic Sweeping of RSAE Frequency (Alfven Cascade)

Upward sweeping of RSAE frequency during q_{min} decrease in time

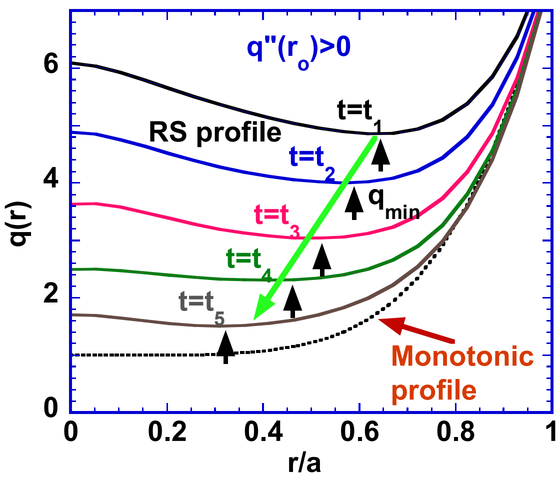
EP effects are important for upward frequency sweeping.



JET

- Interferometer
- Magnetic probe

S. Sharapov et al., PRL (2004)



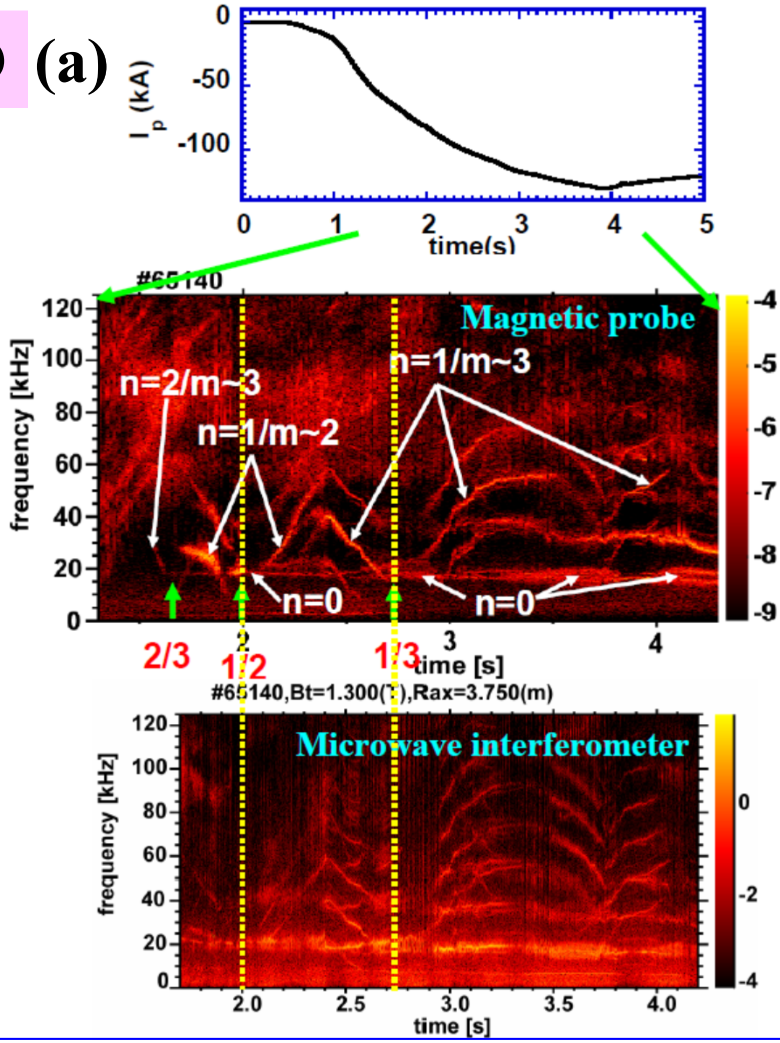
RSAEs are more clearly detected by interferometer than magnetic probe because of internal mode.

Dispersion relation of RSAE:

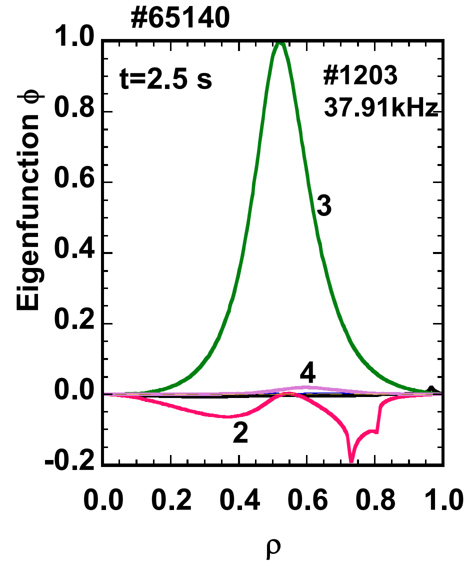
$$\omega^2 - \frac{\upsilon_A^2}{R^2}\left(n - m\frac{\iota}{2\pi}\right)^2 - [\omega_{GAM}^2 + \omega_{\nabla P + \nabla F}^2] = 0$$

RSAEs in a Reversed Shear Plasma on LHD

LHD (a)



(b) Calculated by AE3D

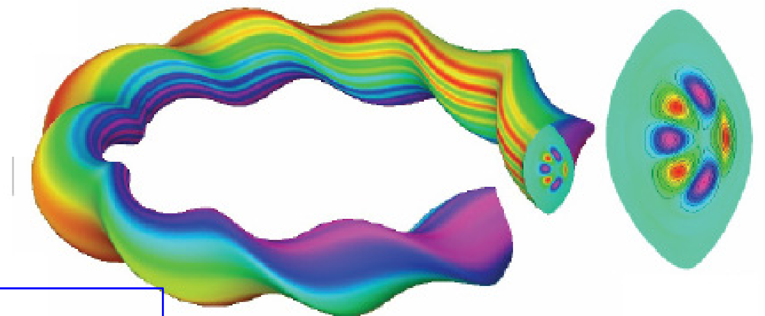


LHD: $q''(r_o)<0$

Tokamak $q''(r_o)>0$

K. Toi et al. PRL(2010)

(c) Calculated by AE3D



D.A. Spong et al.
22th IAEA FEC (2008)

f_{RSAE} is swept with the increase of q_{max} in time
=> downward sweeping to upward sweeping via f_{min}

$f_{min} \approx f(n=0 \text{ mode})$ => EP driven GAM

Frequency Sweeping in RSAEs

- **Eigenmode equation for RSAE *localized at* r=r$_o$ (zero shear surface):**

$$\frac{\partial}{\partial x}(S+x^2)\frac{\partial}{\partial x}U_m+(Q-S-x^2)U_m=0$$

$$x=m(r-r_o)/r_o$$

H.L Berk et al., PRL 2001.
F. Zonca et al., PoP 2002.
B.N. Breizman et al., PoP 2003.
G.Y. Fu & H.L. Berk, PoP 2006.
S.V. Konovalov, PoP 2004.

$$Q=Q_{hot}+Q_{tor}+Q_{press}+Q_{dens}>\frac{1}{4}$$

$$-k_{mo}=(m-nq_o)/q_o,\quad \omega_o=\pm\frac{V_A}{R_o}\left|-k_{mo}\right|,$$

$$<j_{//h}>\approx eV_{//h}<n_{//h}>$$

Dominant terms in tokamaks and LHD

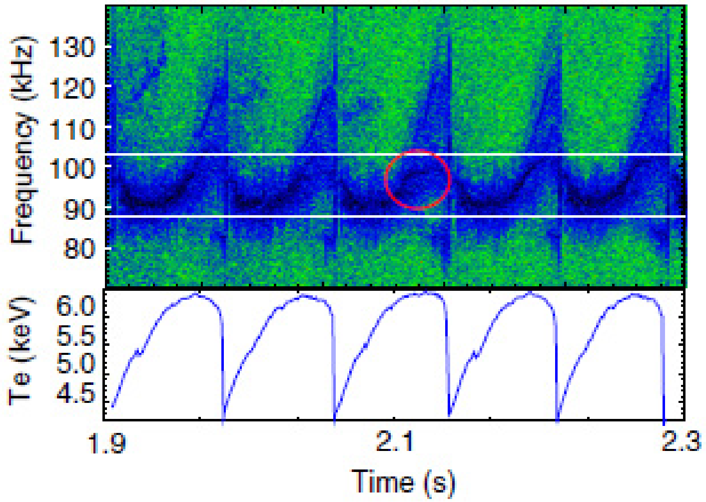
$$Q_{hot}\approx q_o(-k_{mo})\frac{q_o}{r_o^2q_o''}\frac{\omega_{ch}}{\omega_o}\left[1\pm\frac{V_{//h}}{V_A}\frac{(-k_{mo})}{\left|-k_{mo}\right|}\right]_{r=r_o}\left(-\frac{r_o}{\rho_i}\frac{d\langle\rho_h\rangle}{dr}\right)_{r=r_o}$$

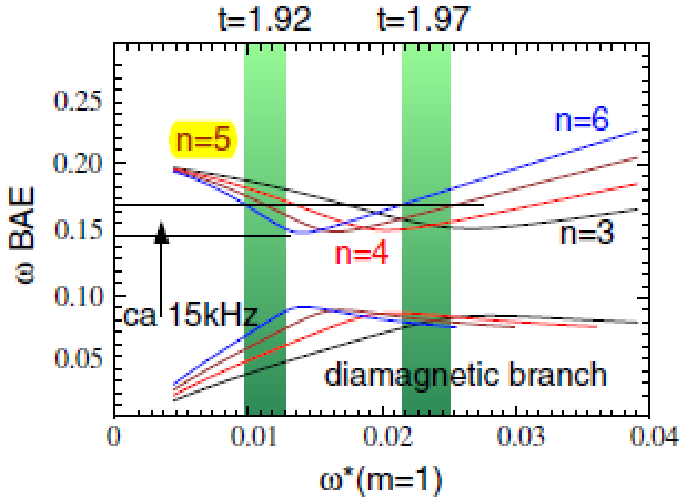
$$Q_{press}=\frac{mq_o}{(-k_{mo})}\frac{q_o}{r_o^2q_o''}\left[\frac{4\Delta'\bar{\omega}^2\alpha-\alpha^2/2q_o^2}{1-4k_{mo}^2q_o^2}+\frac{\bar{\kappa}_r\alpha}{q_o^2}\right]$$

K. Toi et al. PRL(2010)

Tokamak: *Q*>1/4 in upward sweeping=> existence of RSAE
***Q*<1/4 in downward sweeping => no existence of RSAE**
(rarely observed => "quasi-mode" ?)
LHD: Q>1/4 by Q_{hot} in downward sweeping and by Q_{press} in upward sweeping
=> Downward to upward sweeping sequentially

Low Frequency Alfven Eigenmodes in AUG





$$\omega^2\left(1-\frac{\omega_{*p}}{\omega}\right)-k_\parallel^2\omega_A^2R_0^2=2\frac{v_{thi}^2}{R_0^2}\left(-\left[H(x_{m-1})+H(x_{m+1})\right]\right.$$
$$\left.+\tau\left[\frac{N^m(x_{m-1})N^{m-1}(x_{m-1})}{D^{m-1}(x_{m-1})}+\frac{N^m(x_{m+1})N^{m+1}(x_{m+1})}{D^{m+1}(x_{m+1})}\right]\right)$$

Weakly driven beta induced AEs (BAEs) during a sawtooth cycle.
n=5 BAE frequency predicted by the kinetic BAE/GAM dispersion relation evaluated at q=1 BAE accumulation point.
It is confirmed by a linear gyro-kinetic code LIGKA.
The frequency and its evolution is consistent with experiments.
=> MHD spectroscopy

Ph. Lauber et al., PPCF (2009)

EP Driven Geodesic Acoustic Mode in Tokamas

EP driven GAM: n=0 mode destabilized by EPs (GAM: N. Winsor, PF(1968))

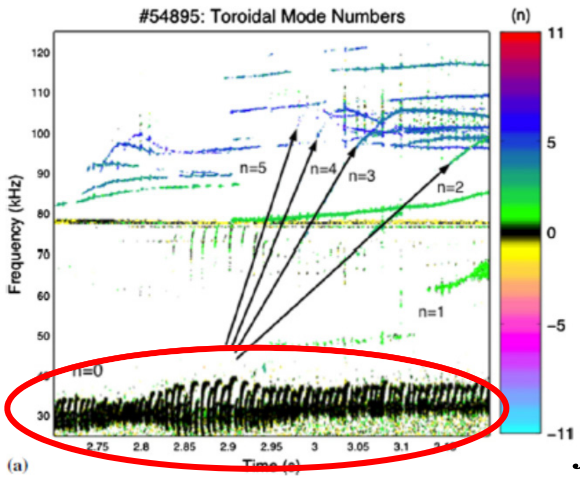
GAM induced by drift waves => localized mode and electrostatic

GAM destabilized by EPs => global modes and partially electromagnetic

In ICRF heated JET plasma: continuous excitation by $\frac{\partial f}{\partial \lambda} \neq 0$ **(H.L.Berk et al., NF(2006))**

In ctr-NBI heated DIII-D: bursts by $\frac{\partial f}{\partial \lambda} \neq 0$ **and/or** $\frac{\partial f}{\partial E} > 0$ **(R. Nazikian et al., PRL(2008))**

GGAM (EGAM) in ICRF heated JET plasma



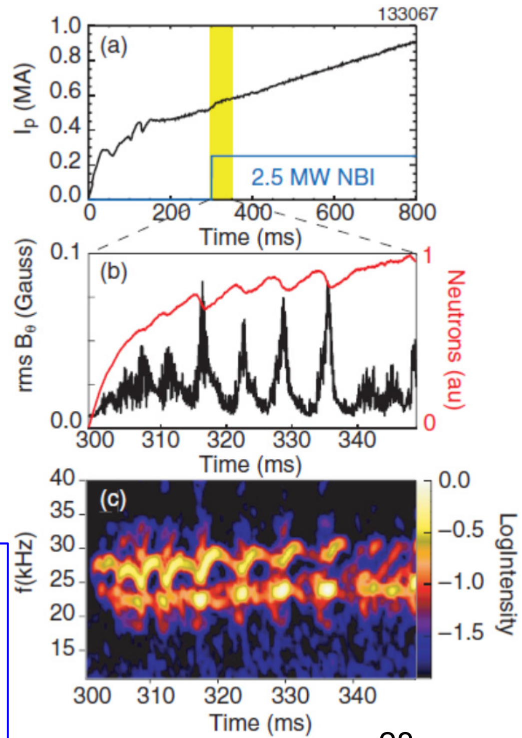
EGAM in DIII-D plasma with ctr-NBI

EGAM theory

G.Y. Fu, PRL(2008)

H.L. Berk, NF(2010)

$f_{EGAM} = f_{GAM} \sim f_{GAM}/2$



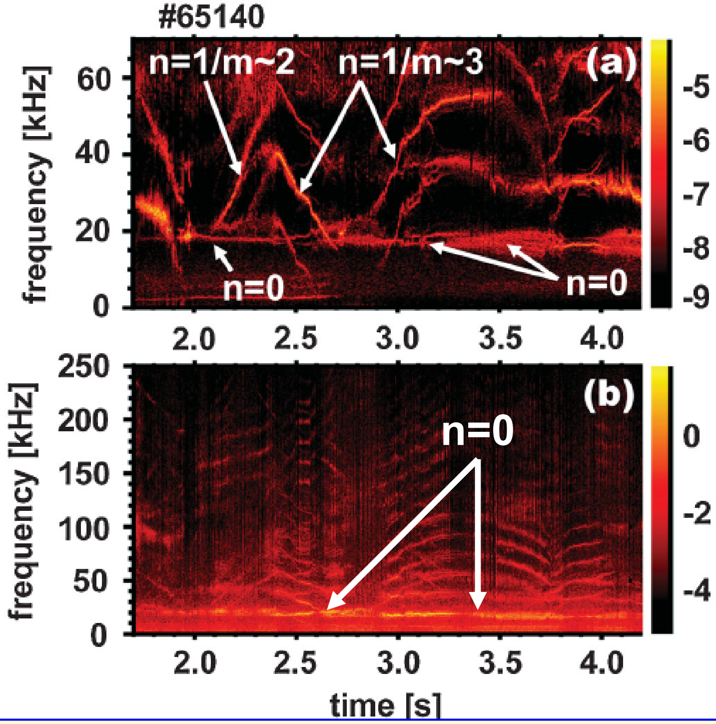
EP losses are induced by EGAM bursts.

R. Nazikian et al., PRL (2008)

G.L. Kramer et al., PRL (2012)

Two Types of EP Driven GAM on LHD

Type I: Quasi-stationary excited type



Quasi stationary excitation
in Reversed shear plasma

$\langle n_e \rangle = 0.4\text{x}10^{19} – 1.0\ \text{x}10^{19}\ \text{m}^{-3}$

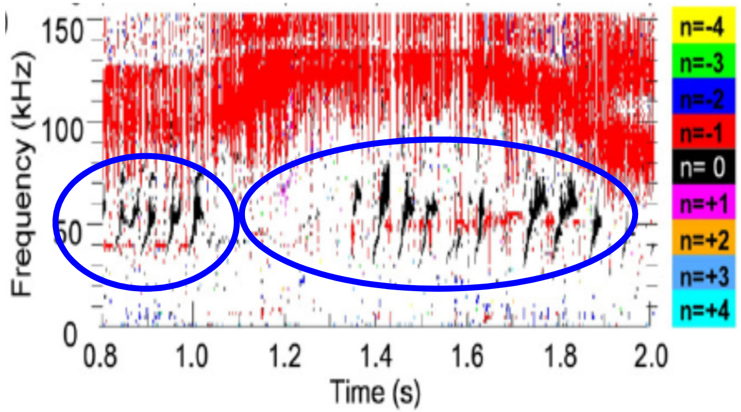
$\beta_{hot} \lesssim \beta_{bulk}$

RS plasmas with counter NBCD

Excited by $\frac{\partial f}{\partial \lambda} \neq 0$

K. Toi et al., PRL (2010)

Type: Bursting mode type



Normal shear plasma

$\langle n_e \rangle \leq 0.1\text{x}10^{19}\ \text{m}^{-3}$ (n_h/n_e~0.1)

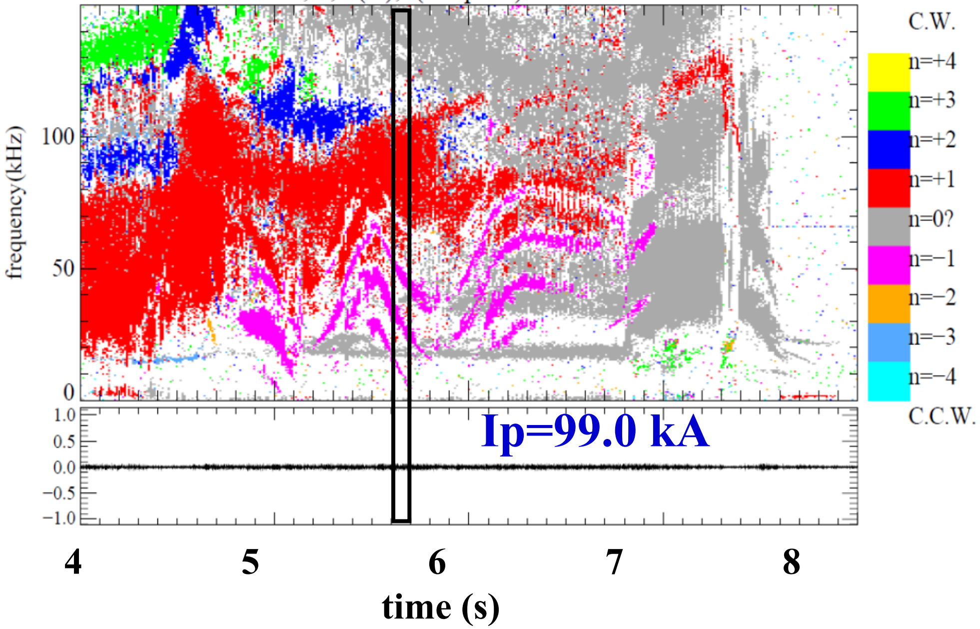
$\beta_{hot} >> \beta_{bulk}$ (very long $\tau_s \gtrsim 2$ s)

Excited by $\frac{\partial f}{\partial E} > 0$ and $\frac{\partial f}{\partial \lambda} \neq 0$

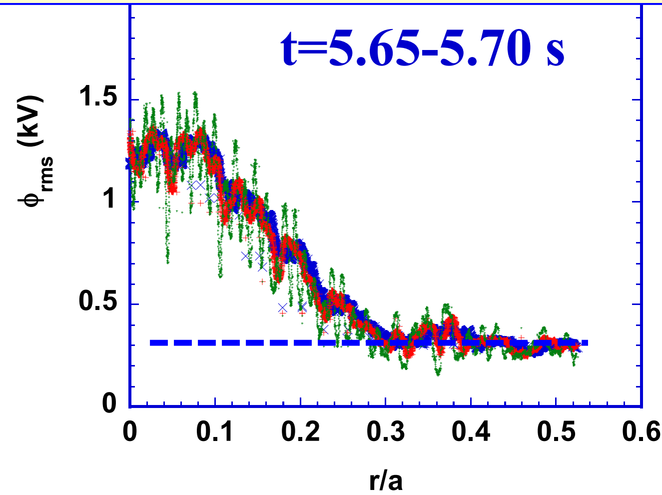
T. Ido et al., 18th ISHW (2012)

Large potential fluctuation amplitude of 2 keV~ 7 keV in both EP driven GAM

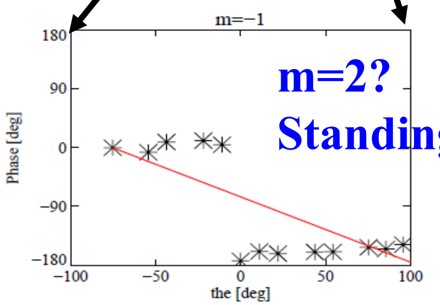
Magnetic & Potential Fluctuations of EP-Driven GAM in LHD Reversed Shear Plasma



Spatial overlap of GAM & RSAE
=> 3-wave coupling



b_θ probe array

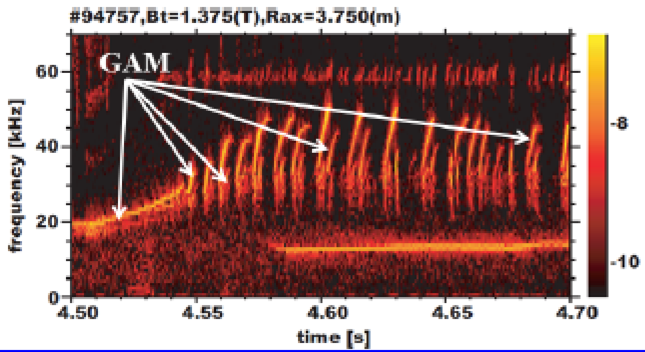


Nonlinear evolution of EP driven GAM

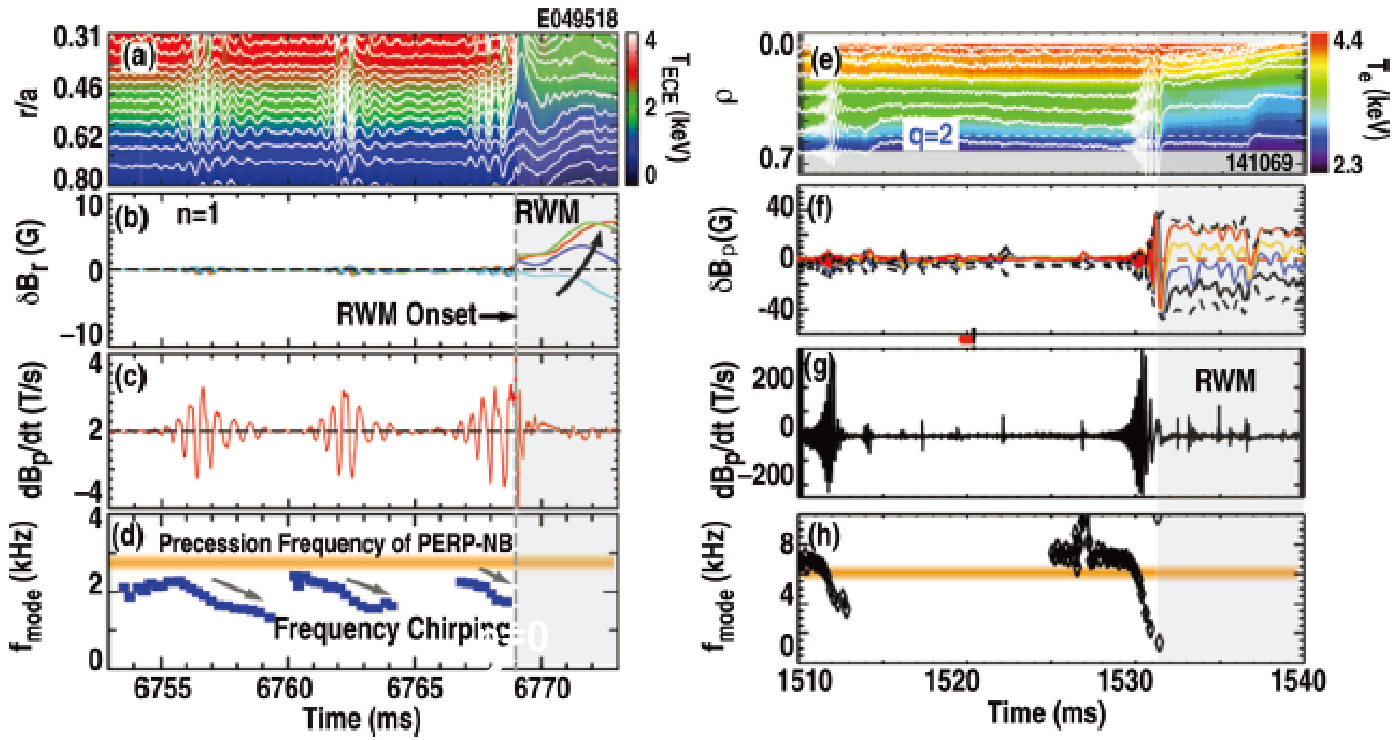
Pitch-fork splitting

Frequency chirp-up and down during ECH

K. Toi, PFR (2013).



EWM/ Off-Axis Fishbone Instabilities in Tokamaks



EWM/ Off axis-fishbones excited by trapped EPs at q=2 in JT-60U and DIII-D

Destabilization above ideal beta limit

Very large magnetic perturbations of ~ 1G

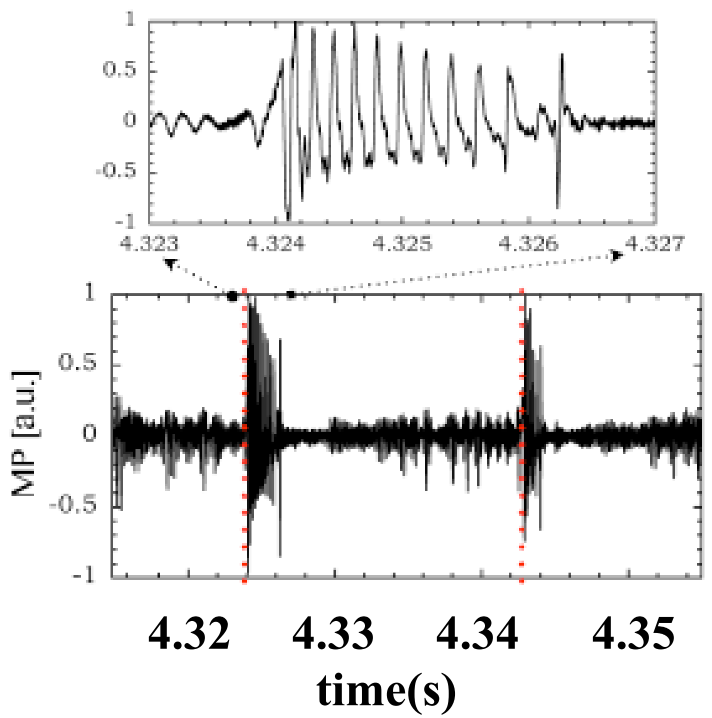
This mode triggers RWM and sometimes ELMs.

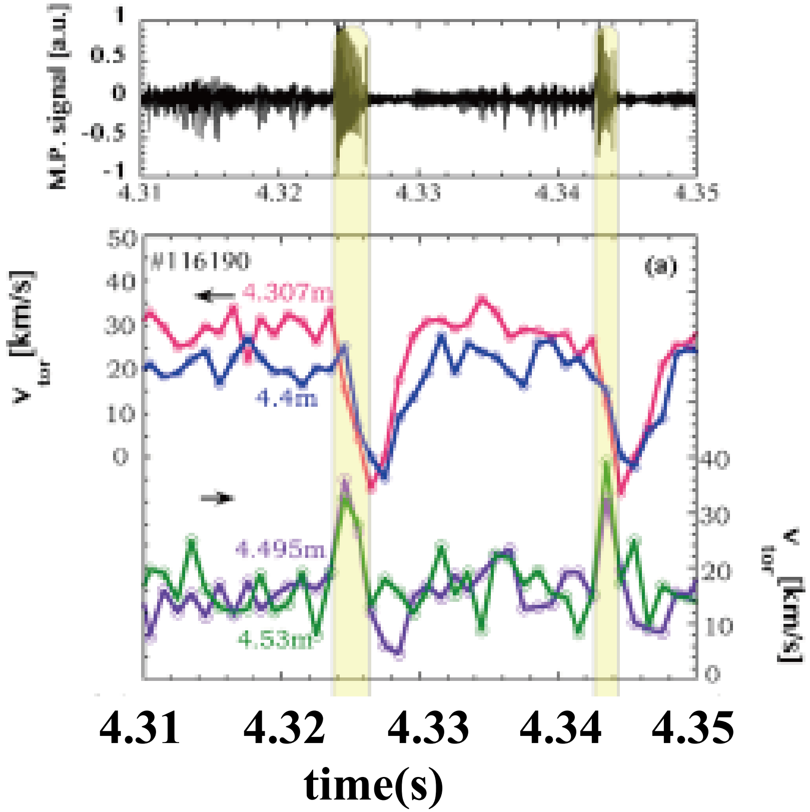
G. Matsunaga et al., PRL (2009)

M. Okabayashi et al., PoP (2011)

G. Matsunaga et al., 24th IAEA FEC, San Diego, 2012.

Off-Axis Fishbone Instabilities on LHD





Resistive interchange mode destabilized by helical-ripple trapped EPs at q=1 on LHD => similar to off-axis fishbones in tokamaks

Initial frequency ~ Precession poloidal drift frequency of initial beam energy (E=40 keV)

Strong drop of toroidal flow velocity at q=1 surface

X.D. Du et al., JPS meeting, March 2013, Kansai-gakuin Univ.

Nonlinear Evolution of AEs (1)

Kinetic instability near threshold (bump-on-tail instability model)

Berk-Breizman model: H.L. Berk et al., PRL (1996)

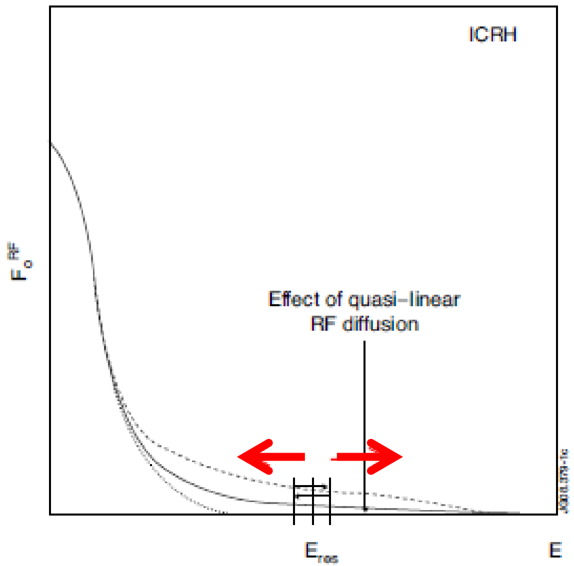
Relaxation process to create unstable f(v)

Quasi-linear v-space diffusion (ICRF)

Krook collision : $\nu_{eff}(f-f_o)$

=> (1)steady-state, (2)periodic, (3)chaotic, (4)explosive(burst)

Good agreement with JET data

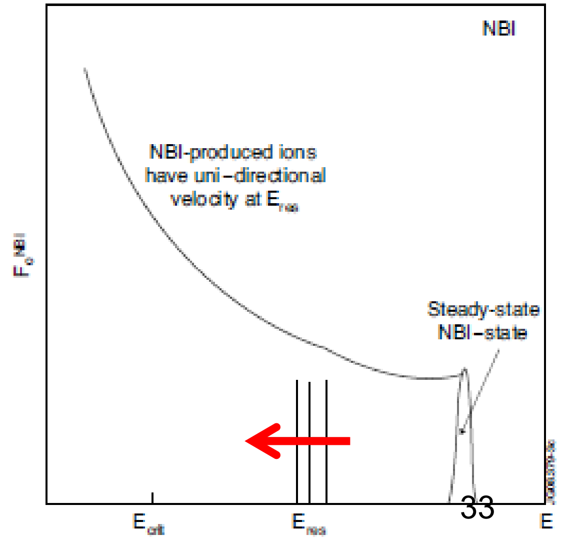


Lilley model: M.K. Lilley et al., et al., PRL (2009)

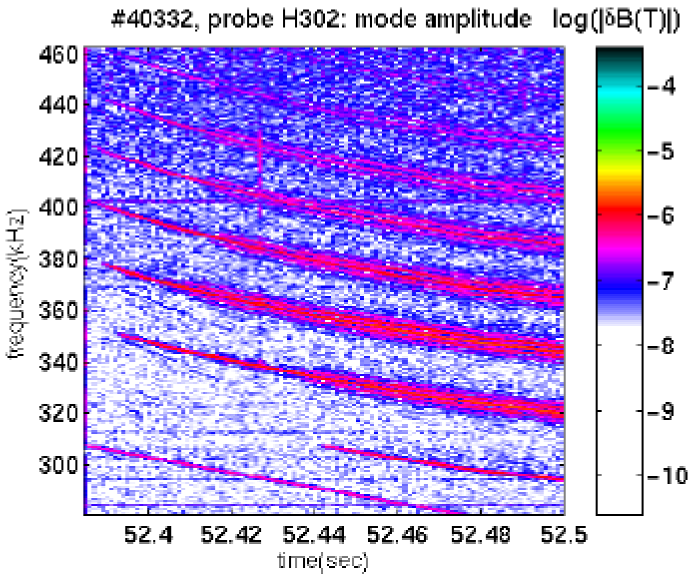
Electron drag (NBI)

=> Only " explosive(burst)" is possible

Good agreement with MAST & JET



Nonlinear Evolution of AEs (2)



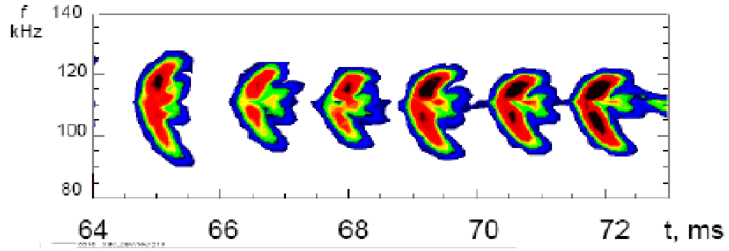
Pitchfork splitting with the same *n* (JET)

A. Fasoli et al., PRL(1998)

Chaotic regime (JET)

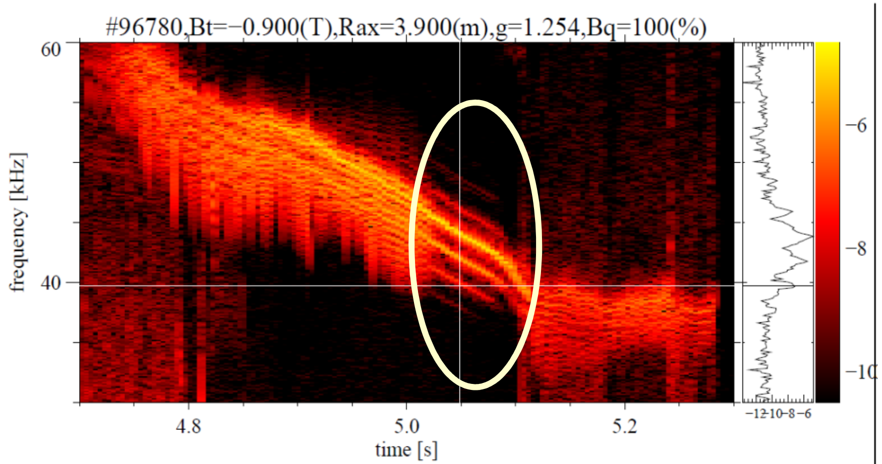
R.F. Heeter et al., PRL(2000)

Good agreement with B-B Model



Explosive TAE on MAST 1n an el. drag dominant case （rapid frequency sweep）

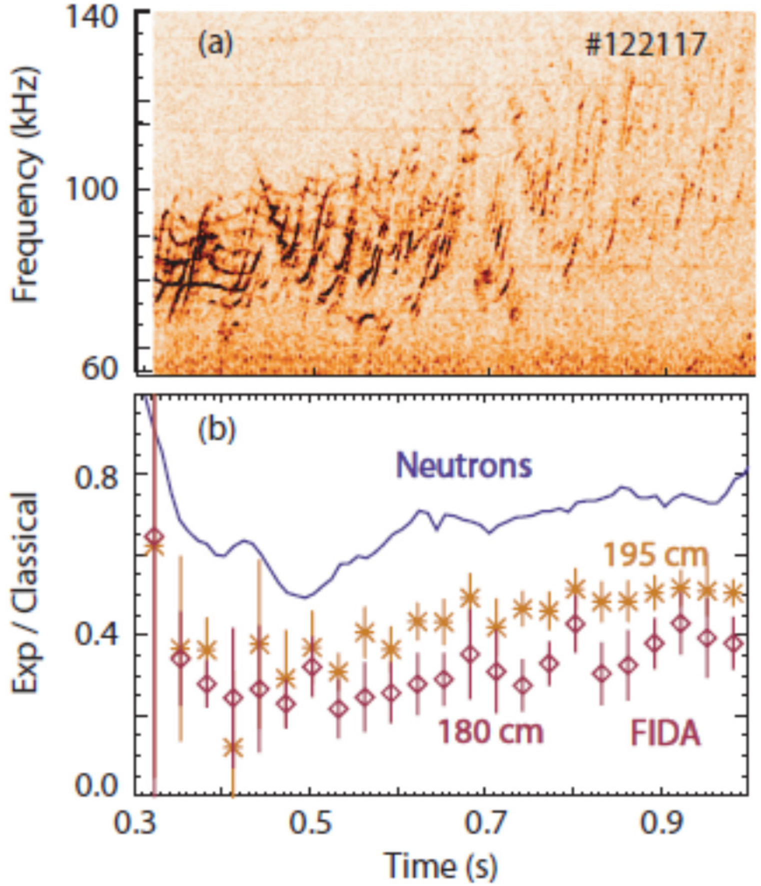
Good agreement with Lilley's theory



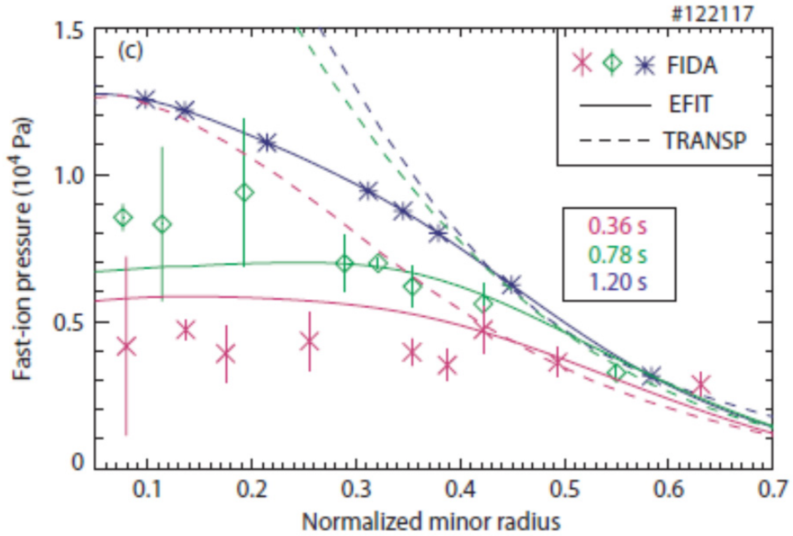
Pitch fork splitting and steady state regime on LHD in an el. drag dominant case

Contradiction to Lilley's theory

Energetic Ion Transport from Core to Edge by TAE & RSAE



DIII-D



Radial profile of confined energetic ions Are obtained by FIDA (fast ion-fast ion charge exchange recombination)

Large deficit of EPs in the plasma central region by RSAE and TAE, compared with that on no AEs (Redistribution of EPs)

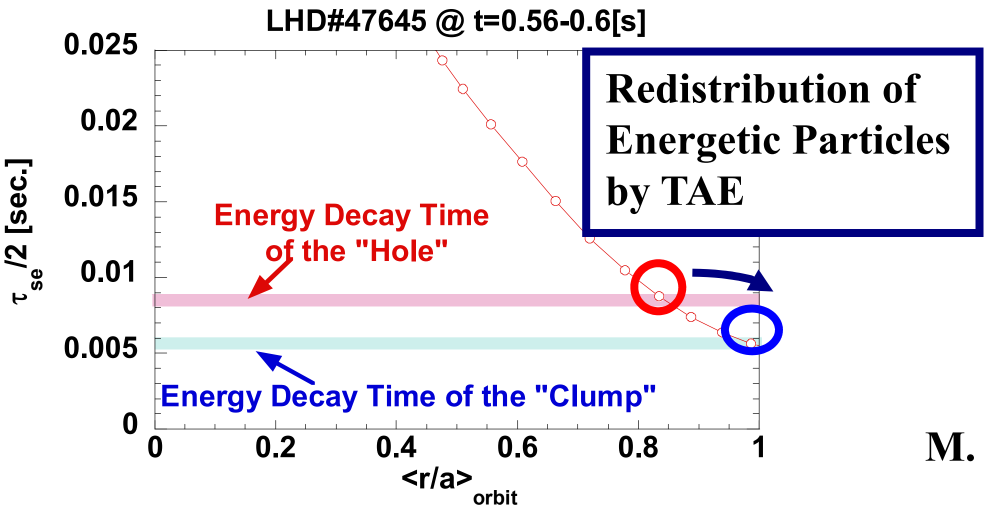
W.W. Heidbrink et al., PRL (2007)

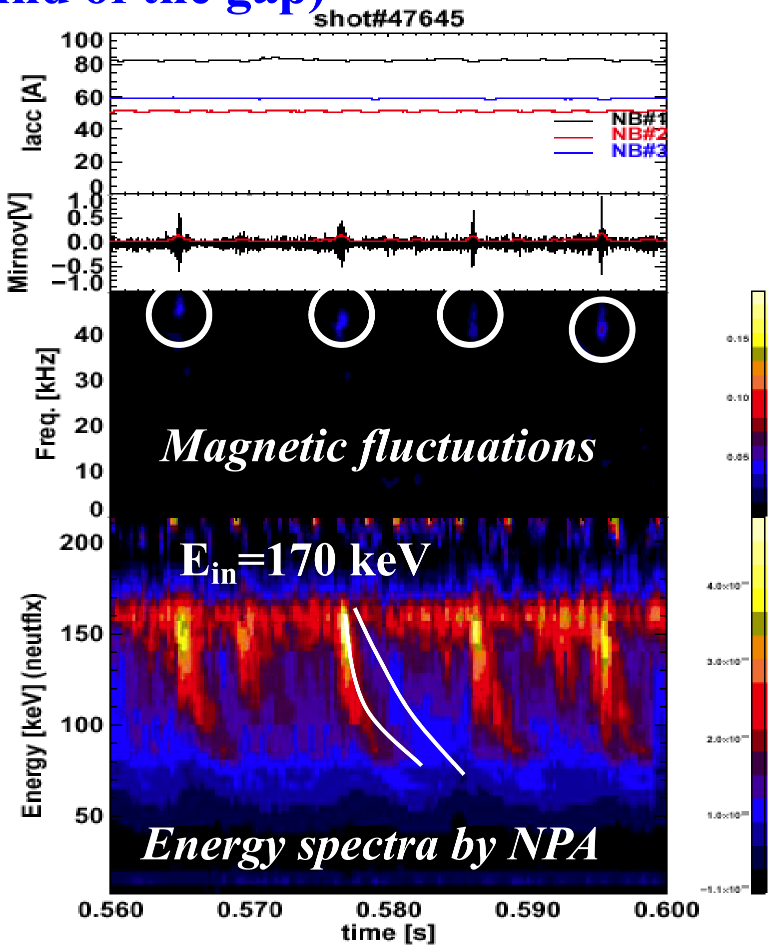
Clump-Hole Pair Formation in Phase Space by TAE Bursts on LHD

Rax=3.6m, Bt=-0.5T (very low field)=> Large orbit deviation of 170 keV beams
TAE peak at r/a~2/3 (*f* close to the upper bound of the gap)

- **The 'hole' starts from 153keVand its typical decay time is τ_s=8.3[ms]**
- **The 'clump' starts from 153keV and its decay time is τ_s=6[ms]**

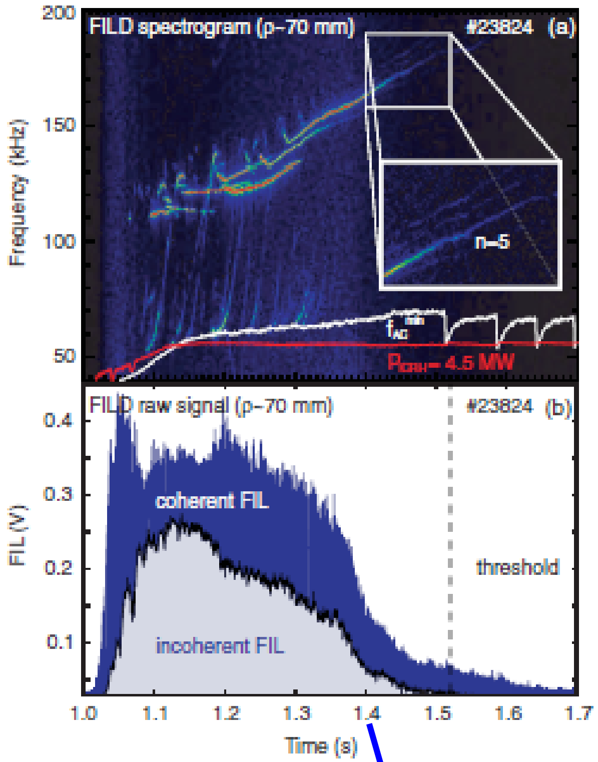
=> Clump is transported to the plasma edge region of short τ_s

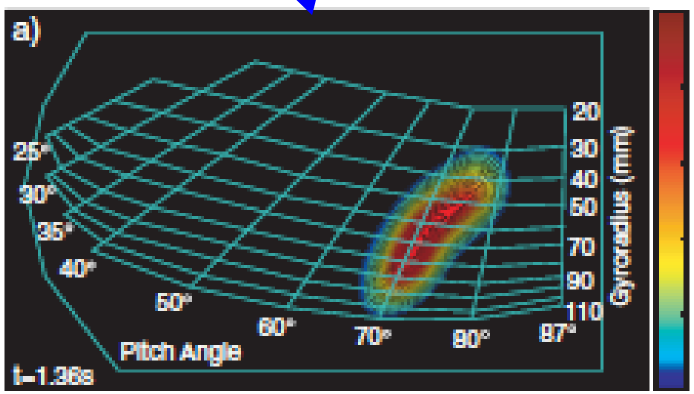




M. Osakabe et al., NF (2006)

Convective and Diffusive Losses by AEs on AUG





Fast ion loss detector (FILD) just inside LCFS

Spectrogram of FILD signal:

Coherent fluctuations by RSAE & TAE

(Resonant interaction between EPs and AEs)

Waveform of FILD signal

Incoherent base plus coherent fluctuations

Coherent loss (Γ_{coh}): convective loss($\propto b_{TAE}$)

Incoherent loss (Γ_{incoh}) :diffusive loss ($\propto b_{TAE}^2$)

M. Garcia Munoz et al., PRL(2010)

In LHD, convective and diffusive losses of EPs by TAE bursts are also observed.

K. Ogawa et al., NF (2013)

Summary and Future Prospect

Summary and Future Prospect

1. **Good agreement between experiments and MHD theories with kinetic effects for various Alfveneigenmodes (frequency, spatial mode structure, …)**

   TAEs, RSAEs/GAEs, HAEs, BAEs,

2. **Progress in AE stability analysis**

   Measurements of low *n* TAE damping rate in JET and C-Mod

   => Good agreement with theories (ITPA)

   Under investigation on damping rate of mid *n* (=10-20) TAEs in JET

   Code bench mark test of TAE growth rate in ITPA EP-TG

   (Less information of EP distribution function in experiments)

3. **Intensive Studies of nonlinear AE studies**

   Rapid frequency chirping, spectrum splitting, chaotic spectra

   => Phase space information may be extracted from nonlinear behaviors of AEs.

Summary and Future Prospect

4. **Loss and redistribution of energetic ions by EP driven modes in tokamak and helical/stellarators**

5. **Possibility of radial transport of well-slowed down energetic ions（E=5-10T_e) by micro-turbulence**

6. **Favorable aspect of energetic ion driven modes**

   (1) MHD spectroscopy by linear characters of EP driven modes

   => Precise information of q-profile

   => Applicability to DEMO

   (2) Stability control of EP-driven modes through *Phase Space Engineering*

   NBI or ICRF +externally applied MPs

   NBI + ICRF

   (3) Favorable effects of EP driven modes on bulk plasma confinement

   Bulk confinement improvement by flow shear generation

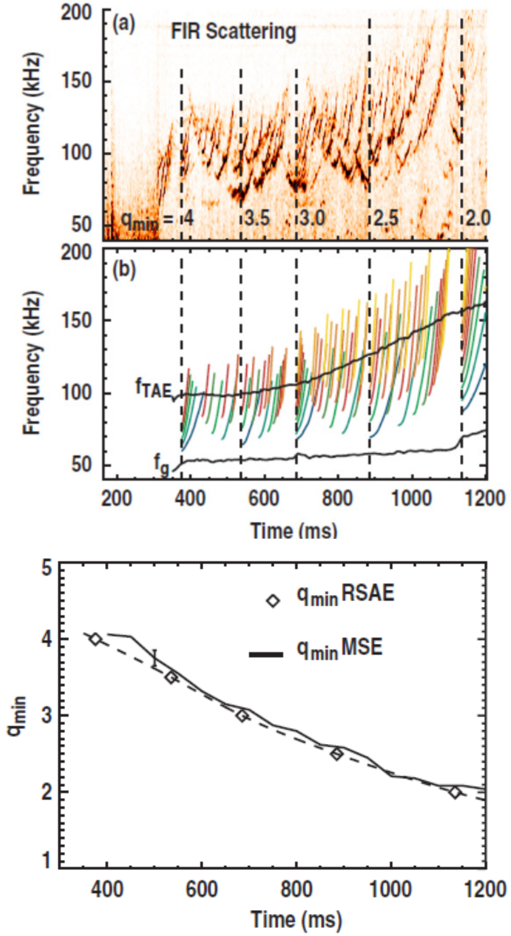
   Slowing down of toroidal current penetration

   => configuration sustainement of RS configuration K. L. Wong et al., PRL (2004)

   Transient confinement improvement (K. Toi et al., PPCF (2010))

MHD Spectroscopy Using EP Driven Global Instabilities

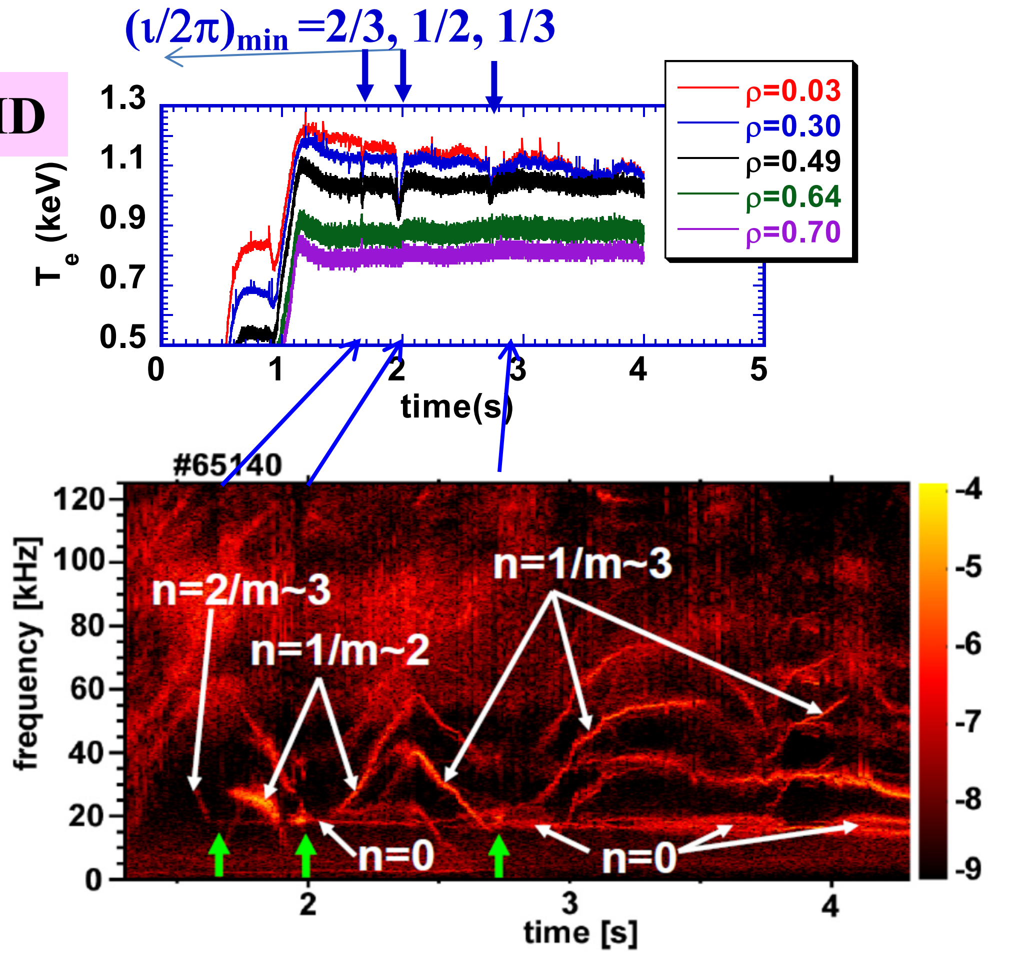
DIII-D



Derivation of q_{min} by RSAE
Good agreement with MSE results

M. Van Zeeland et al., NF 2006.

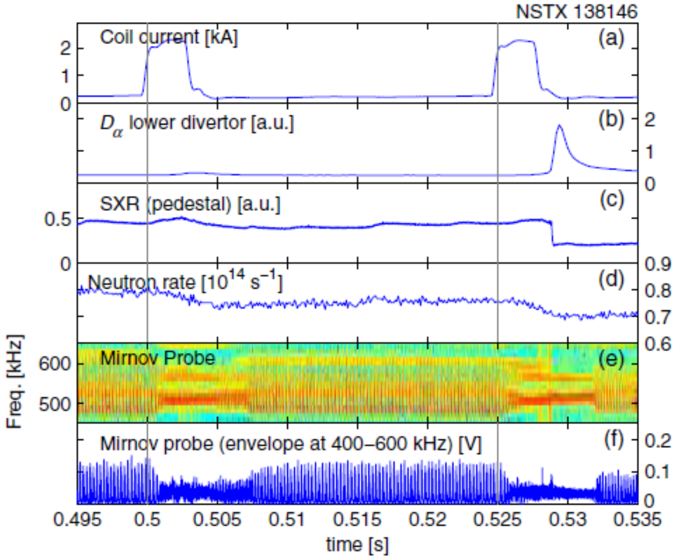
LHD

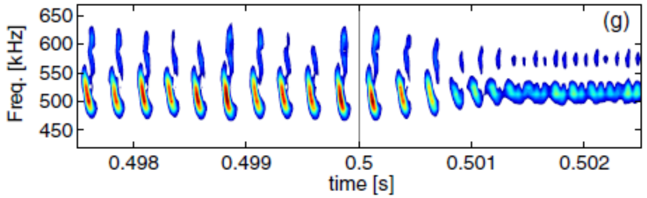


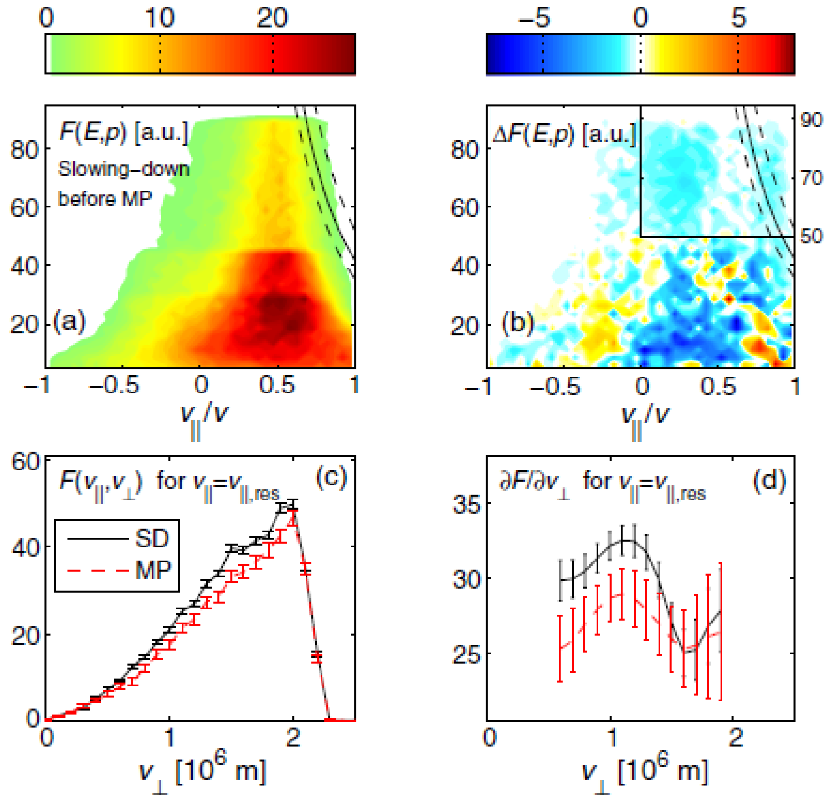
Derivation of q_{max}(=$(\iota/2\pi)_{min}$) by RSAE
Evaluation of β_h from [f_{min} of RSAE = f_{GAM}]

K. Toi et al., PPCF 2010.

AE Mitigation by 3D Magnetic Perturbations on NSTX







Before MPs

1ms after MPs switch-on

Reduction of AE amplitude by large 3D magnetic perturbations (MPs) of δB/B~0.01.

Control of EP distribution function by MPs for MHD stability("Phase space engineering")

Change of $P_h(r)$? Plasma shielding effect?

A. Bortolon et al., PRL 2013.

Sawtooth control by tuned ion heatings through phase space engineering on JET (J.P. Graves et al., Nature Com. (2013))