Theory of Alfvén waves and energetic particle physics in burning plasmas*

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Liu Chen

Dept. of Physics and Astronomy, Univ. of California, Irvine CA
92697-4575, U.S.A.

Acknowledgments: G.Y. Fu, N.N. Gorelenkov, Y. Todo, G. Vlad

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Outlines

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(II) **Linear Shear Alfvén Wave (SAW) and Energetic Particle (EP) Physics**

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- (II.3) Stability Properties: Generic fishbone dispersion relation

(III) **Nonlinear SAW-EP Physics**

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- (III.2) Nonlinear physics of EP Modes (EPMs)

(IV) **ITER Applications**

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(I) Introduction

- Energetic particles (Alpha particles and/or fast ions) integral components of current and ITER burning plasma experiments.
- $V_{EP} \sim V_A$ (Alfvén speed) $\Rightarrow$ Collective excitations of SAW by EPs.
- Superthermal SAW fluctuations $\Rightarrow$ Break EP's adiabatic invariants; J and Ψ (r).

$\Rightarrow$ Anomalous transports (redistribute) in EP's $\left(\varepsilon = v^2/2, r\right)$ phase space

$\Rightarrow$ Potentially significant adverse effects on the performance of burning plasma experiments.

(II) Linear SAW-EP Physics

(II.1) SAW spectra in toroidal plasmas

- SAW – Anisotropic electromagnetic wave in magnetically confined plasmas
  - $\omega^2 = k_\parallel^2 V_A^2 \equiv \omega_A^2,\ k_\parallel = \underset{\sim}{k} \cdot \underset{\sim}{B}/B,\ \underset{\sim}{V}_g = V_A \underset{\sim}{B}/B$
  - $|\omega_A| << \Omega_i;\ \lambda_\parallel \sim R;\ \lambda_\perp \sim \rho_i - a.$
  - Nearly incompressible
- SAW – Fundamental oscillations in laboratory as well as solar/interstellar/magnetosphere plasmas. Important dynamic roles in, e.g., solar corona heating, accelerating aurora electrons
- In toroidal plasmas: Non-uniformities across the magnetic surfaces

  $\Rightarrow k_\parallel = k_\parallel(r), \mathrm{V}_A = \mathrm{V}_A(r) \Rightarrow \omega_A(r) \Rightarrow$ SAW continuous spectrum

(II.1) SAW spectra in toroidal plasmas (continued...)

- Consequences of SAW continuum:
  - Initial perturbations: $\exp[i\omega_A(r)t] \Rightarrow$ perturbations with a finite width Δr decay via phase mixing on a time scale

$$\tau_{pm} \sim \left| \frac{d\omega_A}{dr} \Delta r \right|^{-1} .$$

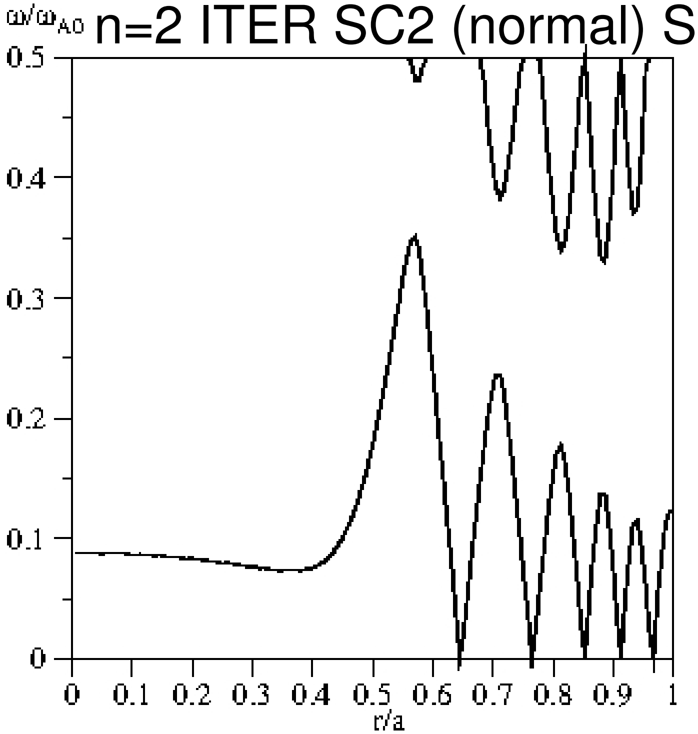
  - Driven perturbation at frequency ω_o
    - $\Rightarrow$ "Singularly" absorbed at the resonant layer $\omega_o^2 = \omega_A^2(r_o)$
    - $\Rightarrow$ Resonant absorption (continuum damping) rate $\propto \dfrac{d\omega_A(r_o)}{dr}$
    - $\Rightarrow$ H. Grad [1969]: phase-mixing and singular absorption – exact analogy with free-streaming and Landau resonance in Vlasov plasma
    - $\Rightarrow$ Kinetic (ρ_i, m_e) and resistivity effects $\Rightarrow$ regularizing the "singular" structures
    - $\Rightarrow$ Kinetic Alfvén wave, radiative damping, etc.

(II.1) SAW spectra in toroidal plasmas (continued...)

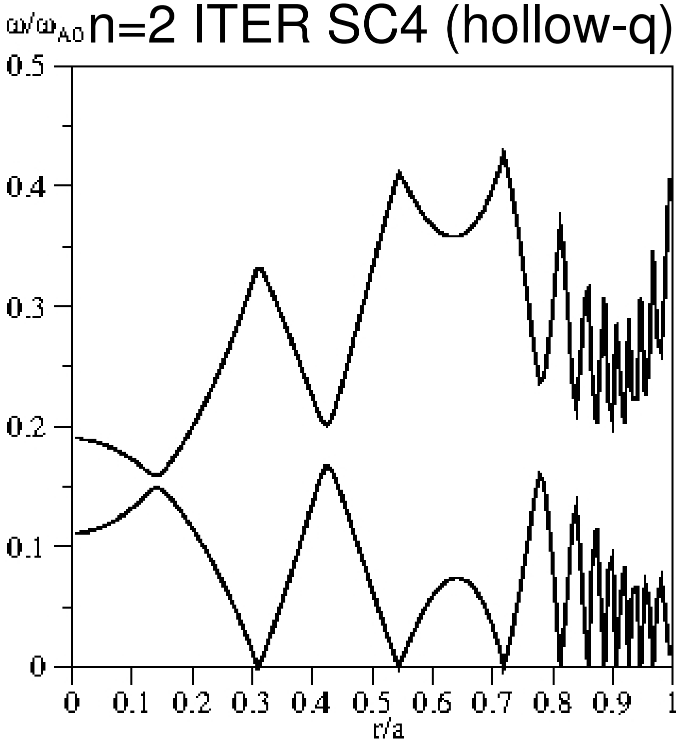
- SAW frequency gaps:
  - ○ Various poloidal asymmetries ⇒ break translational symmetries along **B** into corresponding lattice symmetries.

⇒ Corresponding frequency gaps in SAW continuum.

n=2 ITER SC2 (normal) Scenario



n=2 ITER SC4 (hollow-q) Scenario



G. Vlad, et al., NF **46**, 1, 2006

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(II) Linear SAW-EP Physics

(II.2) Instability Mechanisms

- For SAW waves in $\beta << 1$ plasmas

  $\Rightarrow \delta E_\parallel \approx 0, \ \delta B_\parallel \approx 0$

  $\Rightarrow$ EP experiences $\left(\underset{\sim}{V}_d \times \delta \underset{\sim}{B}_\perp\right)_\parallel$ force; $\underset{\sim}{V}_d =$ magnetic drifts.

- Resonance conditions –
  - Circulating particles: $\omega - k_\parallel v_\parallel - p\omega_t = 0$,

    p=integers, ω_t : transit frequencies.

  - Trapped particles: $\omega - \overline{\omega}_d - p\omega_b = 0$

    p=integers, $\overline{\omega}_d$: toroidal precessional frequency,

    ω_b : bounce frequency.

(II.2) Instability Mechanisms (continued...)

- Expansion free energy
  - Growth rate $\sim \dot{P}_\phi \dfrac{\partial F_{EP}}{\partial P_\phi} \sim n \dfrac{\partial F_{EP}}{\partial r}$

    n: toroidal mode number
  - Instability drive maximizes around

    $k_\perp \rho_{EP,\mathrm{d}}$, $k_\perp \rho_{EP,\mathrm{b}} \sim O(1)$
- Background plasmas provide additional kinetic damping.

(II) Linear SAW-EP Physics

(II.3) Stability Properties

- To nullify/minimize continuum damping

  $\Rightarrow$ localize SAW excitations inside the gaps and/or around $\frac{d\omega_A}{dr} = 0$.

- EP pressure perturbations $\Rightarrow$ instability drive $\Rightarrow$ coupled to SAW vorticity equation via ***B*** curvature.

- Perturbations generally consist of singular (inertial) and regular (ideal MHD) mode structures

  $\Rightarrow$ Generic Fishbone Dispersion Relation

$$i\sqrt{\Lambda^2(\omega)} = \delta\hat{W}_f + \delta\hat{W}_K .$$

(II.3) Stability Properties (continued...)

- Generic Fishbone Dispersion Relation

$$i\sqrt{\Lambda^2(\omega)} = \delta\hat{w}_f + \delta\hat{w}_K.$$

  - ○ $\Lambda^2(\omega)$: inertial-layer contributions due to thermal particles
  - ○ $\delta\hat{w}_f$, $\delta\hat{w}_K$: background MHD and EP contribution in the regular regions.
  - ○ $\Lambda^2(\omega) = 0$: accumulation points of SAW continuum.

- Example: Toroidal AE (TAE) near the lower accumulation point ω_ℓ .
  - ○ $\Lambda^2(\omega) \Rightarrow \omega_\ell^2 - \omega^2$, formally

(II.3) Stability Properties (continued...)

- Two types of modes –
  - ○ Gap Mode (AE) $\Rightarrow \mathrm{Re}(\Lambda^2) < 0 \Rightarrow \mathrm{Re}\left(\delta\hat{w}_f + \delta\hat{w}_K\right) > 0.$
    - $\Rightarrow$ “localization” of AE in the frequency gap.
    - $\Rightarrow$ $\mathrm{Re}(\delta\hat{w}_K)$: Non-resonant EP effects.
    - $\Rightarrow$ various effects in $\mathrm{Re}\left(\delta\hat{w}_f + \delta\hat{w}_k\right)$ can lead to AE “localization” in various gaps $\Rightarrow$ AE “zoology”!!
  - ○ Continuum mode (EPM) $\Rightarrow \mathrm{Re}(\Lambda^2) > 0 \Rightarrow$ EPM inside the SAW continuum
    - $\Rightarrow$ EPM existence: $\mathrm{Im}\left(\delta\hat{w}_k\right) > \sqrt{\Lambda^2}$.

      EP instability drive > continuum damping
    - $\Rightarrow \omega_{EPM}$: EP’s characteristic dynamic frequencies; $\omega_t, \overline{\omega}_d, \omega_b$.
- Similar pictures could also emerge around the upper SAW accumulation point

(II.3) Stability Properties (continued...)

- "Classical" example of EPM: Fishbone instability.
  - $\Lambda^2 \approx \omega^2 \quad \Rightarrow \quad i\omega = \delta\hat{W}_f + \delta\hat{W}_K.$
  - $\omega \sim \overline{\omega}_{db}$
- Lower-frequency SAW gap
  - $|\omega| \sim |\omega_{*i}| \sim |\omega_{ti}|$ of thermal ions

  $\Rightarrow$ (ideal MHD) accumulation point (at $\omega = 0$) shifted by thermal ion kinetic effects

  $\Rightarrow$ New low-frequency gap!
    - Diamagnetic drift: KBM
    - Parallel ion compressibility: BAE
    - ∇T_i and wave-particle resonance: AITG

  $\Rightarrow$ unstable SAW accumulation point

  $\Rightarrow$ "localization" $\Rightarrow$ unstable discrete AITG mode!

Experimental Observations of AEs

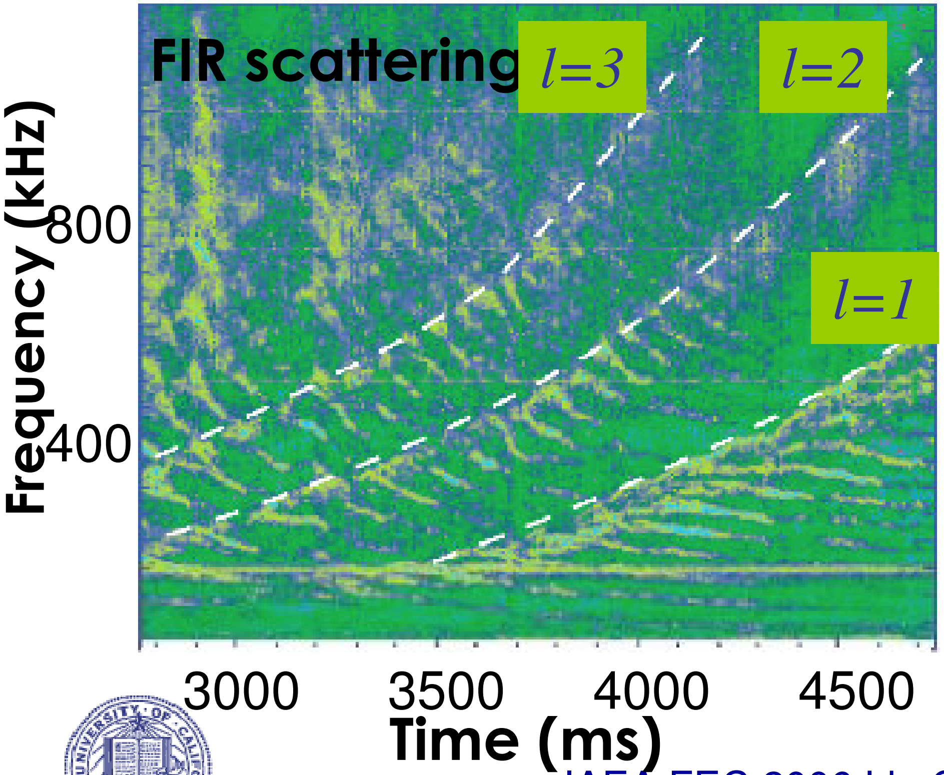
- TAE well documented [Heidbrink et al.]
- Reverse shear AE (RSAE/AC) [Nazikian et al.,]

$\Rightarrow$ up to $n \sim O(40) \Rightarrow k_\theta \rho_i \sim 0(1)$

$\Rightarrow$ demonstrate the destabilization of RSAE/AC via the AITG mechanism.

Observation of sea of
RSAE/AC Alfvén Eigenmodes
in DIII-D

R. Nazikian, et al.,
PRL **96**, 105006, 2006



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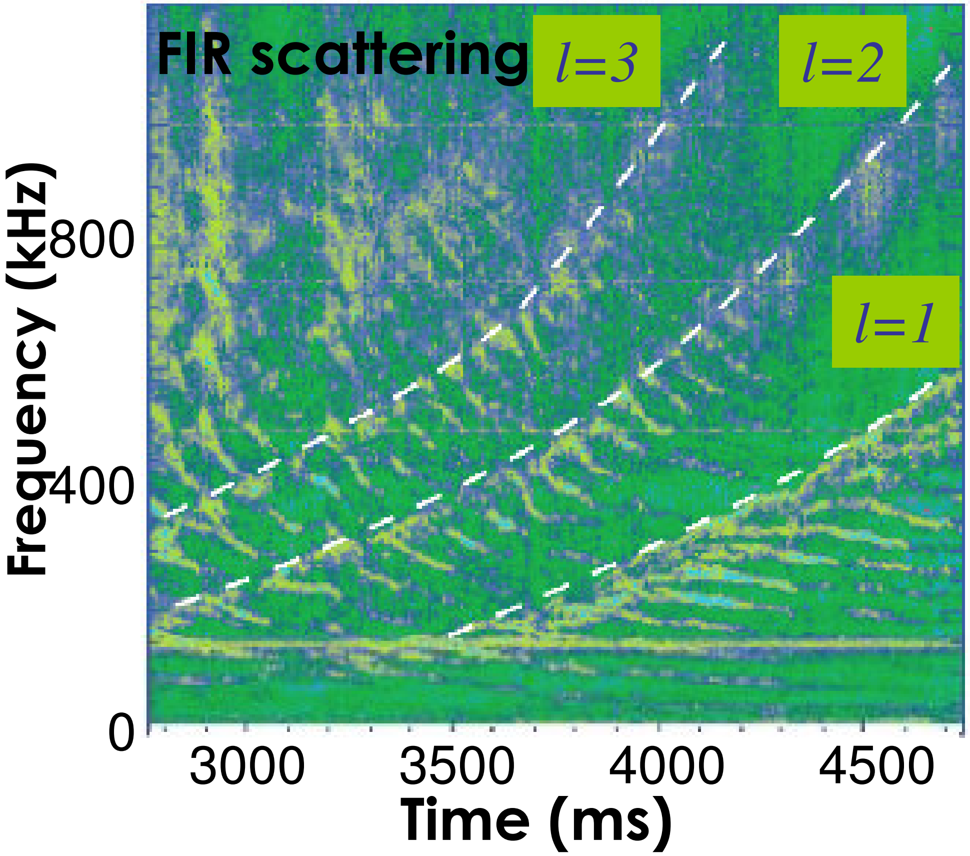
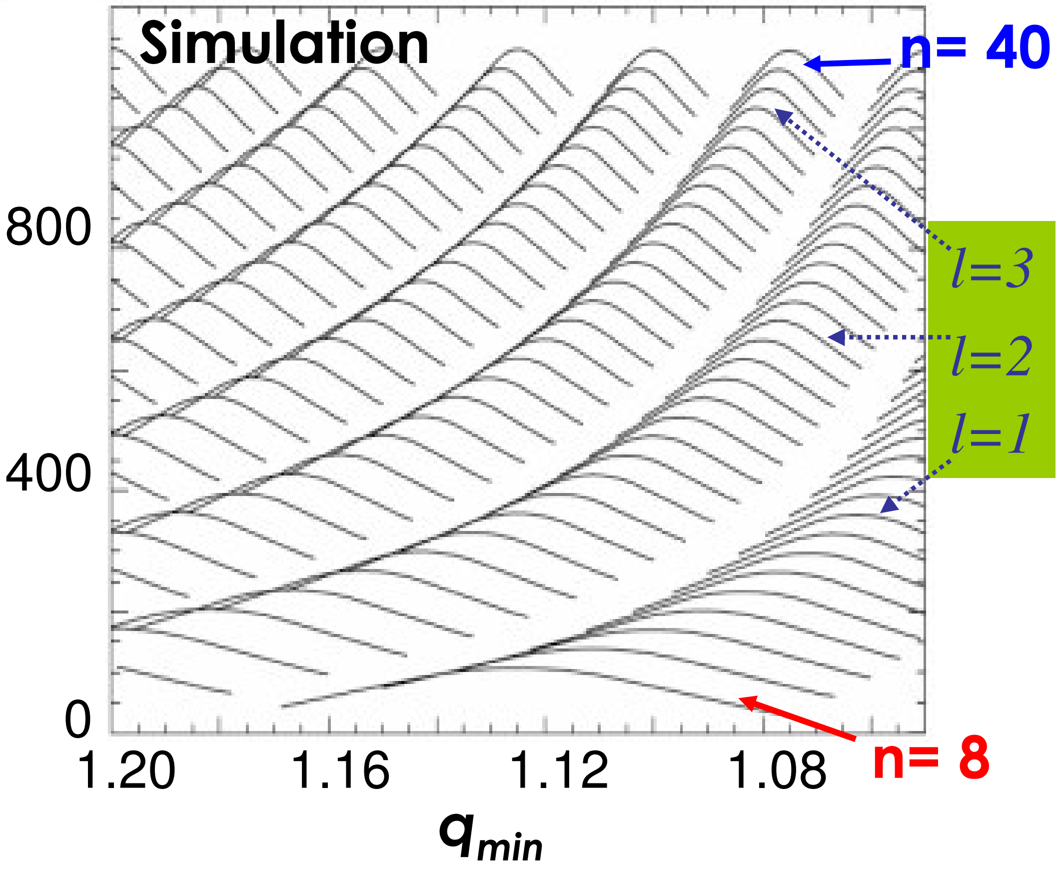
A “Sea of Core Localized Alfvén Eigenmodes” Observed in DIII-D Quiescent Double Barrier (QDB) plasmas





- **Bands of modes *m=n+l, l*=1, 2, …** **$\omega_{n+1} - \omega_n \approx \omega_{rot}$ (CER)**
- **Neutral beam injection opposite to plasma current: $V_{||} \approx 0.3 V_A$**

R. Nazikian, et al., PRL **96**, 105006, 2006

(III) Nonlinear SAW-EP Physics

(III.1) Nonlinear Physics of AE

o Weak instabilities $\Rightarrow \frac{\gamma}{\omega} \sim 0(10^{-2}) \Rightarrow$ weak nonlinear perturbations.

(i) Wave-Trapping Physics [Berk, Breizman, et al.]

o Single linear TAE + nonlinear resonant EP

⇒ analogy to the single-wave bump-in-tail paradigm

o $\omega_{TAE} \Rightarrow \omega_{pe}\,; P_\phi \Rightarrow \mathrm{v}$ $\quad F_{EP}(P_\phi | \mu, J) \Rightarrow F_b(\mathrm{v})$

o Include background dissipation and restoring F_b via collisions (or F_{EP} via source inputs)

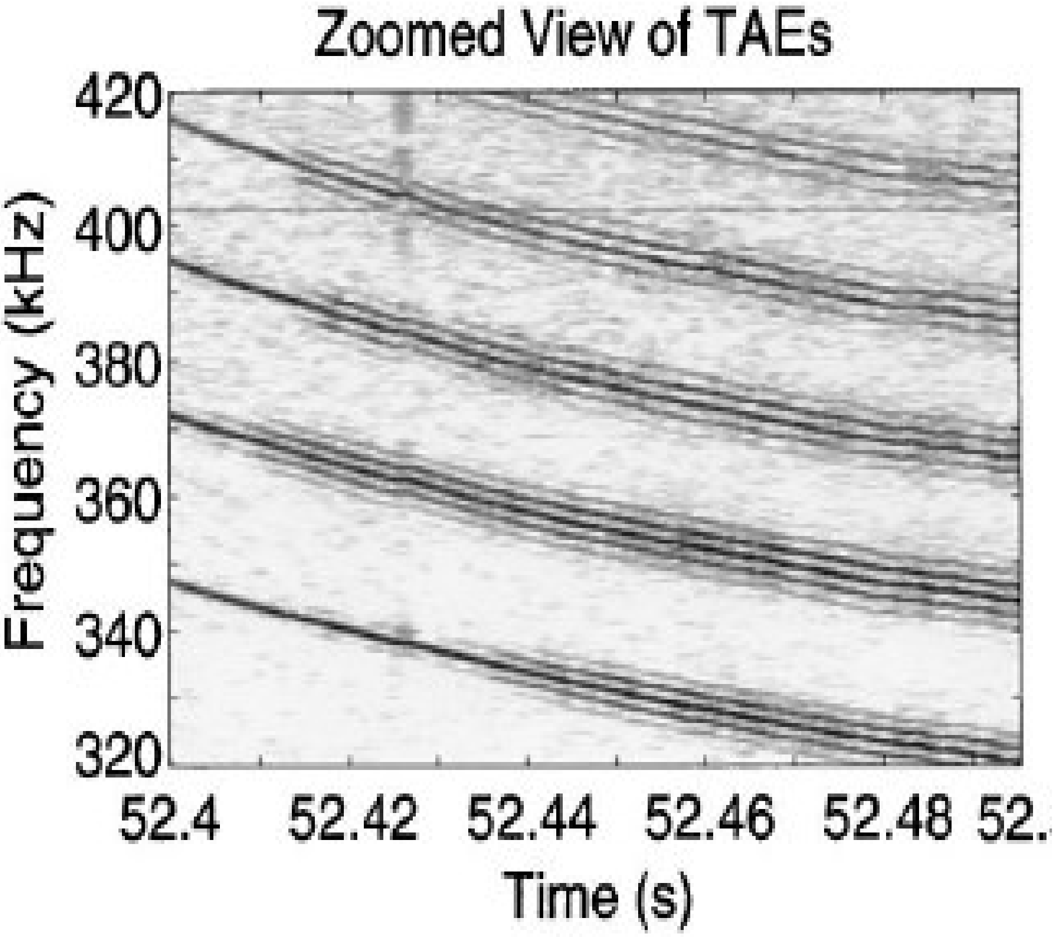
o Wave trapping of resonant EPs

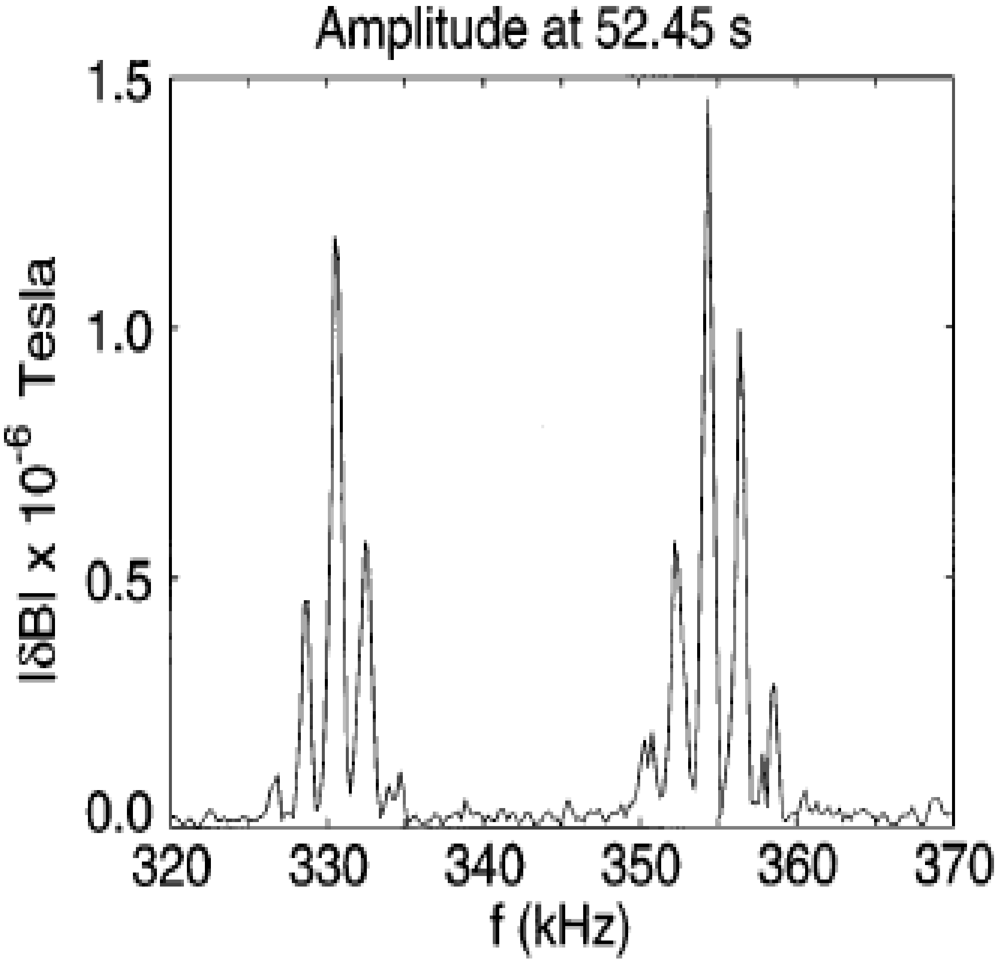
⇒ hole/clump production in $F_b \Rightarrow$ sidebands generation

⇒ Theoretical explanation of JET observations of pitchfork splitting of ω_{TAE} [Fasoli, et al.]

Pitchfork splitting of TAE in JET

Fasoli, et al., PRL **81**, 5564, (1998)





(III) Nonlinear SAW-EP Physics

(III.1) Nonlinear Physics of AE (continued…)

(ii) Nonlinear Frequency Shifts

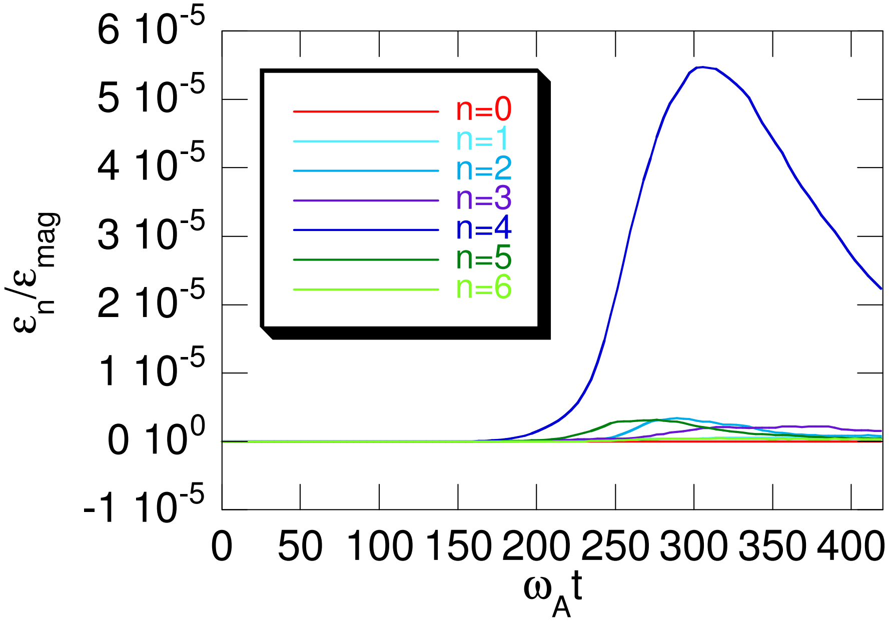
- o Single TAE $\Rightarrow (n=0, m=0)$ zonal flows/fields and/or $(n=0, m=\pm 1)\delta \underset{\sim}{B}$ and δn.
  - ⇒ radially local nonlinear equilibrium modifications.
  - ⇒ narrowing of TAE frequency gap and/or lowering ω_{TAE}
  - ⇒ enhancing continuum/radiative damping.
- o Simulations (Todo et al.): n=0 perturbations effective in lower TAE saturation amplitudes

TAE-induced Losses of Fast Ions

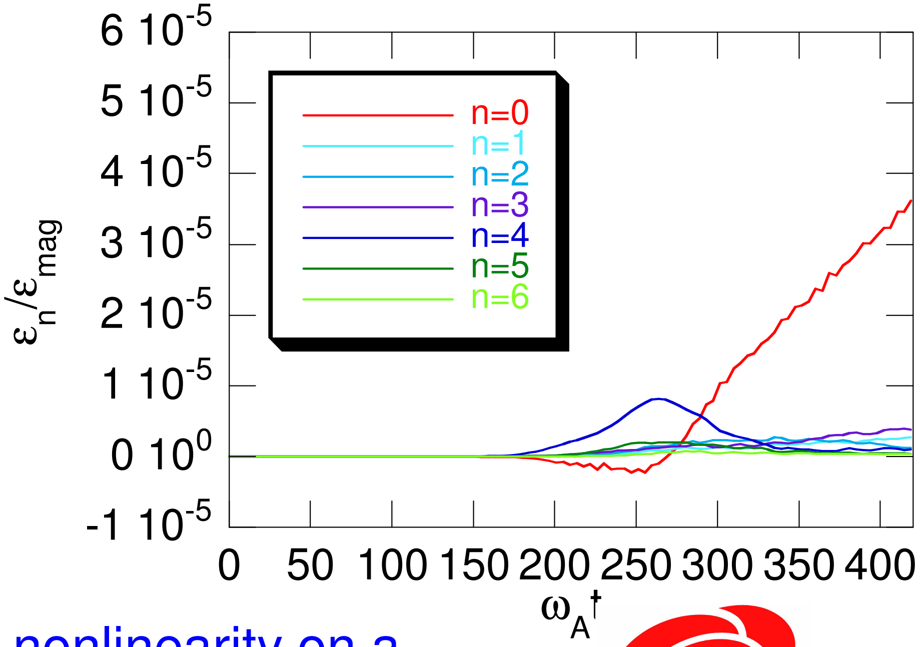
IFS-NIFS collaboration, 9th IAEA TCM on Energetic Particles (2005)

MHD nonlinearity reduces the saturation level of the dominant (n=4) mode and generates a zonal flow (n=0)

Wave energy burst in quasilinear simulation



Wave energy burst with MHD nonlinearity included



Future work: examine the effects of MHD nonlinearity on a longer (experimentally relevant) time interval.

(III) Nonlinear SAW-EP Physics

(III.1) Nonlinear Physics of AE (continued…)

(iii) Nonlinear Downward Frequency Cascading

- o Multiple TAEs ⇒ nonlinear ion Landau damping
  - ⇒ Cascading to lower-frequency, more stable TAEs.
  - ⇒ Enhancing effective continuum/radiative damping.

(iv) Additional Considerations

- o Each toroidal-n mode: O(nq) AEs localized at different radial locations
- o Different-n AEs have nearly degenerate frequencies.
  - ⇒ Within the TAE frequency gap: dense populations of AEs ("lighthouses") with "unique" frequencies and radial locations.
  - ⇒ Significant multiple-TAE nonlinear interactions
  - ⇒ Diffusive redistribution of $F_{EP}\left(\varepsilon, p_\phi(r)\middle|\mu\right)$
  - ⇒ AE – avalanche: turbulence spreading

(III) Nonlinear SAW-EP Physics

(III.2) Nonlinear Physics of EPM

- Stronger instability drive (to overcome continuum damping)

  $\Rightarrow \gamma/\omega \sim O\left(10^{-2} - 10^{-1}\right)$
- $\omega_{EPM} \sim$ characteristic EP dynamic frequencies
- EPM in-situ at where drive, $\alpha_{Ep} \propto \beta_{Ep}'$ maximizes.

  $\Rightarrow$ EPM rapidly redistribute $F_{EP}(\varepsilon, P_\phi)$

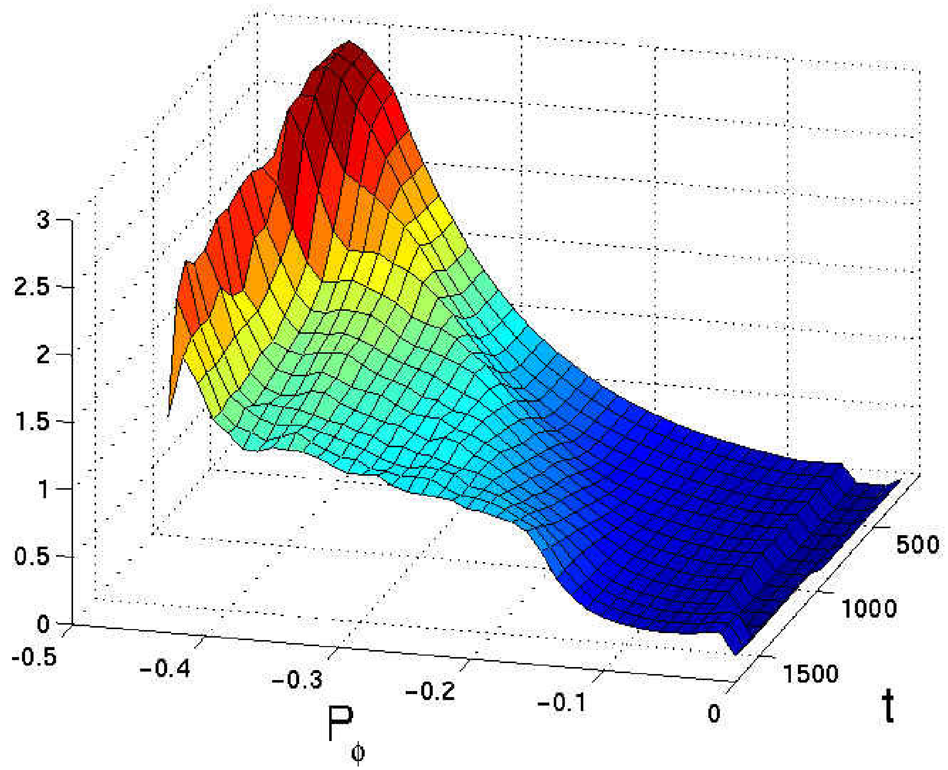
(i) Fishbone Paradigm

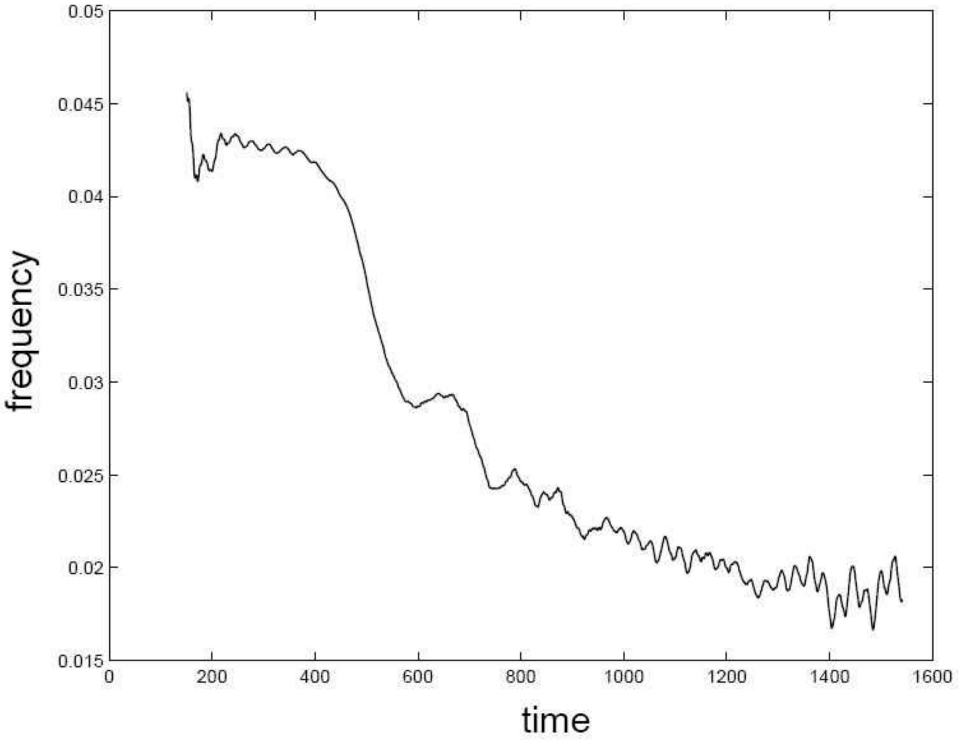
- o n=1 internal kink
- o $\omega \sim \overline{\omega}_{db}$
- o Simulations [Fu et al.] : Rapid radial redistribution of F_{EP} saturation and downward frequency chirping.

Hybrid MHD-GK simulations of fishbones

G.Y. Fu, et al. POP 13, 052517, (2006)

As flattening region of distribution function increases, the mode frequency chirps down.





G.Y. Fu, et al. POP **13**, 052517, (2006)

Hybrid MHD-GK simulations of ALE on JT-60U

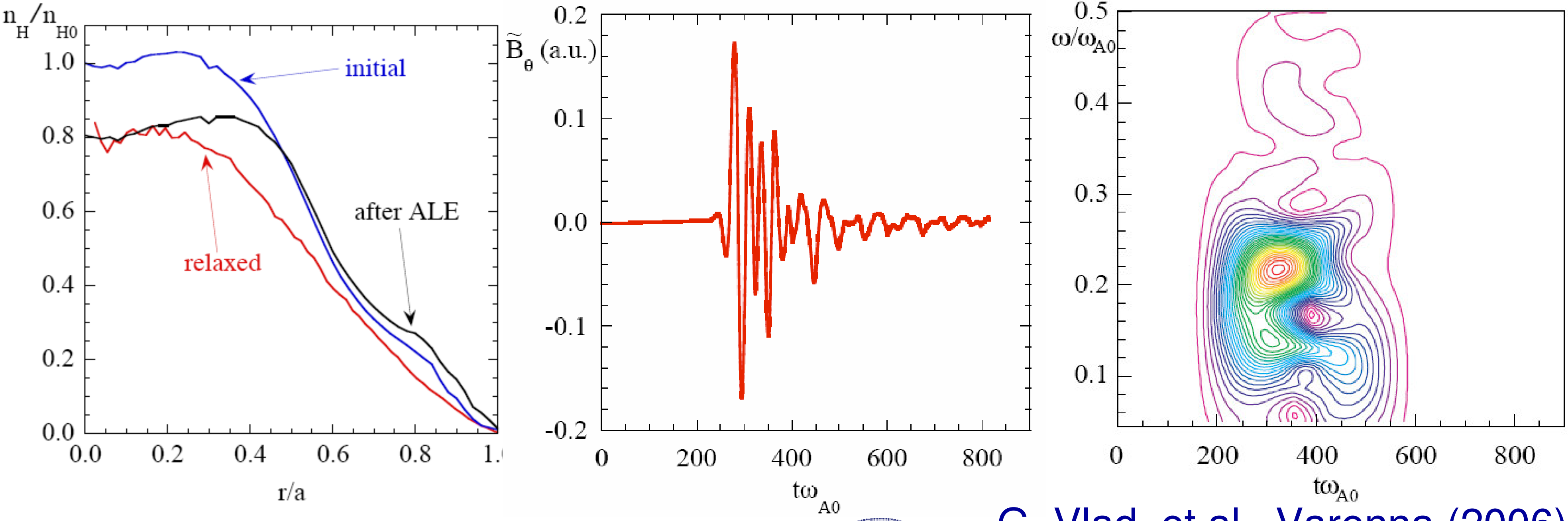
G. Vlad, et al., IAEA FEC 2006, TH/P6-4

(III.2) Nonlinear Physics of EPM (continued...)

(ii) EPM at the TAE range

- Abrupt Large Event (ALE) in observed JT - 60U [Shinohara et al.]
- Simulations [Vlad et al.] : n = 1 EPM redistributes F_{EP} radially

$\Rightarrow$ results consistent with ALE.

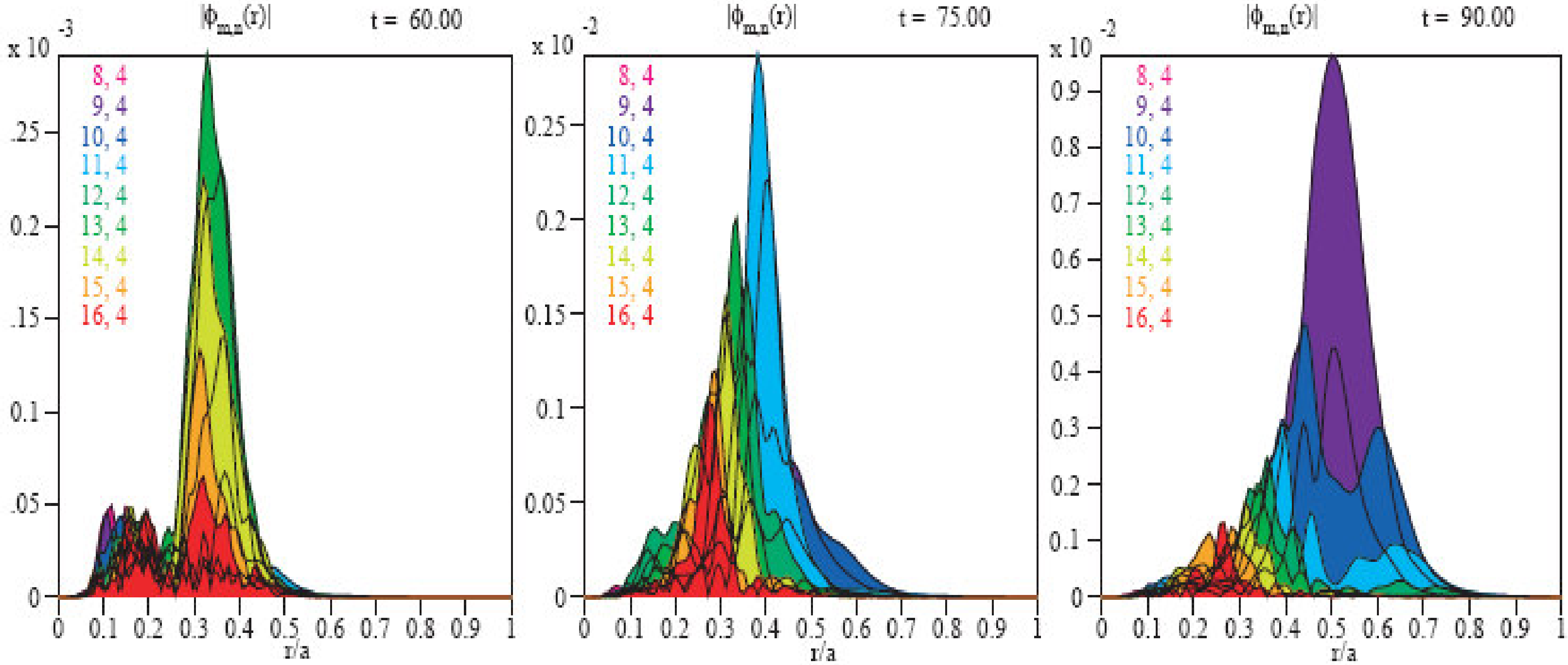


G. Vlad, et al., Varenna (2006)

(III.2) Nonlinear Physics of EPM (continued...)

(iii) EPM – Avalanche paradigm

- o Strong EP drive ⇒ EPM localized at β_{EP}' max
- o Convective radial transport of EP
- o Radial propagation of EPM turbulence via couplings between poloidal harmonics
  - ⇒ Propogation of EPM "unstable" front (EPM-Avalanche)



F. Zonca, et al., NF **45**, 477, (2005)

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(III.2) Nonlinear Physics of EPM (continued...)

(iv) Analytical description [Zonca et al.]

- o $\Rightarrow \quad D^{\ell}_{EPM}\left(-i\omega+\partial_t,\partial_r,r\right)A(r,t)=\delta\hat{W}^{n\ell}_{k}\left(\partial_t,\partial_r,r,|A|^2\right)A(r,t)$
  - ⇒ Radial convective amplication
  - ⇒ Source propagation
- o Consistent with simulations

(v) Additional Considerations

- o EPM has stronger n dependences $(\overline{\omega}_d \; \alpha \; n) \Rightarrow$ narrow unstable spectrum in n
- o Single-n dynamics dominates the initial rapid convective phase
- o Reduced instability drive ⇒ AE dynamics.

(IV) ITER Applications

- α particles + fast ions $\Rightarrow$ unstable AE and/or EPM in ITER in various scenarios. [Gorelenkov et al.; Vlad et al.]
- Unstable n spectrum: $n_{\max} \sim O(10-20)$

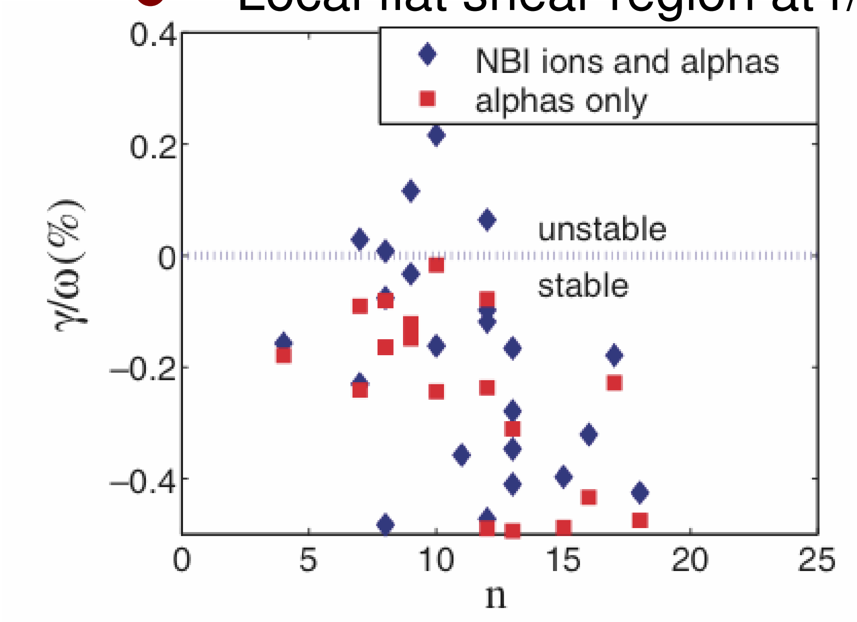
  $\Rightarrow$ Dense AE “lighthouse” spectrum in (ω,r)

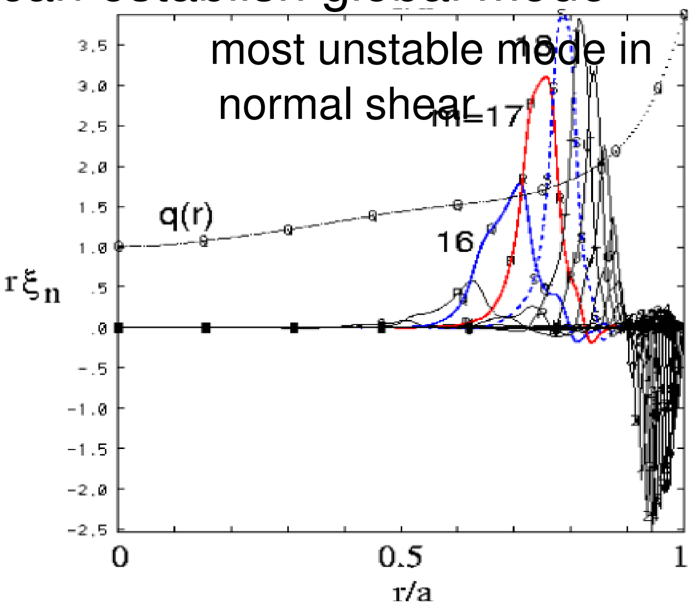
  $\Rightarrow$ Significant implications to the nonlinear AE physics!

TAE Instability in ITER

(N.N. Gorelenkov, et al., NF **45**, 226, 2005)

- Neutral Beams Have Comparable Linear Drive as Alpha particles
- Local flat shear region at r/a ~ 0.5 can establish global mode




most unstable mode in normal shear

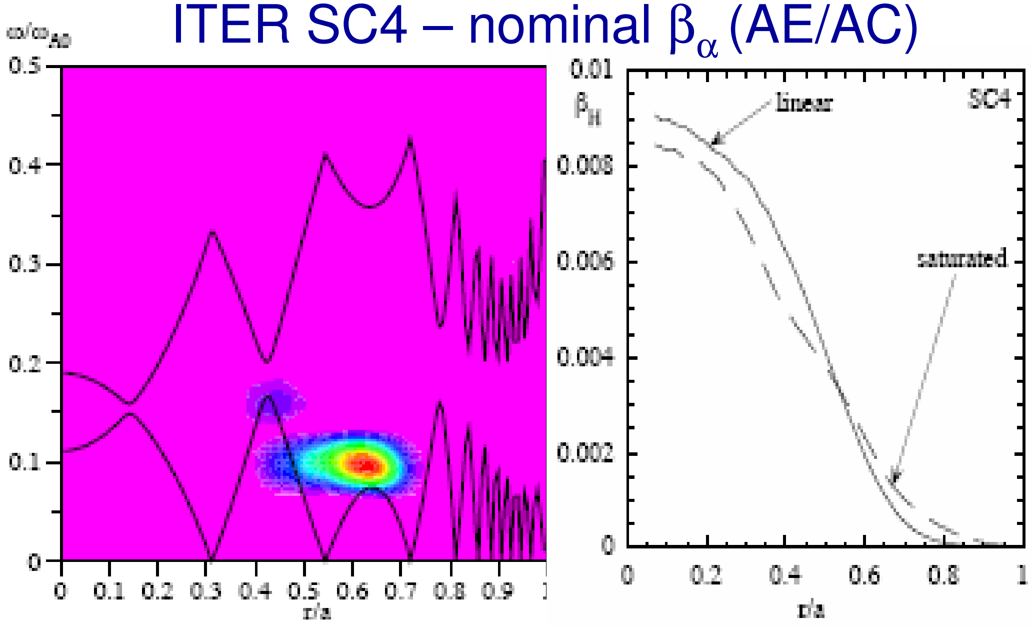
- Global nature of the TAE can cause alpha loss
- Nominal plasmas are close to thresholds for alphas losses based on quasilinear marginal stability postulate (Gorelenkov,'05)
- Reversed shear scenario plasmas is more TAE unstable with n from 1 to 7 and with ~2% growth rate.
- The most unstable modes are localized at the strongest fast ion pressure gradient

AE/EPM Transport in ITER

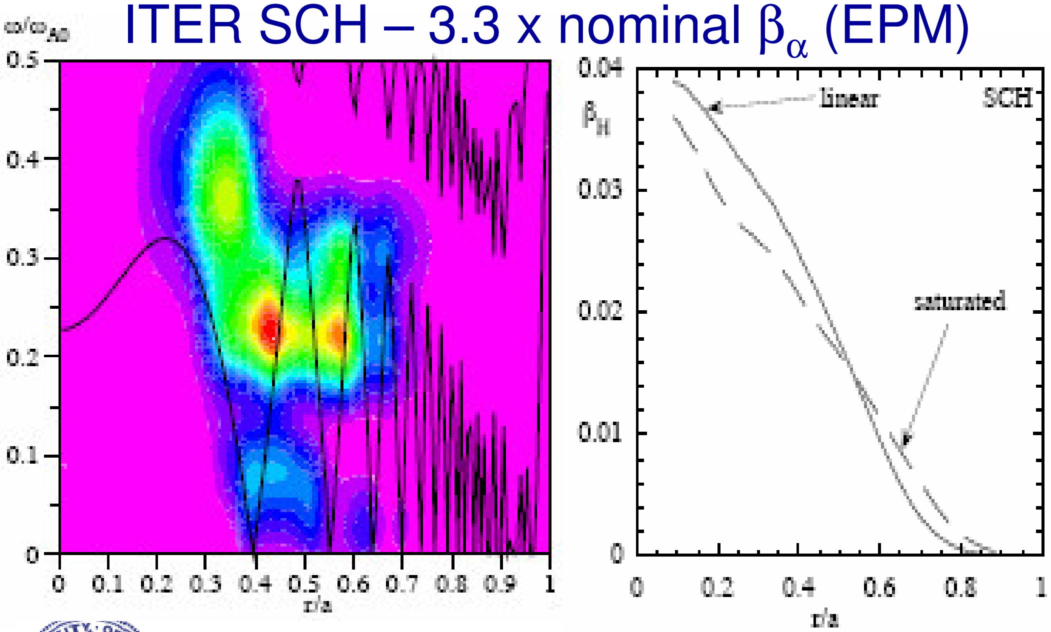
(G. Vlad, et al., NF **46**, 1, 2006)

- Global Hybrid MHD-Gyrokinetic simulations of ITER operation scenarios: SC2(normal shear), SC4 (reversed shear), SCH (hybrid scenario).
- Assuming only fusion alphas, AE are marginally unstable in all scenarios.
- Only SC4 (reversed shear) shows significant broadening of the alpha particle profiles at nominal values of alpha particle power density.
- EPM are excited in SCH above a threshold ~1.6 the nominal value of alpha particle power density.

ITER SC4 – nominal β_α (AE/AC)



ITER SCH – 3.3 x nominal β_α (EPM)



(V) Summary and Discussions

- Linear physics well at hand.
- Still need comprehensive linear code to accurately evaluate the stability properties.
- ITER (alpha + fast ions) ⇒ SAW excitations ⇒ consequences on EP transports remain uncertain.
- Key nonlinear physics mechanisms identified and some “verified” either by customized simulations and/or experimental observations.
- Multi-n simulations up to n ~ 0(10-20) with accurate background kinetic damping, realistic geometries, and boundaries needed to push forward this area.
- In the longer time scales, interactions between SAW-EP dynamics and Drift/Alfvén-thermal particles dynamics will emerge

  ⇒ challenging multi-scale physics.

(V) Summary and Discussions

(continued)

- SAW EP research ⇒
  - Intellectually challenging (complexities in geometries and nonlinearities) and programmatically important
  - Strong and healthy positive interplays among experiments, theory and simulations!!
  - Electron-fishbones via $\omega = \overline{\omega}_d$ resonance [this Conference] also shed interesting physics insights.