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Collective effects and self-consistent energetic particle dynamics in burning plasmas

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Collective effects and self-consistent energetic particle dynamics in burning plasmas *

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*Acknowledgments: S. Briguglio, L. Chen, G. Fogaccia, G. Vlad

Outline

- Historic Background.
- Overview of shear Alfvén Spectra.
- Eigenmodes vs. Resonant Modes.
- Nonlinear Dynamics Aspects.
- 3D Hybrid MHD-Gyrokinetic Simulations.
- Transition from weak to strong energetic particle transport: Avalanches.
- Discussions.

Historic Background

- Possible detrimental effect of Shear Alfvén (SA) instabilities on energetic ions recognized theoretically before experimental evidence was clear.

- Mikhailowskii, Sov. Phys. JETP, **41**, 890, (1975)
  Rosenbluth and Rutherford, PRL **34**, 1428, (1975)
  $\Rightarrow$ resonant wave particle interaction of $\approx$ MeV ions with SA inst. due to $v_E \approx v_A$ $(k_\parallel v_A \approx \omega_E)$

- Experimental observation of fishbones on PDX – McGuire et al., PRL **50**, 891, (1983) – fast $\perp$ injected ion losses ...
  ...followed by numerical simulation of mode-particle pumping loss mechanism – White et al., Phys. Fluids **26**, 2958, (1983)
  ...and by theoretical explanation of internal kink excitation –
  Chen, White, Rosenbluth, PRL **52**, 1122, (1984)
  Coppi, Porcelli, PRL **57**, 2272, (1986)

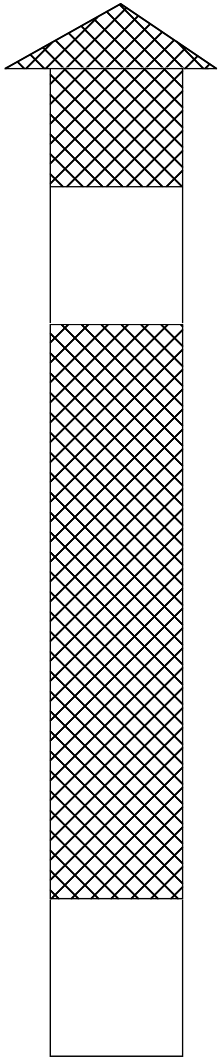
- Existence of gaps in the SA continuous spectrum (due to lattice symmetry breaking) $\omega \approx v_A/2qR$ – Kieras and Tataronis, J. Pl. Phy. **28**, 395, (1982)
- Existence of discrete modes (TAE) in the toroidal gaps – Cheng, Chen, Chance, Ann. Phys. **161**, 21, (1985)
- Possible excitations of TAE by energetic particles . . .
  Chen, "Theory of Fusion Plasmas, p.327, (1989)
  Fu, Van Dam, Phys. Fluids B **1**, 1949, (1989).
- KBM excitation by fast ions: Biglari, Chen, PRL **67**, 3681, (1991)
- Experimental evidence . . .
  Wong et al., PRL **66**, 1874, (1991)
  Heidbrink et al, Nucl. Fusion **31**, 1635, (1991)
  Heidbrink et al, PRL **71**, 855, (1993) $\Rightarrow$ BAE $\omega \approx \omega_{ti} \approx \omega_{*pi}$

- TAE modes are predicted to have small saturation levels and yield negligible transport unless stochastization threshold in phase space is reached: H.L. Berk and B.N. Breizman, Phys. Fluids B **2**, 2246, (1990) and D.J. Sigmar, C.T. Hsu, R.B. White and C.Z. Cheng, Phys. Fluids B, **4**, 1506, (1992).

- Excitation of Energetic particle Modes (EPM), at characteristic frequencies of energetic particles when free energy source overcomes continuum damping L. Chen, Phys. Plasmas **1**, 1519, (1994). [...also RTAE excitation C.Z. Cheng, N.N. Gorelenkov, C.T. Hsu, Nucl. Fusion **35**, 1639, (1995).]

- Strong energetic particle redistributions are predicted to occur above the EPM excitation threshold in 3D Hybrid MHD-Gyrokinetic simulations: S. Briguglio, F. Zonca and G. Vlad, Phys. Plasmas **5**, 1321, (1998).

Overview of shear Alfvén spectra



Energetic Particle Modes (EPM) : forced oscillations

TAE – KTAE ⇒ Transition to EPM

Energetic Particle Modes (EPM) : forced oscillations

Beta induced Alfvén Eigenmodes (BAE)
Kinetic Ballooning Modes (KBM)
KBM ⊕ BAE ⇒ Alfvén ITG (AITG)

Eigenmodes vs. Resonant Modes

- Fundamental difference in mode dynamics and particle transports is to be attributed to mode excitation and particle phase space motion
- Use Secular Perturbation Theory in nonlinear Hamiltonian dynamics ...
- Extended Phase Space to treat explicit time dependencies: $2N \Rightarrow (2N+2)$-dim.; for low frequency modes $(\omega \ll \omega_{ci})$ the resulting 8-dim phase space reduces (μ and $\mathcal{H} \equiv H(\mu, P_\phi, J_\parallel) - H$ are conserved) to 4-dim phase space, i.e. the general problem is equivalent to an autonomous Hamiltonian with 2 degrees of freedom
- Use Secular Perturbation Theory is a method for locally removing a single resonance: what happens in the multiple resonance case ???

$$H = H_0(\mathbf{J}) + \epsilon H_1(\mathbf{J}, \theta)$$

$$\omega_1 = \frac{\partial H_0}{\partial J_1} \qquad \omega_2 = \frac{\partial H_0}{\partial J_2} \qquad \frac{\omega_2}{\omega_1} = \frac{h}{k} \quad h, k \in \mathbb{Z}$$

- Canonical transformation with generating function $F_2 = (h\theta_1 - k\theta_2)\hat{J}_1 + \theta_2 \hat{J}_2$

$$J_1 = \frac{\partial F_2}{\partial \theta_1} = h\hat{J}_1 \qquad J_2 = \frac{\partial F_2}{\partial \theta_2} = \hat{J}_2 - k\hat{J}_1$$

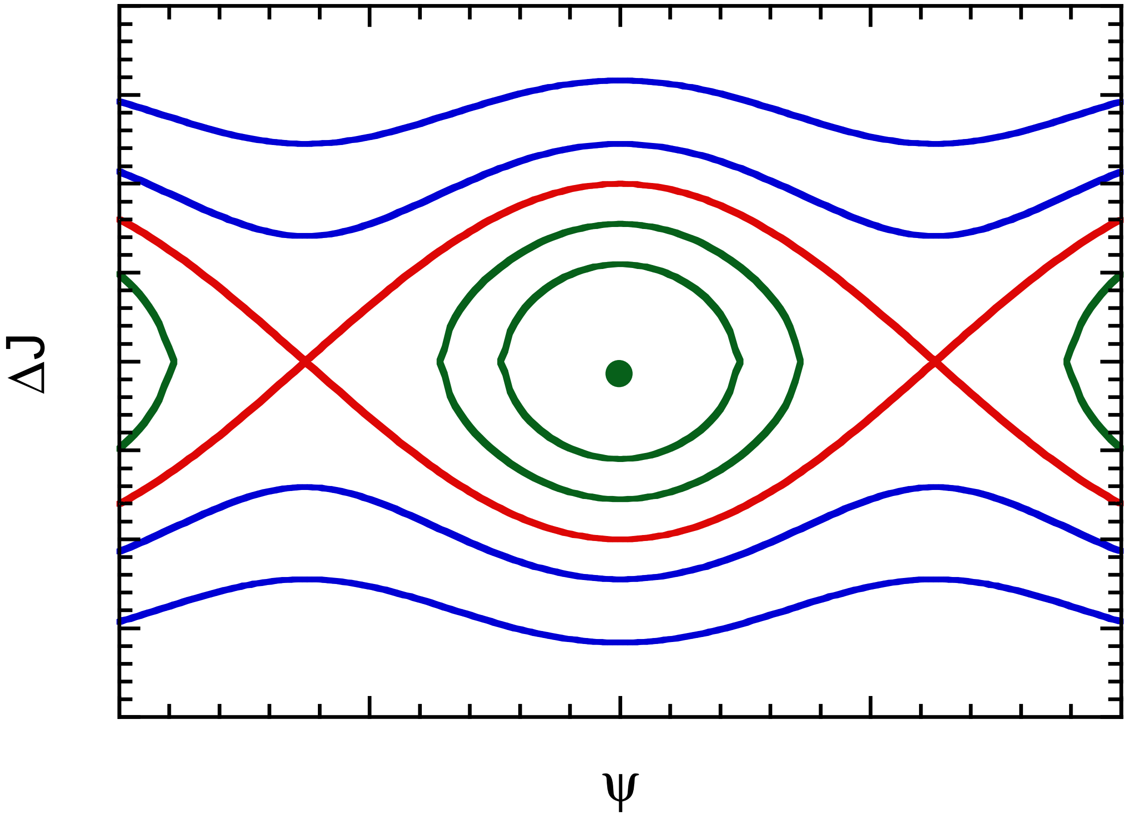
$$\hat{\theta}_1 = \frac{\partial F_2}{\partial \hat{J}_1} = h\theta_1 - k\theta_2 \qquad \hat{\theta}_2 = \frac{\partial F_2}{\partial \hat{J}_2} = \theta_2$$

- After averaging on $\hat{\theta}_2$ (near resonance)

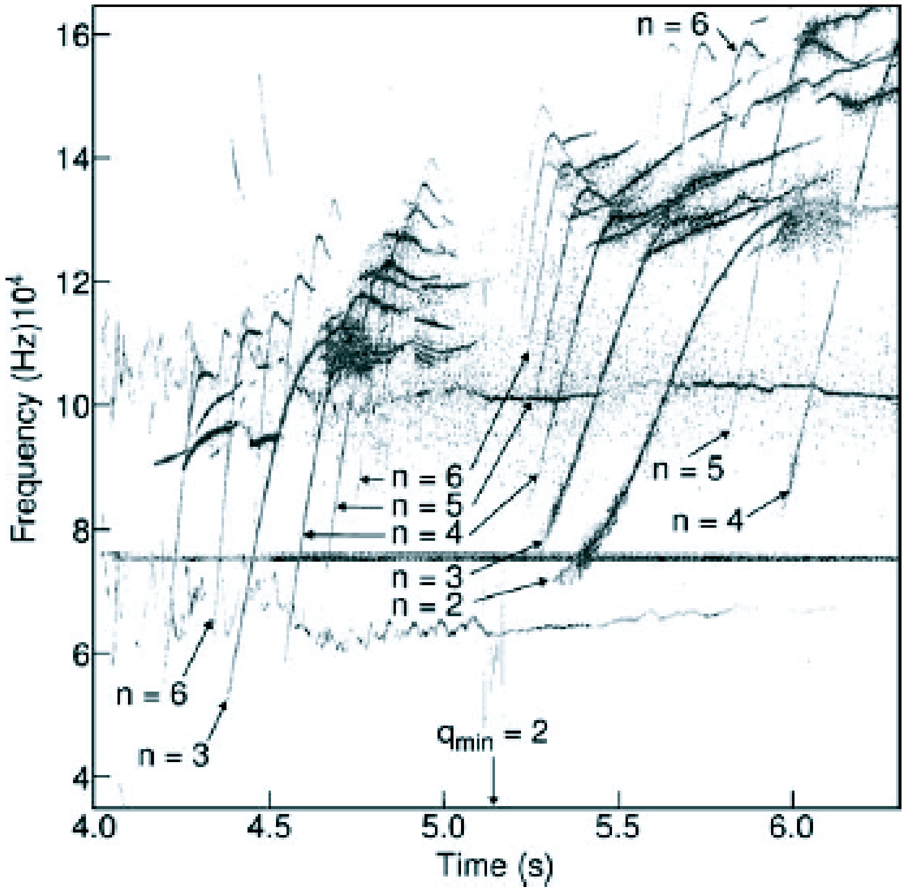
$$\bar{H} = \bar{H}_0(\hat{\mathbf{J}}) + \epsilon \bar{H}_1(\hat{\mathbf{J}}, \hat{\theta}_1) = \bar{H}_0(\hat{\mathbf{J}}_\mathbf{0}) + \Delta \bar{H}$$

□ Standard Hamiltonian

$$\Delta\bar{H} \simeq (1/2)F(\Delta\hat{J}_1)^2 - G\cos\theta_1 \qquad F = \partial^2\bar{H}_0/\partial\hat{J}_{10}^2 \qquad G\cos\theta_1 \simeq -\epsilon\bar{H}_1$$



- Further complications: mode frequency often sweeps: fast vs. slow sweeping
  From S.E. Sharapov *et al.*, Phys. Lett. A **289**, 127, (2001)



- Qualitative description in terms of frequency sweeping,

$$\frac{\dot{\omega}}{\omega} \sim \gamma_L \ll \omega_B^2/\omega; \qquad \text{adiabatic(TAE)}$$

$$\frac{\dot{\omega}}{\omega} \sim \gamma_L \gg \omega_B^2/\omega; \qquad \text{fast(EPM)}$$

- Adiabatic (TAE) case: quasilinear flattening is dominant and, in the absence of externally imposed adiabatic frequency chirping (e.g., via equilibrium changes), saturation is either at $\omega_B \approx \gamma_L$ or it occurs via other mode-mode coupling mechanisms

- Fast (EPM) case: there no time for the distribution to flatten and the mode should freely grow $\Rightarrow$ particle convection/mode particle pumping ??? Saturation should occur at $\omega_B \approx (\omega\gamma_L)^{1/2}$; consistent with F. Zonca and L. Chen BAPS **43**, 1921, (1999).

(Weak) Modes in the Toroidal gap: linear

- High-n modes $n \gtrsim \epsilon a/\rho_{LE}$ are most unstable
- Kinetic ($n \gg 1$) analyses refer to simple and/or model equilibria
  - TAE modes: weakly damped. But equilibrium effects (e.g., finite-β enhance continuum damping
  - KTAE modes: localized near the frequency gap boundaries. (Upper: weak damping; Lower: strong damping; Mett and Mahajan, Phys. Fluids B **4**, 2885, (1992).
- Low shear (core region) is characterized by modes localized in a single gap – Fu, Phys. Plasmas **2**, 1029 (1995) $\oplus$ Berk et al, Phys. Plasmas **2**, 3401 (1995)
- Are there possible tokamak operation regimes free of TAE modes???? (in the case of model equilibria yes: $\alpha = -R_0 q^2 \beta' > \alpha_{crit}$)

(Weak) Modes in the GAP: nonlinear

- NL Saturation via mode-mode coupling (also Thyagaraja et al., Proc. EPS-97, vol 1, p 277, 1997):
  - Saturation via "ion Compton scattering" at $\delta B_r/B \approx \epsilon^2(\gamma_L/\omega)^{1/2}$ (Hahm and Chen, PRL **74**, 266, (1995))
  - Saturation via $\delta \mathbf{E}^* \times \delta \mathbf{B}$ at $\delta B_r/B \approx \epsilon^{5/2}/nq$ (Zonca et al., PRL **74**, 698, (1995))
  - Saturation via $\delta n/n$ at $\delta B_r/B \approx \epsilon^{3/2}\beta^{1/2}$ (Chen et al., PPCF **40**, 1823, (1998))
- NL Saturation via phase-space nonlinearities (wave-particle trapping):
  - Steady-state: $(\delta B_r/B)^{1/2} \approx \omega_B \approx \gamma_L(\nu_{eff}/\gamma_d)$ for $\gamma_d \ll \nu_{eff} \sim \nu(\omega/\omega_b)^2$ (Berk, Breizman, Phys. Fluids B **2**, 2246, (1990))

- TAE pulsations: $(\delta B_r/B)^{1/2} \approx \omega_B \approx \gamma_L$ for $\gamma_d \gg \nu_{eff0} \sim \nu(\omega/\gamma_L)^2$ (Berk et al, PRL **68**, 3563, (1992))

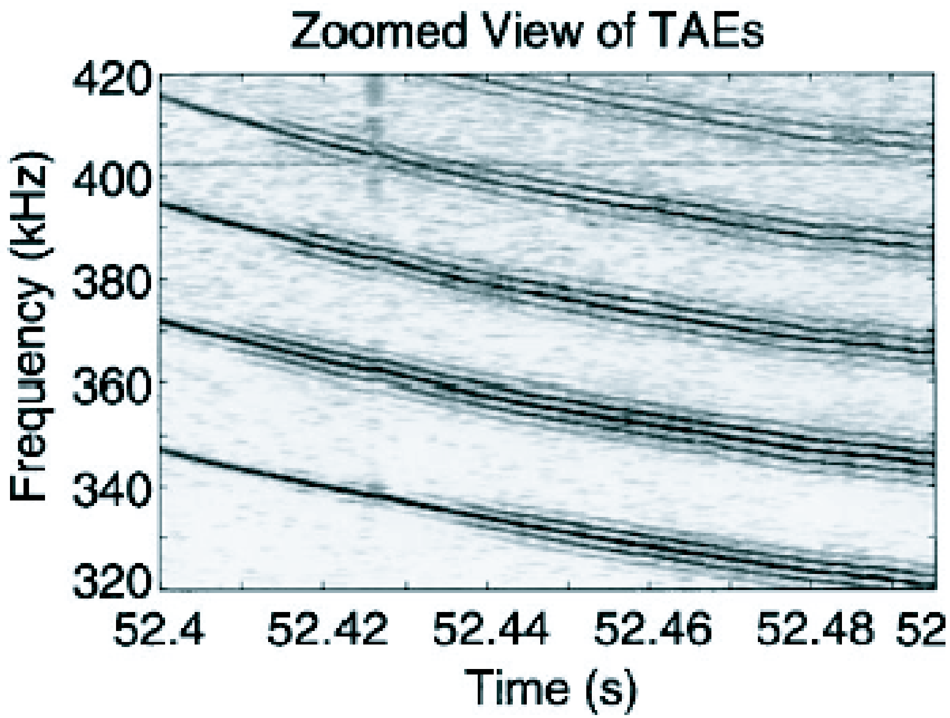
- Both steady-state and TAE pulsations yield negligible losses unless phase-space stochasticity is reached, possibly via domino effect (Berk et al, Nuc. Fus. **35**, 1661, (1995))

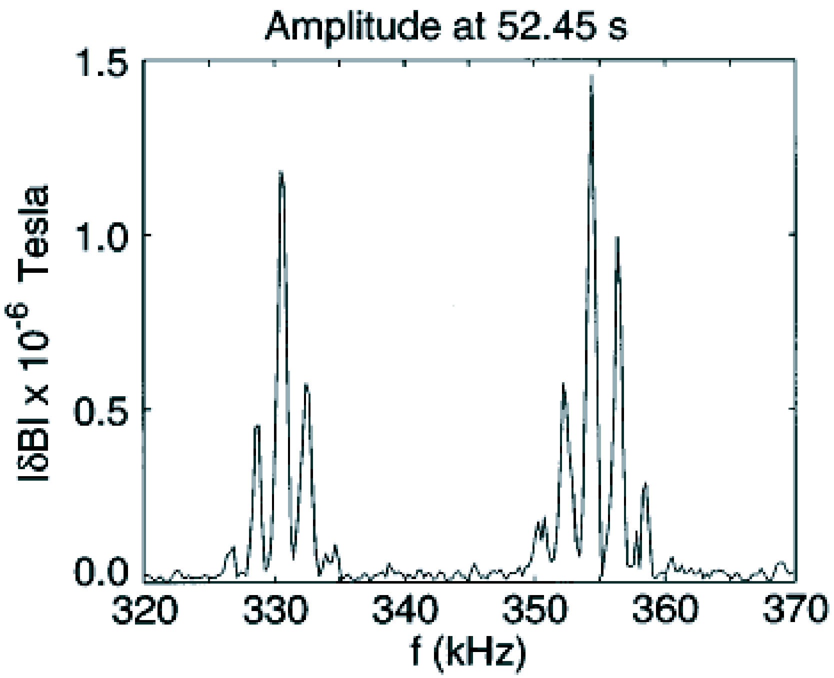
- In the case of a single mode, spontaneous formation near threshold of hole-clump pair in phase space (Berk et al., Phys. Lett. A, **234**, 213, (1997)) may yield to frequency chirping and/or pitchfork splitting of mode-frequency

- Theory seems to explain pitchfork splitting of TAE lines observed in JET (Fasoli, IAEA-TCM-97); however, $\delta\omega \sim \gamma_L(\gamma_d/\gamma_L)^{1/2}(\gamma_L/\nu_{eff})^{3/2}$; thus, large chirping requires very small ν_{eff}.

Pitchfork splitting of TAE in JET

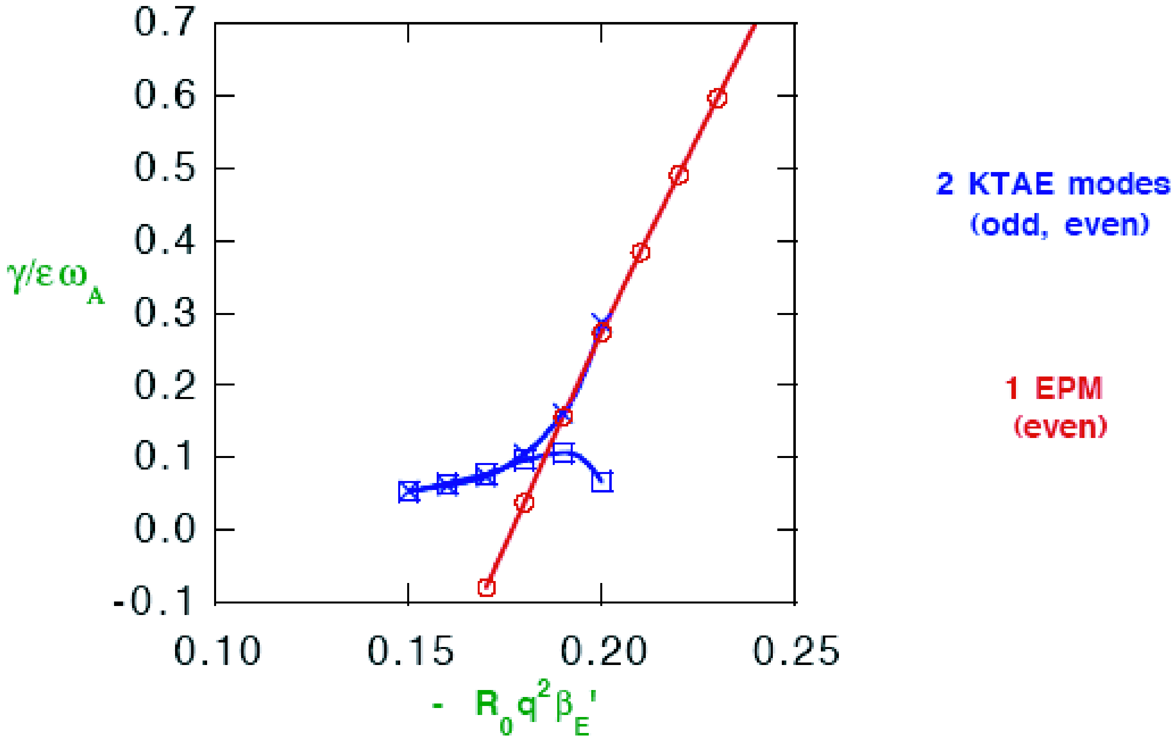
Fasoli, Phys. Rev. Lett. **81**, 5564, (1998)



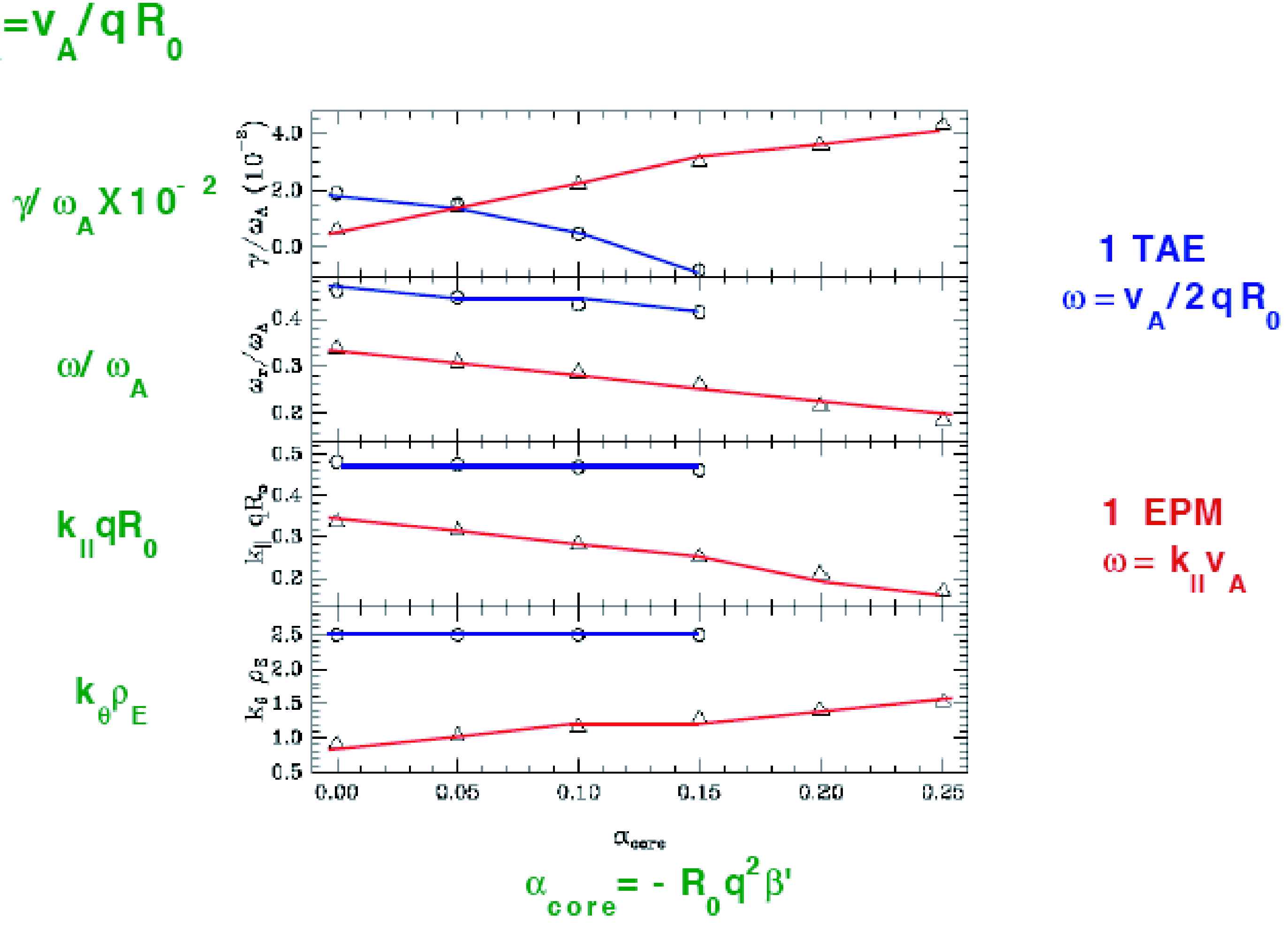


Energetic Particle Modes (EPM)

- Chen, Phys. Plasmas **1**, 1519 (1994).
- KTAE are only moderately unstable
- If strongly driven, KTAE merge into an EPM (forced oscillation ⇔ resonant excitation) Zonca, Chen, Phys. Plasmas **3**, 323, (1996)

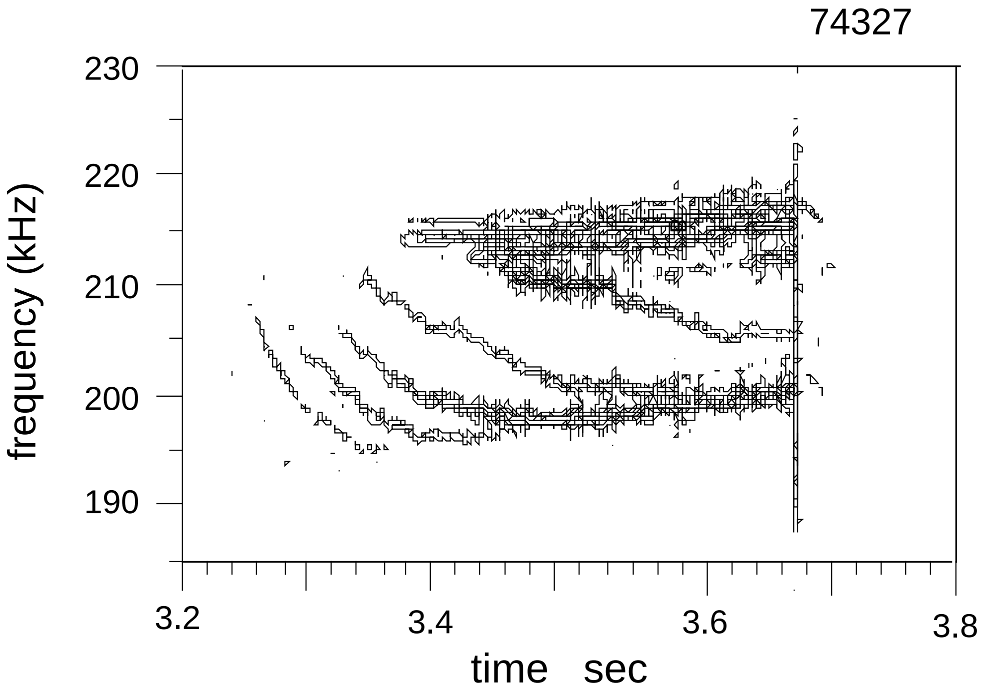


• TAE to EPM transition as $\alpha_{core} = -R_0 q^2 \beta'$ increases (Santoro, Chen, Phys. Plasmas **3**, 2349, (1996))



ICRF Experiments on TFTR

- EPM and TAE excitations, by ICRF induced fast minority ion tails on TFTR. From **Bernabei** *et al.*, Phys. Plasmas **6**,1880, (1999).

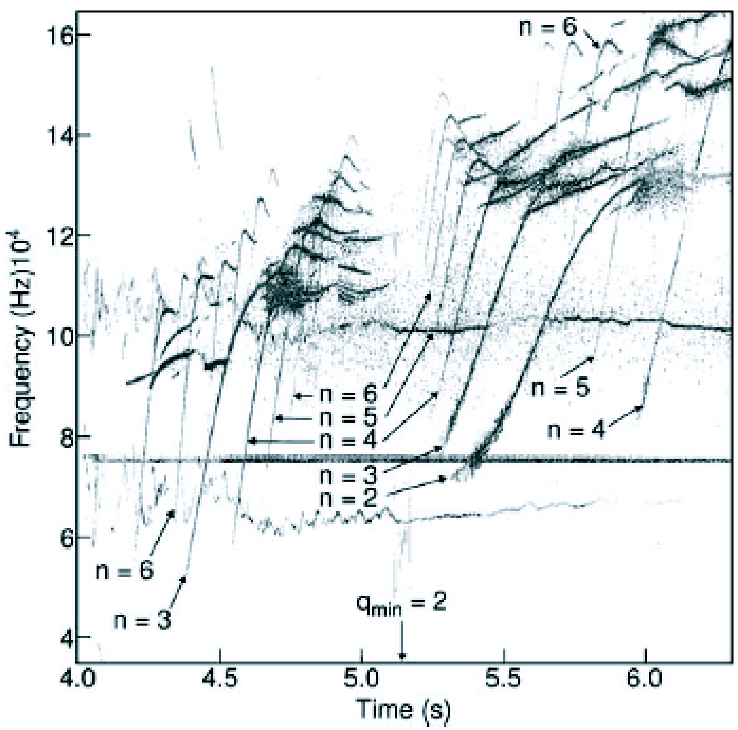


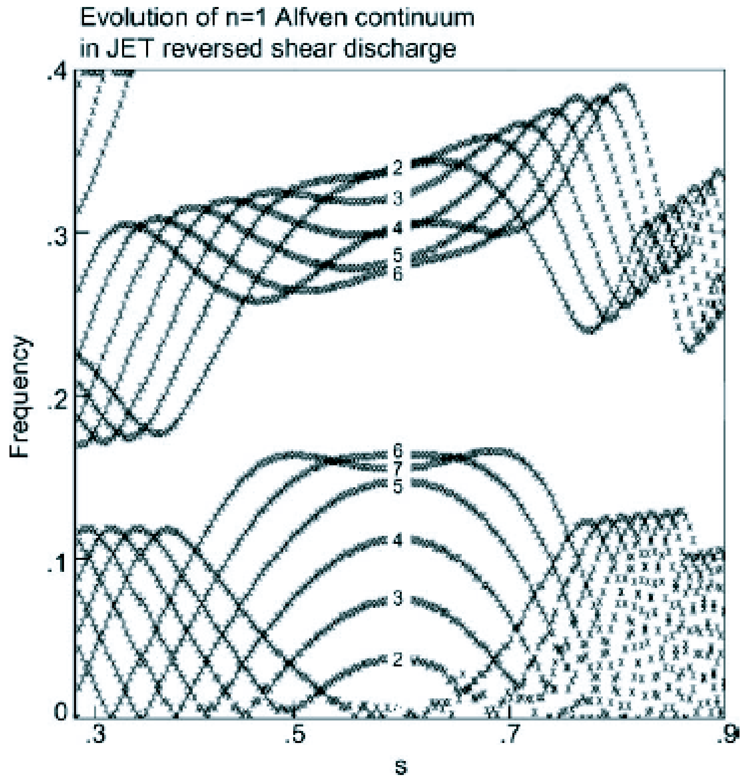
- Energetic Particle Modes*, appear to be excited in the plasma core, due to strong energy source due to ICRF tail ions
- Energetic Particle Modes*, are forced oscillations at $\omega \simeq \bar{\omega}_{dE}$. They chirp downward in frequency because $\bar{\omega}_{dE} = k_\theta \rho_{LE} v_{thE}/R_0$ (cf. later).
- TAE Modes, are eventually excited at the plasma edge, due to ICRF tail ions transported outward by EPM.
- Fast Ion Losses, seem associated with TAE's, and appear to be related to EPM frequency chirping.

*L. Chen, Phys. Plasmas **1**, 1519, (1994).

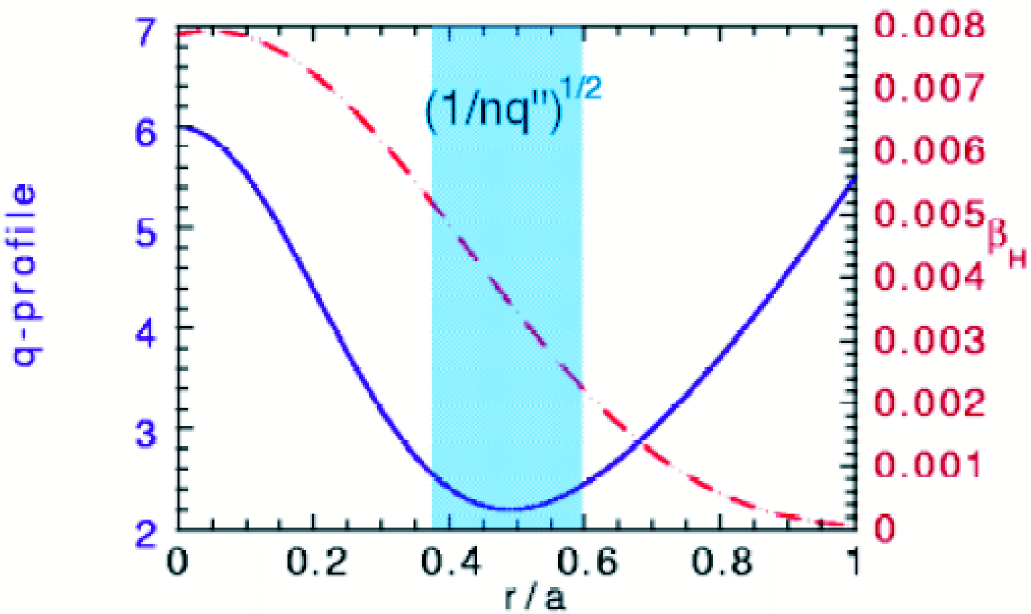
ICRF Experiments on JET

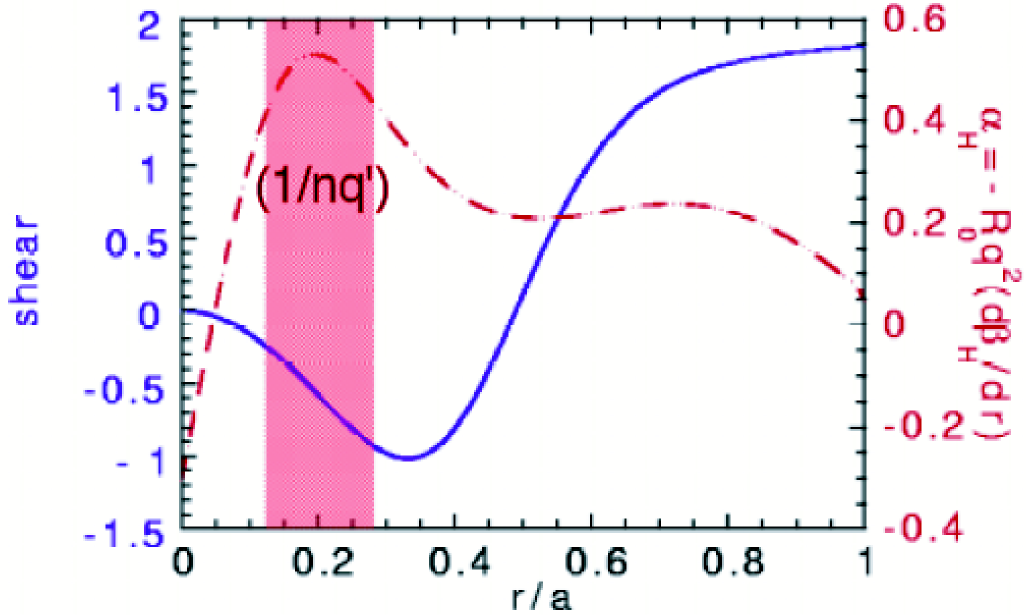
☐ EPM and TAE excitations, by ICRF induced fast minority ion tails on JET. From S.E. Sharapov *et al.*, Phys. Lett. A **289**, 127, (2001). **Alfvén Cascades** in reversed-q equilibria (advanced tokamak)





EPMs are excited at different radial locations



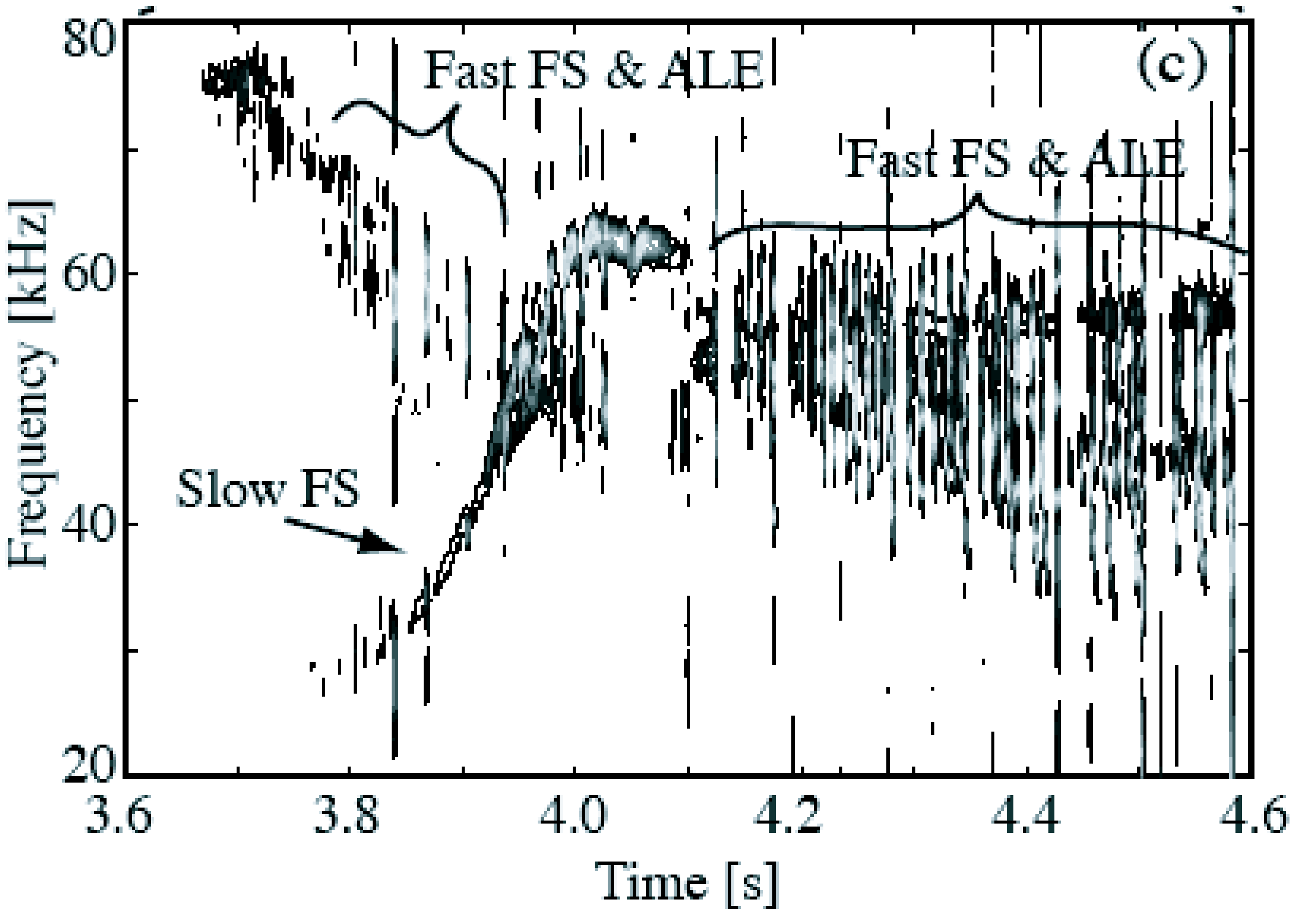


- Strong resonant excitation of EPMs should occur at $r/a \approx 0.2$, where α_H is maximum.L. Chen, Phys. Plasmas **1**, 1519, (1994).
- Natural gap in the Alfvén continuum appears at q_{min} Berk *et al.*, Phys. Rev. Lett., **87**, 185002, (2001) $\Rightarrow$ EPM Gap Modes.

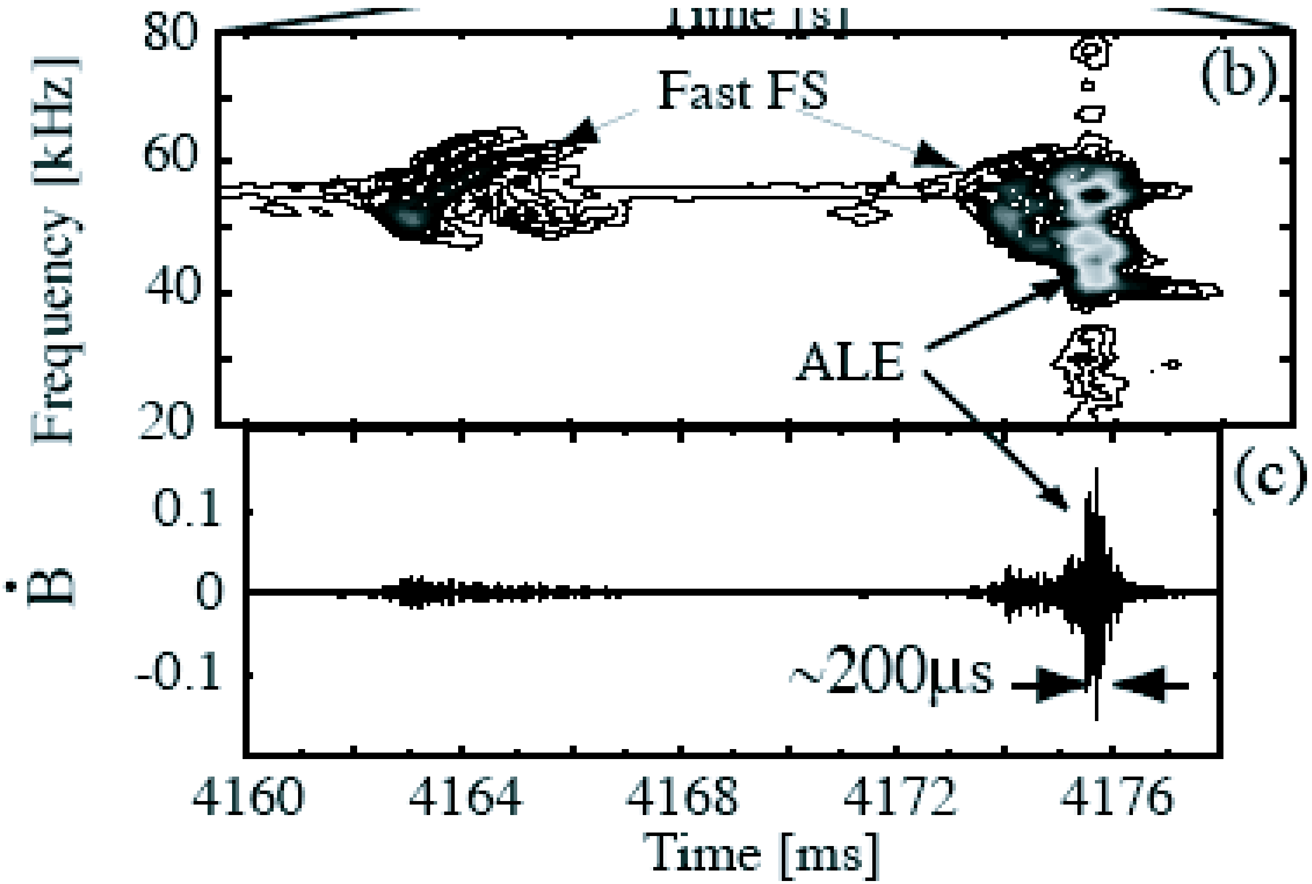
- Alfvén Cascades: theoretical description in Berk *et al.*, Phys. Rev. Lett., **87**, 185002, (2001) and Breizman *et al.*, Phys. Plasmas. **10**, 3649, (2003)
- EPM/Alfvén Cascades: linear stability and non-linear analyses Zonca *et al.*, Phys. Plasmas. **9**, 4939, (2002)
- Energetic Particle Modes, appear to be excited in the plasma core, due to strong energy source due to ICRF tail ions
- Energetic Particle Modes, are resonant at $\omega \simeq \bar{\omega}_{dE}$, $\omega \simeq \bar{\omega}_{dE} + \ell\omega_{BE}$. $\Rightarrow$ frequency chirping (preferentially downward) (cf. later).
- Alfvén Cascades, alone cause only weak (local) particle redistributions
- Alfvén Cascades in combination with EPMs, are eventually excited at $q-min$, due to ICRF tail ions transported outward by EPM.
- Fast Ion Losses, seem associated with combined effect of EPM/Alfvén Cascades. Briguglio *et al.*, Phys. Lett. A, **302**, 308, (2002). Hybrid MHD-GK simulations predict energetic ion transport in avalanches (cf. later)

NNBI Experiments on JT-60U

- EPM and TAE excitations, by negative neutral beam injection induced fast minority ion tails on JT-60U. From **Shinohara** *et al.*, Nucl. Fusion **41**, 603, (2001).

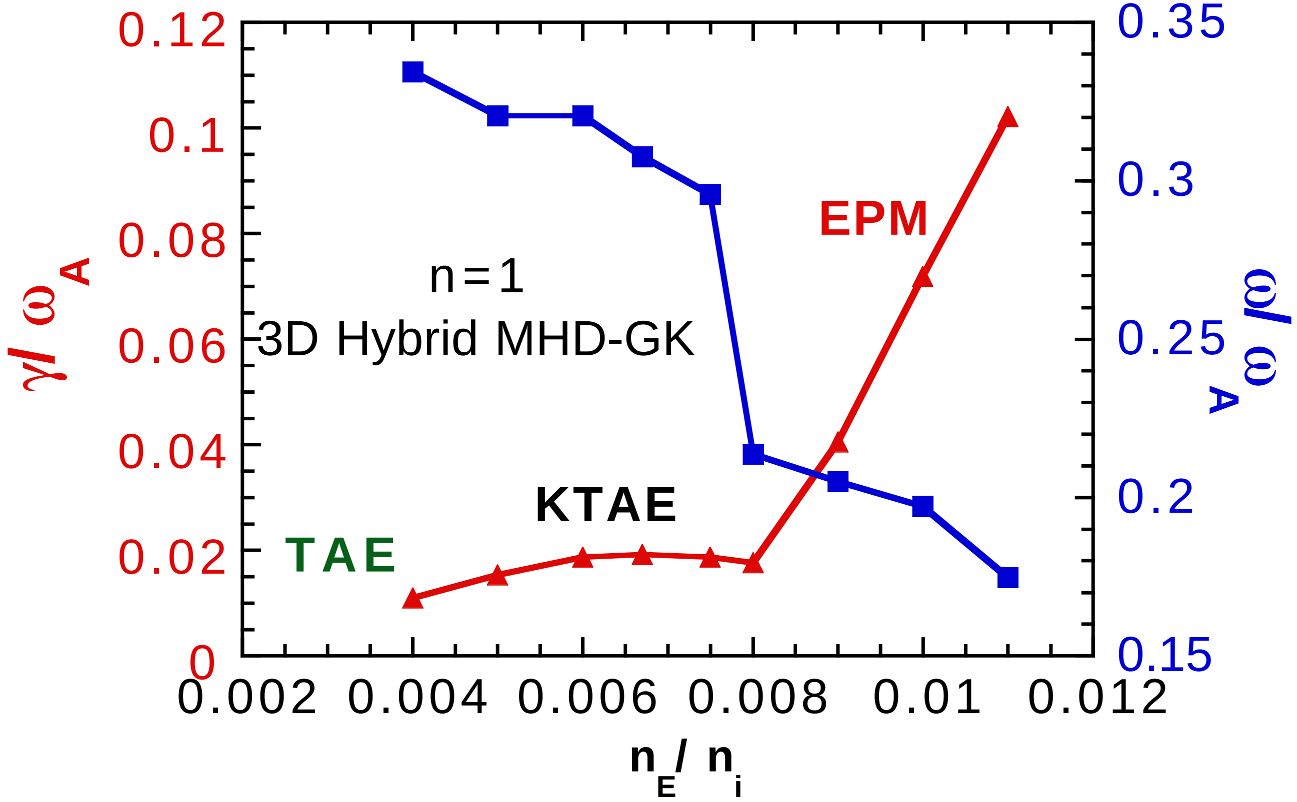


- Losses due to Abrupt Large amplitude Events (ALE), are consistent with resonant mode excitation. From **Shinohara** *et al.*, Nucl. Fusion **41**, 603, (2001).

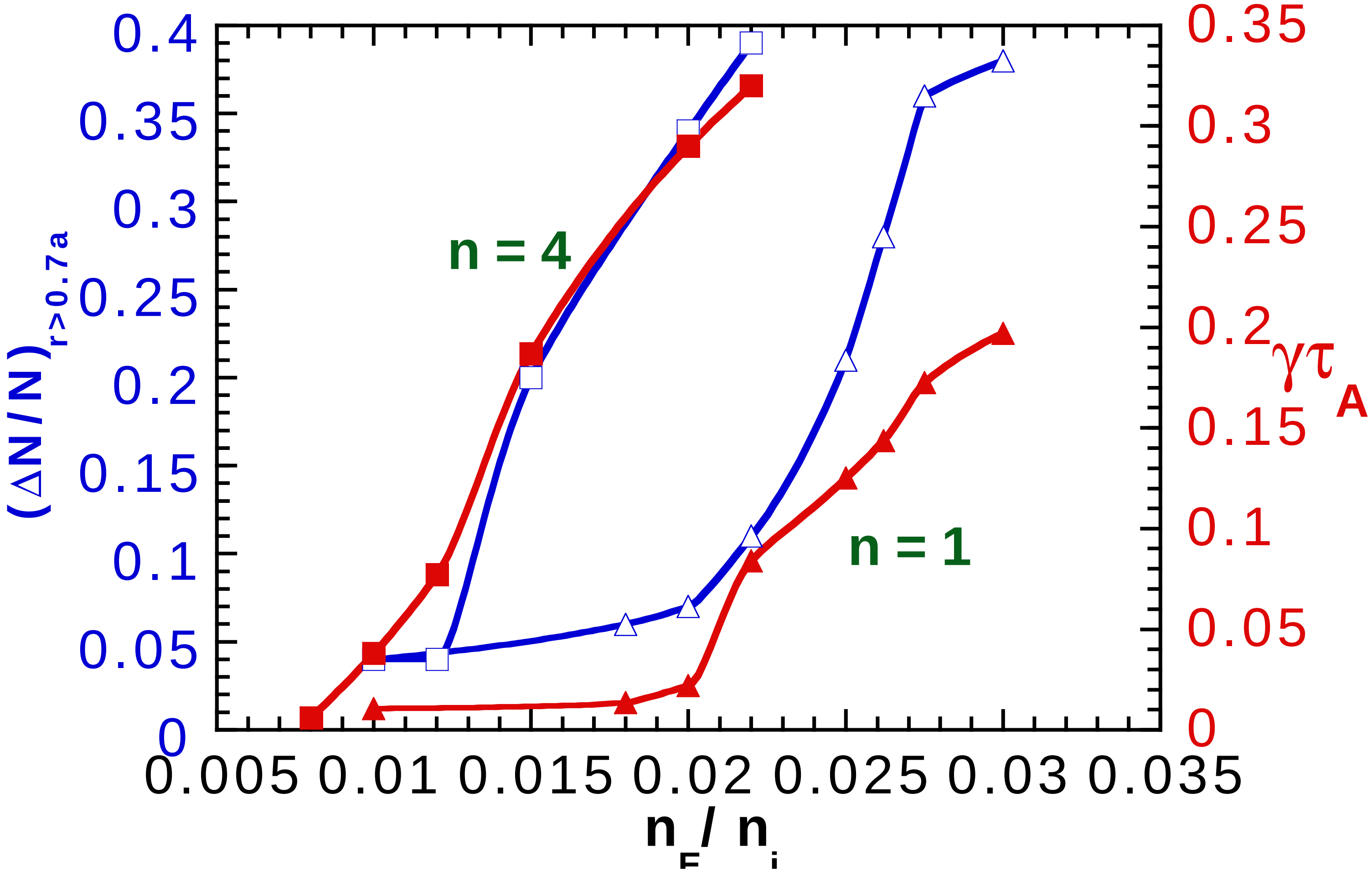


3D Hybrid MHD-GK simulation of EPM

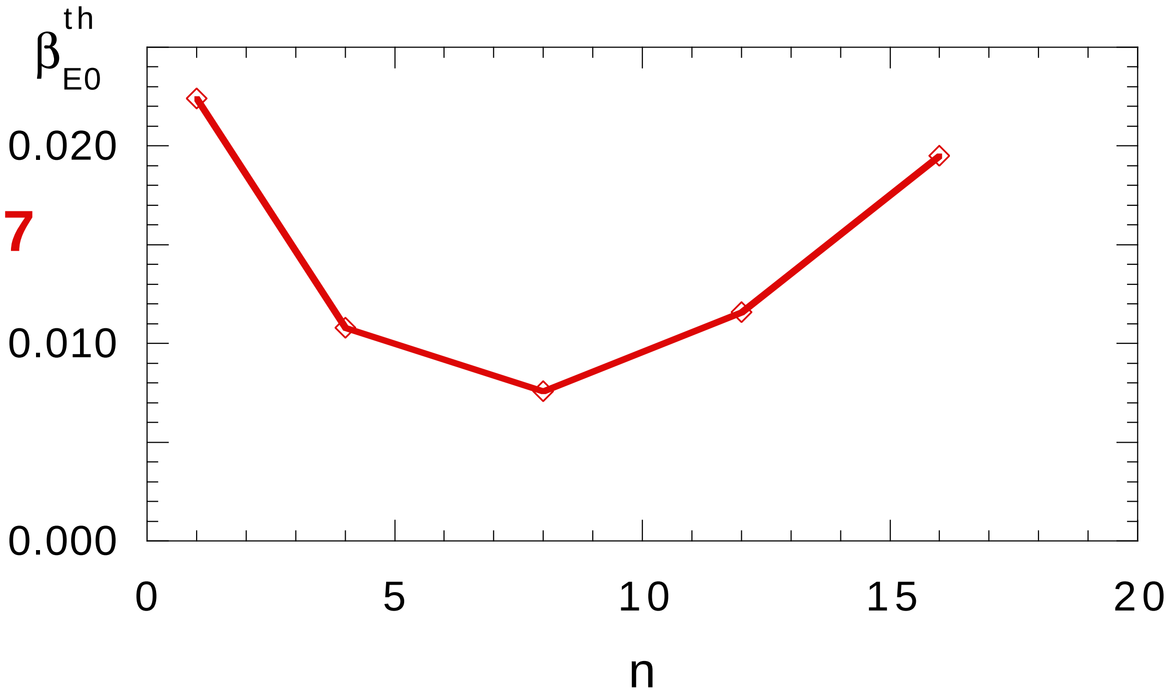
Briguglio et al., PoP **2**, 3711 , (1995); and PoP **5**, 3287, (1998)



EPM: Energetic Particle Transports



EPM: Threshold depends on n

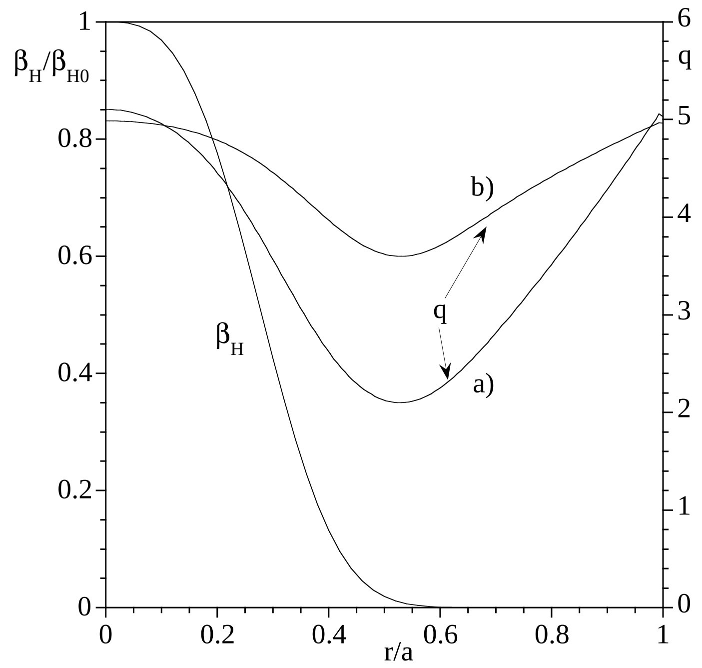


L_{PE}/R_0=0.07

Minimum β_{Eo}^{th} = 0.7% at n=8

3D Hybrid MHD-GK simulations: JET rev. q[1]

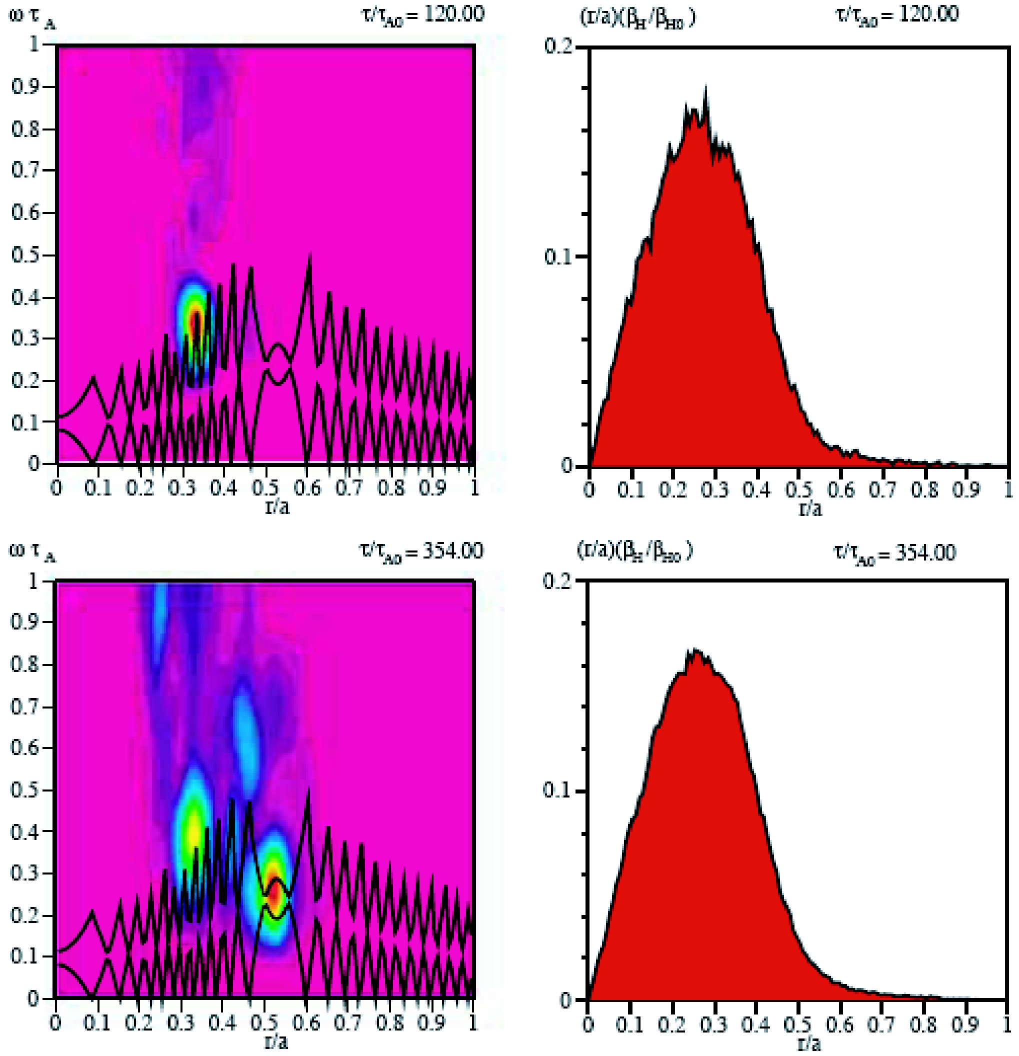
- ☐ Confirm expectation of resonant EPM excitation at the radial position of max drive
- ☐ EPM gap modes are also excited near q_{min} with weaker growth rate
- ☐ Depending on β_H, rapid non-linear fast particle transport may or may not establish a link between modes excited at different radial locations



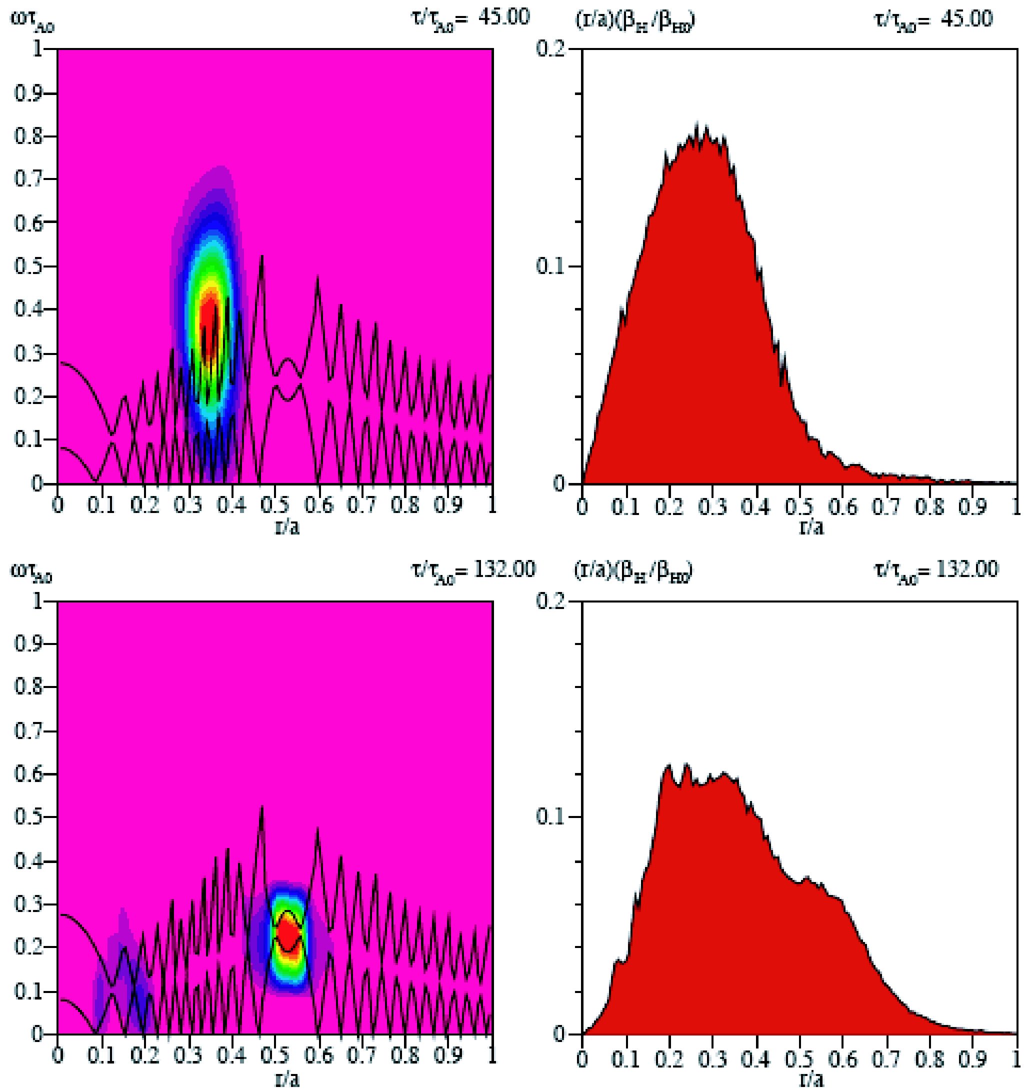
Isotropic Maxwellian Distribution
Circular Shifted Flux Surfaces
Const. Fast Ion Temperature Profile
Peaking Factor $\beta_{H0}/\langle\beta_H\rangle = 9.2$
$v_H/v_A = 1.0$, $\rho_{LH}/a = 0.02$, $n = 4$

[1] F. Zonca, *et. al.* Paper TH/4-4. 19.th IAEA FEC, Lyon, France,(2002)

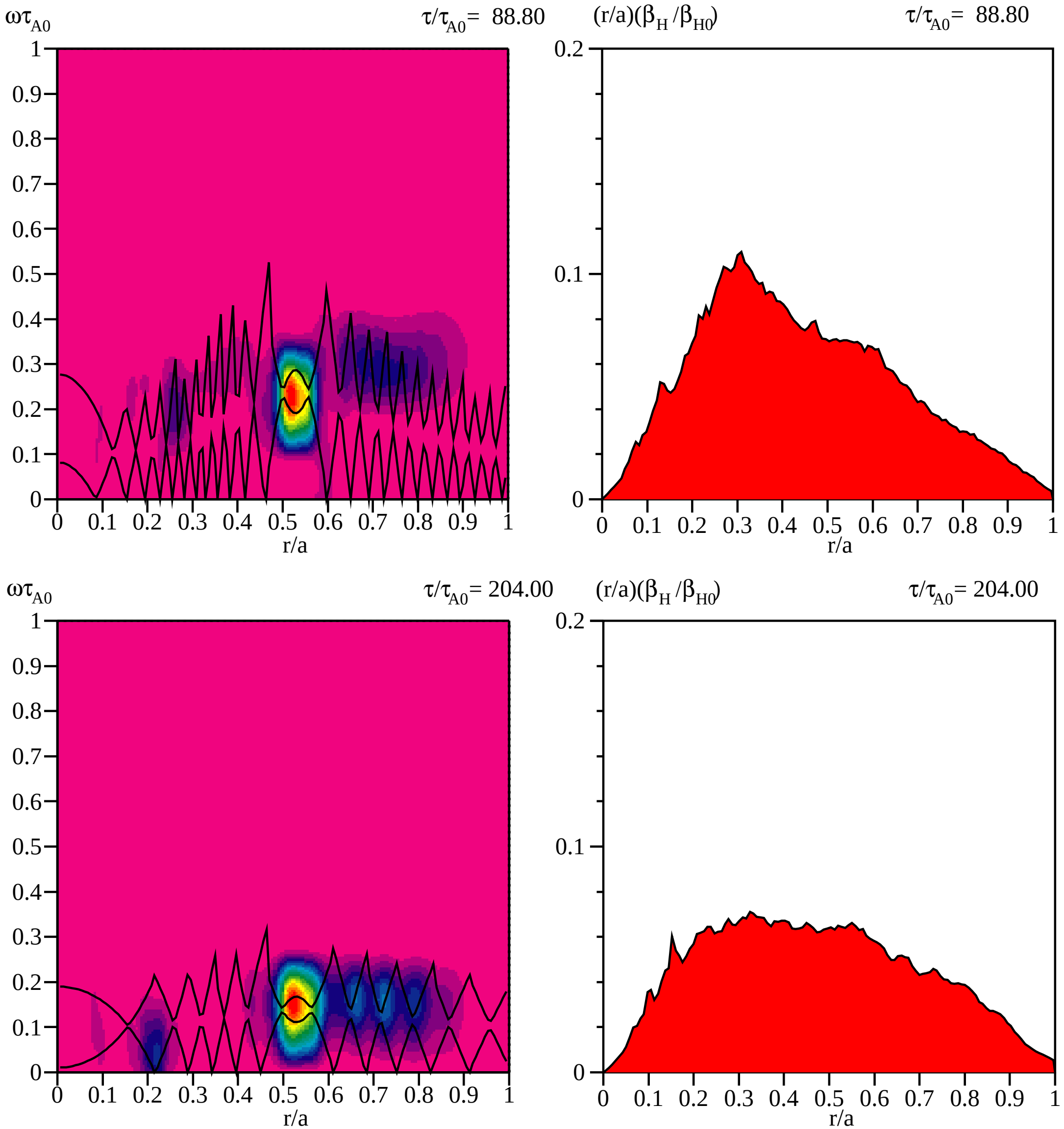
Weak Drive, $\beta_{H0} = 0.01$, and hollow q profile (a)



Moderate Drive, $\beta_{H0} = 0.025$, and hollow q profile (a)



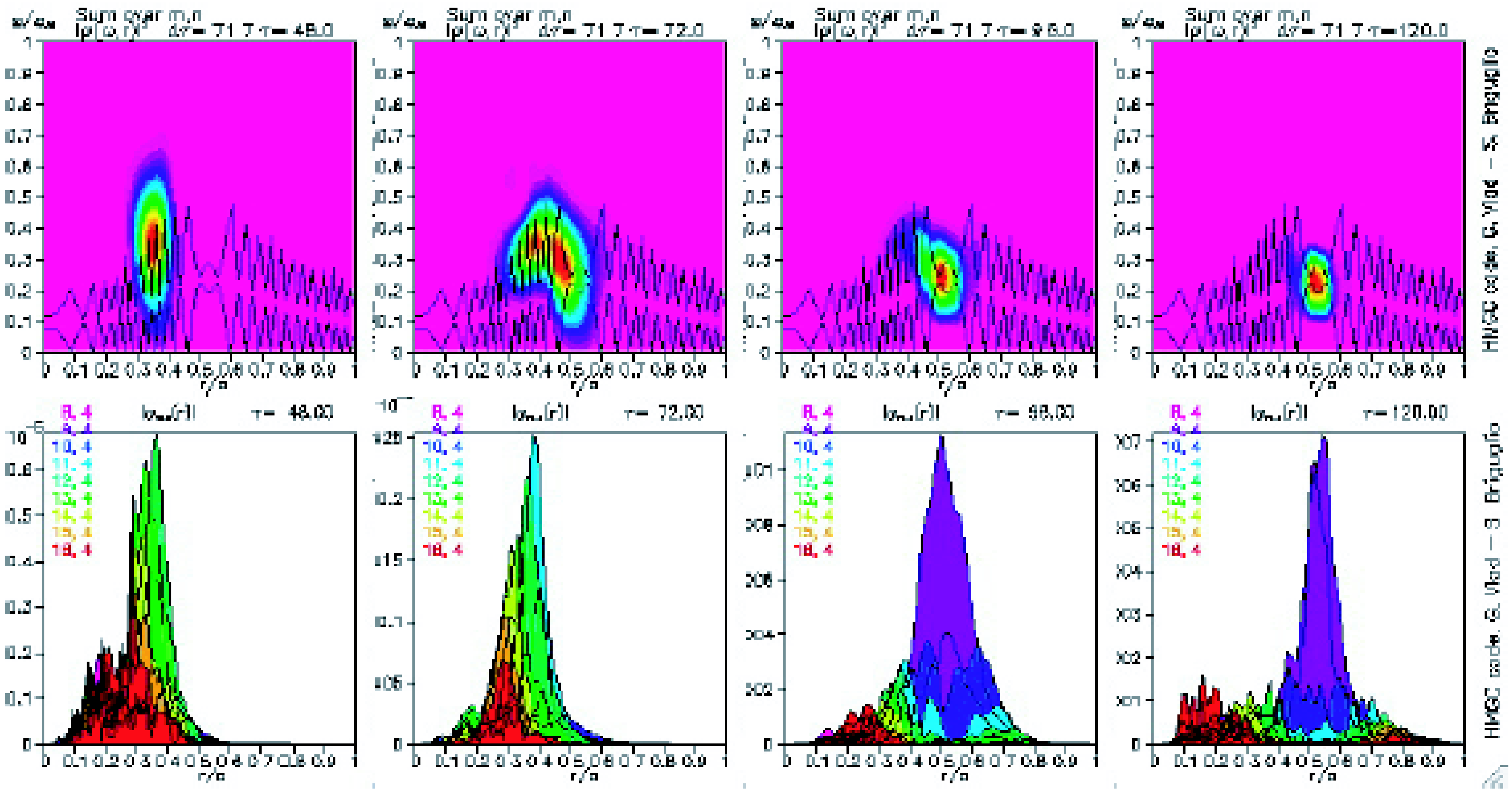
Fast ion Transport. . .



$\beta_{H0} = 0.05$, hollow q-profile

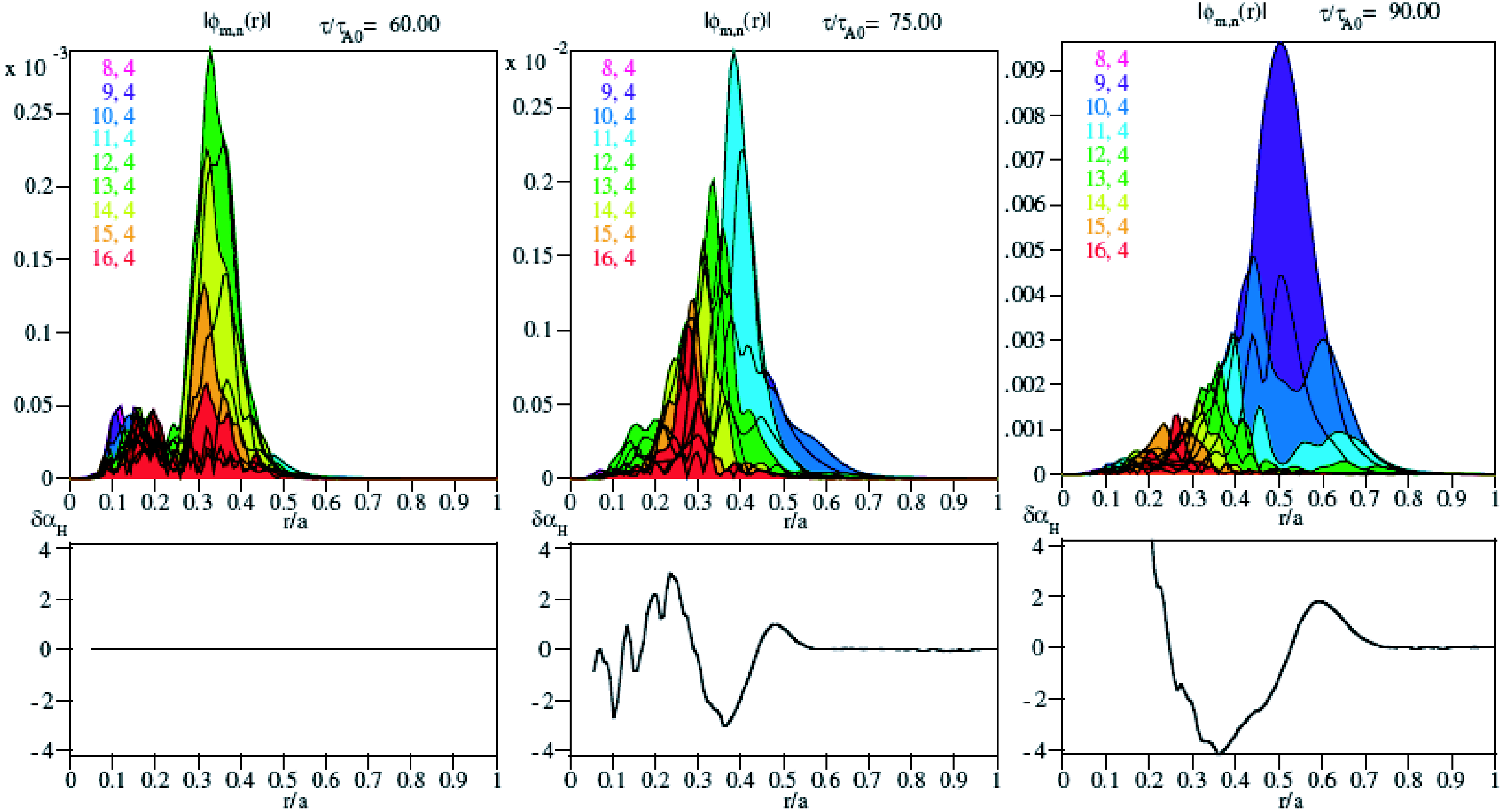
$\beta_{H0} = 0.025$, weakly hollow q-profile

Energetic Ion Avalanches and EPMs[2]

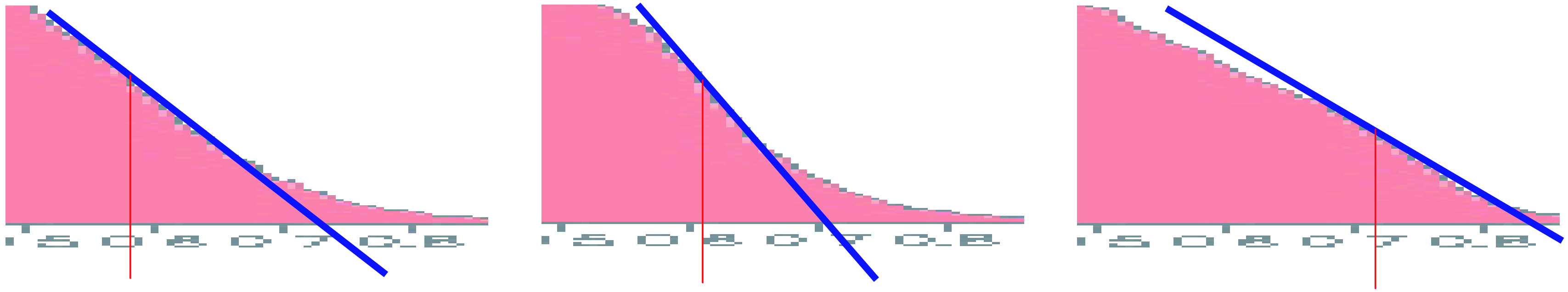


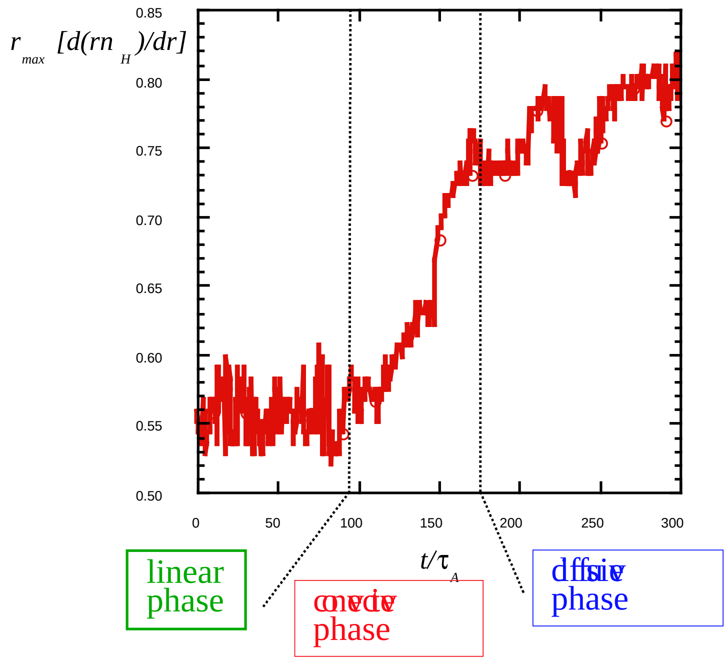
[2] Vlad *et. al*, IAEA-TCM, San Diego, Oct. 6-8 (2003); Zonca *et. al*, *ibid.*

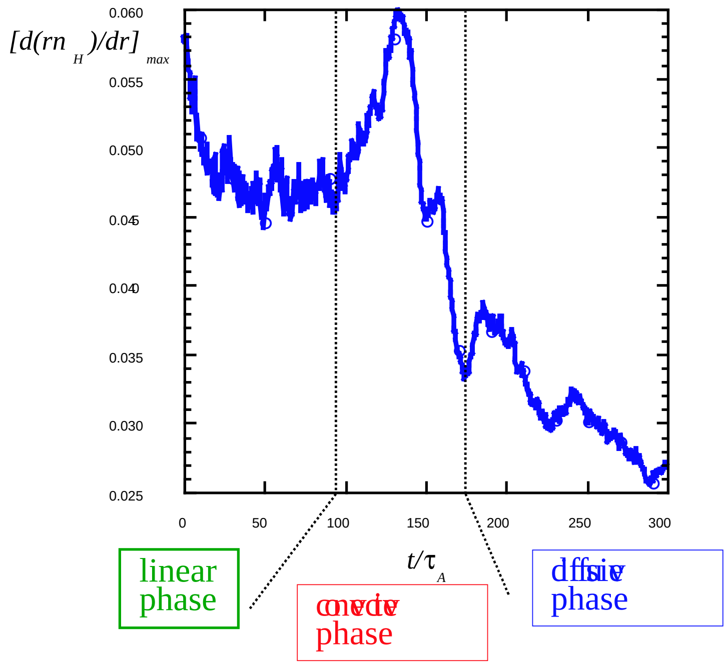
Relay-runner model for NL EPM dynamics



Propagation of the unstable front[3]







[3] Vlad *et. al*, IAEA-TCM, San Diego, Oct. 6-8 (2003)

Conclusions from EPM simulations with 3D Hybrid MHD-Gyrokinetic code

- Significant particle redistributions take place above linear excitation threshold of EPM: Transition from weak (diffusive) to strong (ballistic) energetic ion transport in avalanches at values that are relevant for burning plasmas
- Nonlinear saturation is due to (convective) displacement of the source (rather than wave-particle trapping)
- At present: single n (but multiple m) simulations $\Rightarrow$ generalize to multiple n !!!!
- Long time scale phase space dynamics (Fokker-Planck collision operator) missing $\Rightarrow$ difficult to generalize to $10^4 - 10^5$ Alfvén times

Discussions

- Linear Theory: sound and well understood. However, most codes still do not include nonperturbative particle dynamics
- Nonlinear Theory: Partially understood
  - Theory of Non-linear phase space dynamics (single mode) seems to explain a number of experimentally observed phenomena: saturation levels, pitch-fork splitting of spectral lines, chirping ... (possibly)
  - NL GK-MHD simulations of EPM's indicate saturation via source redistribution rather than $\omega_b \approx \gamma_L$; fast ion radial convection
  - What happens in the multiple (m, n) case??? ... and for a strong source??? ...
  - Chirping is a very complex phenomenon, observed in most tokamaks with intense hot particle tails: due to equilibrium variations??? and/or Nonlinear

dynamics???

- Prediction and interpretation of particle losses is still lacking: domino effect (phase space stochasticity) ... and/or mode-particle pumping (particle convection)???

• Nonlinear Hamiltonian Dynamics: Strong mathematical methods exist ... but what about the plasma physicist original sin, ... solving the self-consistent problem???

• Experimental investigations: Understanding local transport , using ... high power density sources seems the key for a crucial progress and physics insights (... similar to thermal plasma transport problem ...)