Alfvénic turbulence in tokamaks: from micro- to meso-scale fluctuations*

Fulvio Zonca[1,2] in collaboration with Liu Chen[2,3]

http://www.afs.enea.it/zonca

[1]Associazione Euratom-ENEA sulla Fusione, C.R. Frascati, C.P. 65 - 00044 - Frascati, Italy.

[2]Institute for Fusion Theory and Simulation, Zhejiang University, Hangzhou 310027, P.R.C.

[3]Department of Physics and Astronomy, University of California, Irvine, CA 92697-2575

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Motivation

- The challenge of understanding fast particle collective behaviors in burning plasmas of fusion interest, is to develop a predictive capability for describing energetic particle confinement and its link to the dynamic evolution of thermal plasma profiles.

- Theory and simulation must play fundamental roles:

  - fusion plasmas are complex systems in which long time scale behaviors will be determined by cross-scale couplings of phenomena occurring on micro- and meso-spatiotemporal scales

  - existing experiments can look at these issues separately, since cross-scale couplings are not those of burning plasmas

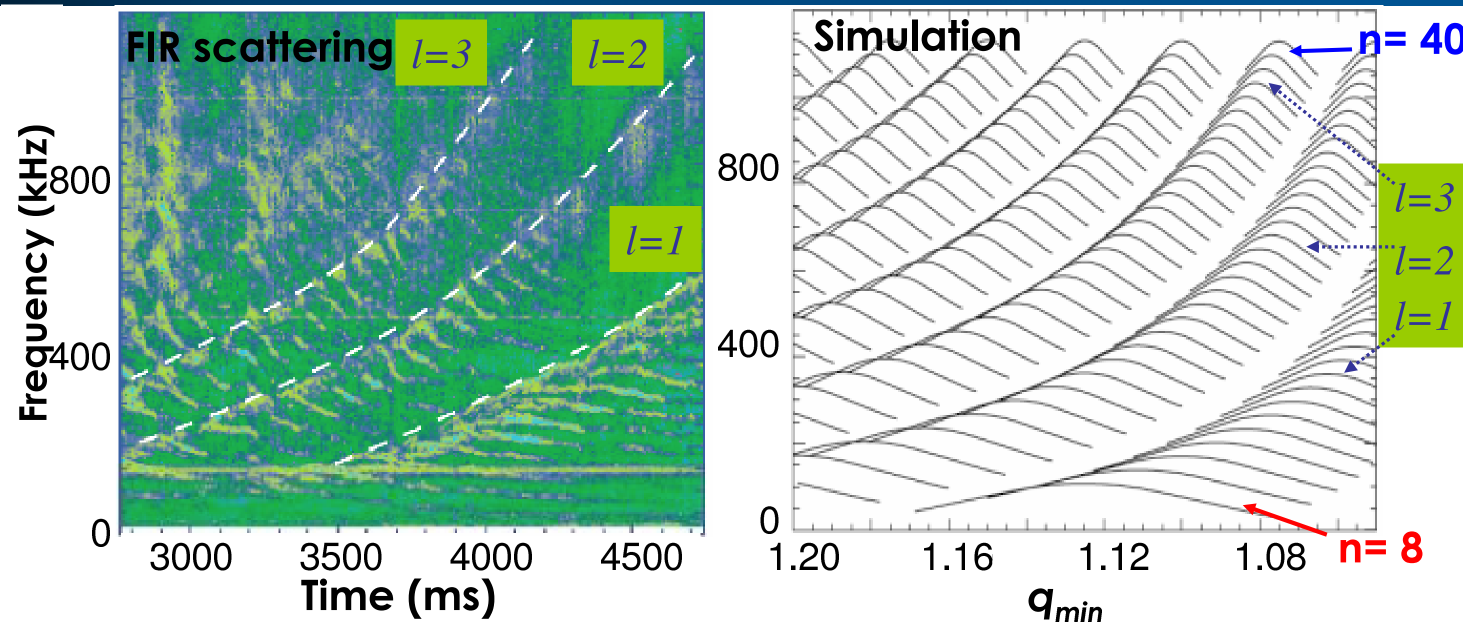
  - mutual positive feedbacks are necessary between theory, simulations and experiments for V&V of present predictive capabilities

From micro- to meso-scales

- Drift wave plasma turbulence is well known and turbulent plasma transport is widely studied (ITG/TEM/ETG).
- Alfvénic turbulence has been addressed mostly for plasma edge conditions [Scott PPCF97], but much less studied in the tokamak core [Chen et al NF78, Tang et al NF80].
- The investigation of Alfvénic ITG activity [Zonca and Chen PPCF96] is more recent. It is of relevance to burning plasmas of fusion interest since it can be excited at acoustic frequencies over a broad range of scale-lengths, from thermal ion Larmor radius to the typical fast ion orbit width [Zonca and Chen POP99], with a smooth transition to MHD modes [Zonca and Chen PPCF06, NF07, NF09].
- There is a wide observation database of these phenomena, accumulated in the recent years after the first observations in DIIID [Nazikian et al PRL06]

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

R. Nazikian, *et al.* 06, *PRL* **96**, 105006



- **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:** $V_{||} \approx 0.3 V_A$

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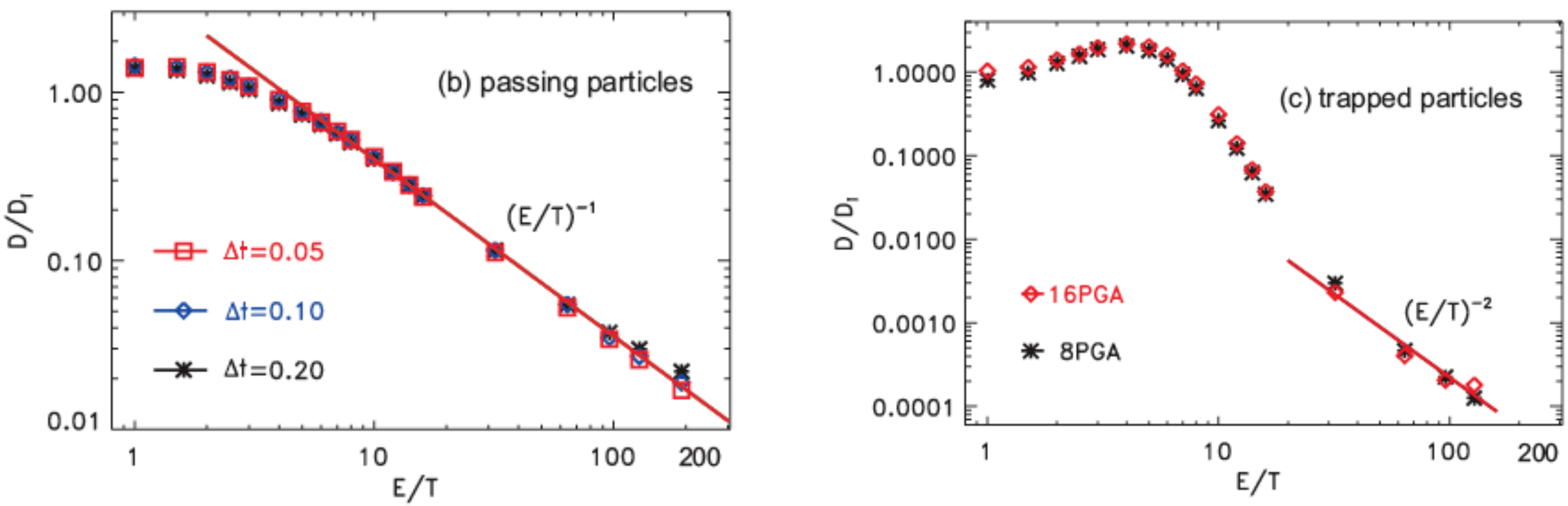
Fast particle transport by plasma turbulence

- Significant interest on this topic was triggered by recent AUG [Günter et al NF07], JT-60U [Suzuki et al NF08] and DIIID [Heidbrink et al PRL09] experimental results with NBI, showing evidence of anomalies in fast ion transport (clarified now: [Zhang et al POP10])

From Zhang et al POP **17** 055902 (2010)



- Diffusivity behaviors are consistent with theoretical predictions based on quasi-linear theory [Chen JGR99]
- Intrinsic interest is mostly connected with explanation of present day experiments, with low characteristic values of E/T; e.g., evidence of ITG induced transport of NBI supra-thermal ions in DIIID [Heidbrink et al PPCF09].
- Results show that fast ion transport by micro/turbulence above the critical energy is negligible. Effects are expected on He ashes or medium energy supra/thermal tails: possible good news?
- Fairly complete reconstruction of original theoretical works, e.g. [White and Mynick PFB89], theoretical issues, and experimental evidence in recent paper [Zhang et al POP10]. See also Heidbrink et al 2010 EPS invited talk [PPCF10].

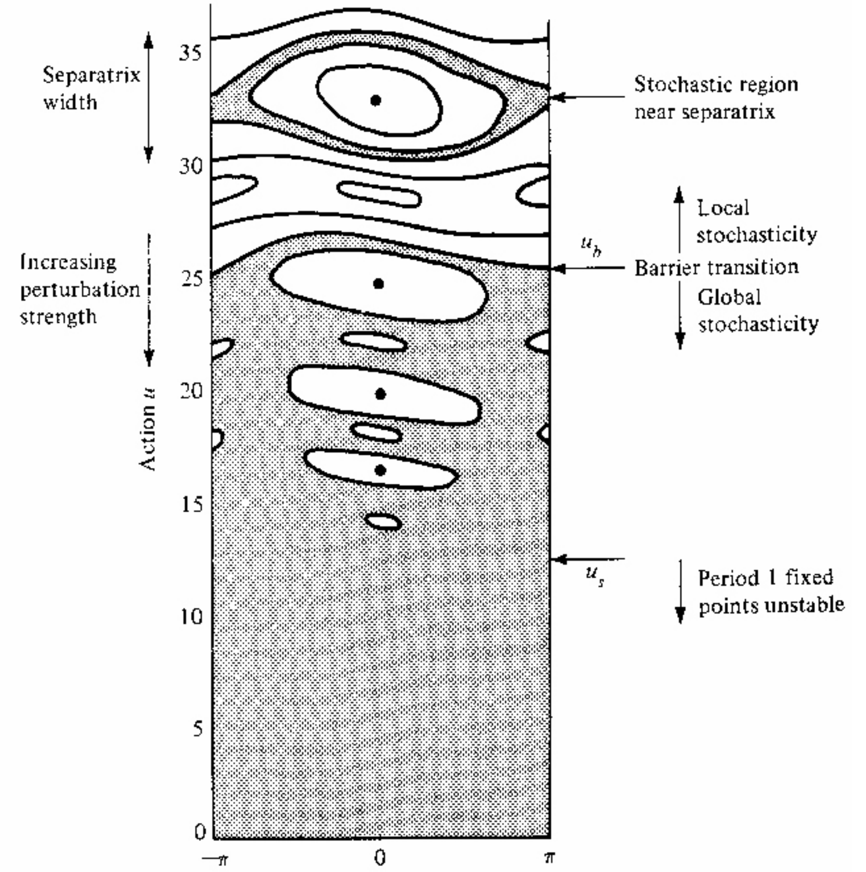
Fast ion transports in burning plasmas

- Alfvén Eigenmodes (AE) modes are predicted to have small saturation levels and yield negligible transport unless stochastization threshold in phase space is reached [Berk and Breizman, PFB90; Sigmar et al PFB92].
- Strong energetic particle redistributions are predicted to occur above the Energetic Particle Modes (EPM) excitation threshold in 3D Hybrid MHD-Gyrokinetic simulations [Briguglio et al POP98].
- Nonlinear Dynamics of Burning Plasmas: energetic ion transport in burning plasmas has two components:
  - slow diffusive processes due to weakly unstable AEs and a residual component possibly due to plasma turbulence [Vlad et al PPCF05, Estrada-Mila et al POP06].
  - rapid transport processes with ballistic nature due to coherent nonlinear interactions with EPM and/or low-frequency long-wavelength MHD: fast ion avalanches & experimental observation of Abrupt Large amplitude Events (ALE) on JT60-U [Shinohara et al PPCF04].

Phase space structures: fast ion resonant interactions with AE

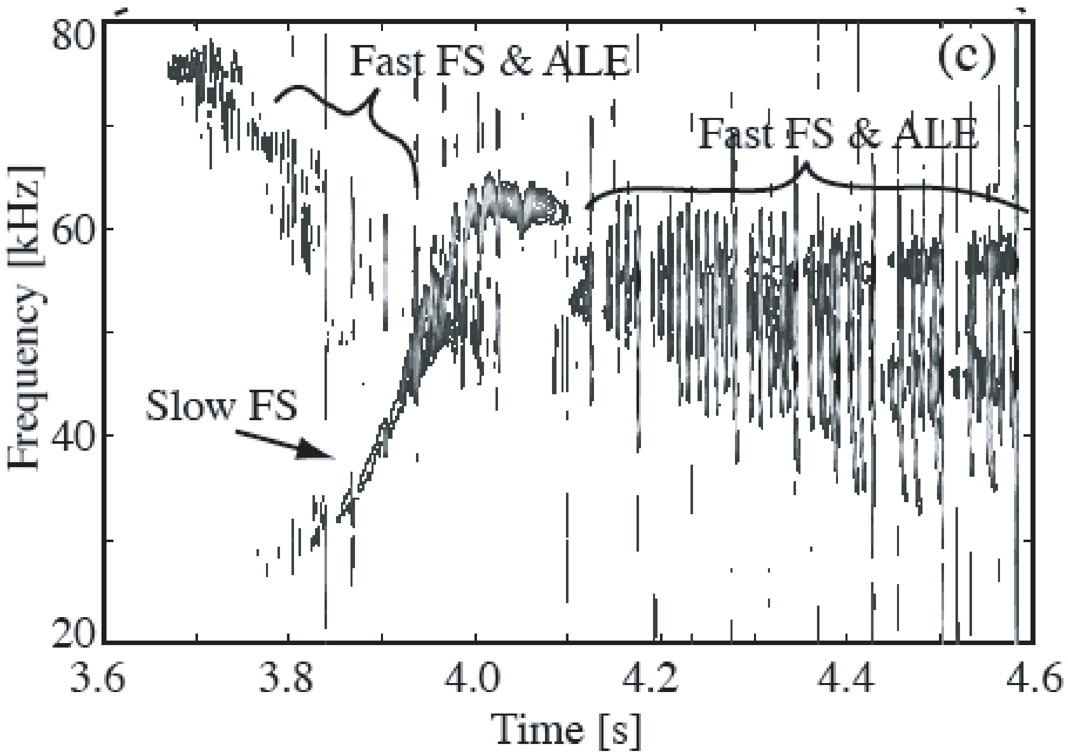
D.J. Sigmar, *et al.* 1992, *PFB* **4**, 1506 ; C.T. Hsu and D.J. Sigmar 1992, *PFB* **4**, 1492

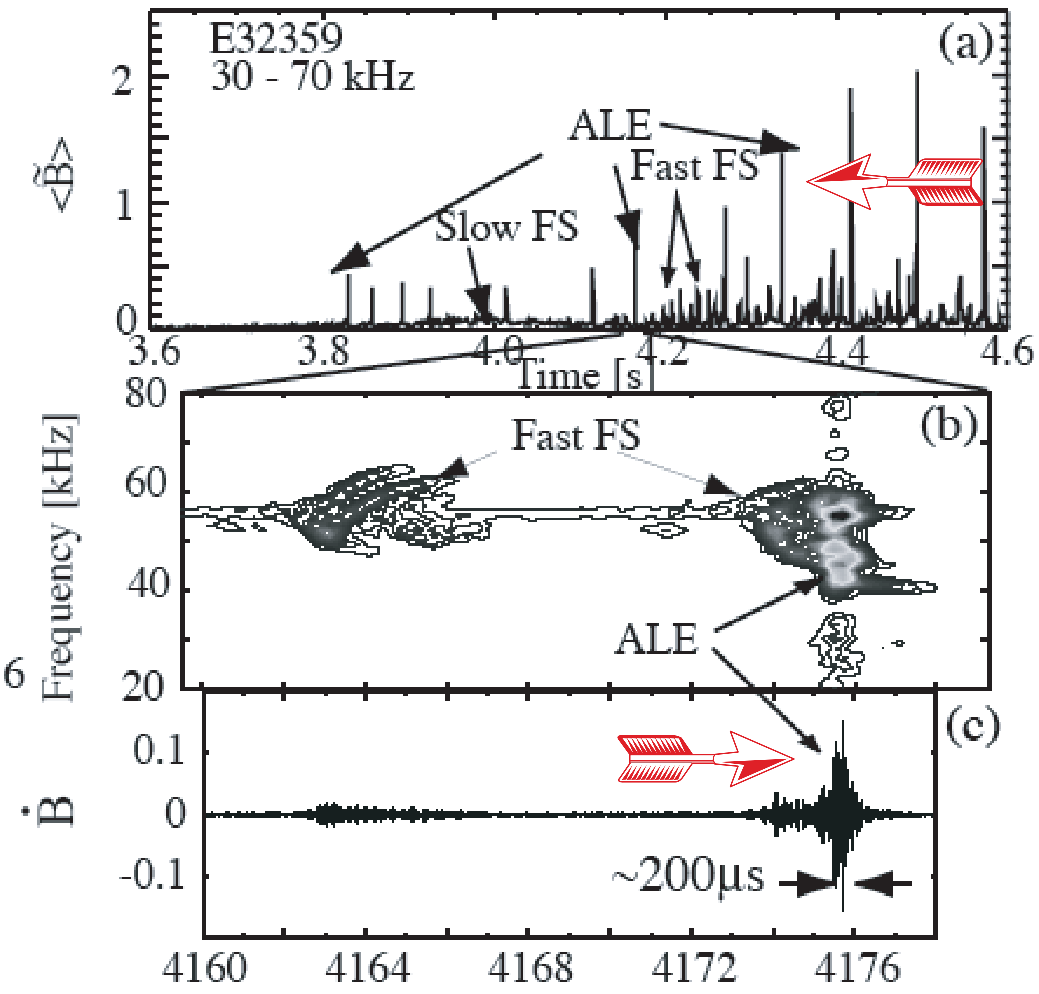
- Transient losses $\approx \delta B_r/B$: resonant drift motion across the orbit-loss boundaries in phase space
- Diffusive losses $\approx$ $(\delta B_r/B)^2$ above a stochastic threshold, due to stochastic diffusion in phase space across orbit-loss boundary
- Uncertainty in the stoch. threshold: $(\delta B_r/B) \lesssim 10^{-4}$ in the multiple mode case. Possibly reached via phase space explosion: "domino effect" [Berk et al POP96]



Lichtenberg & Lieberman 1983, Sp.-Ver. NY

ALE on JT-60U [Shinohara et al. NF01]



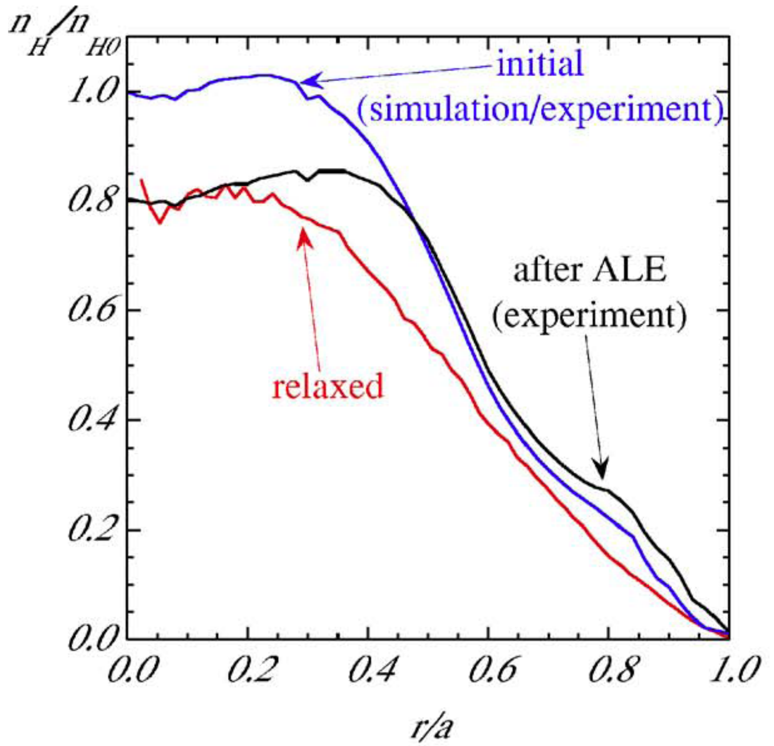


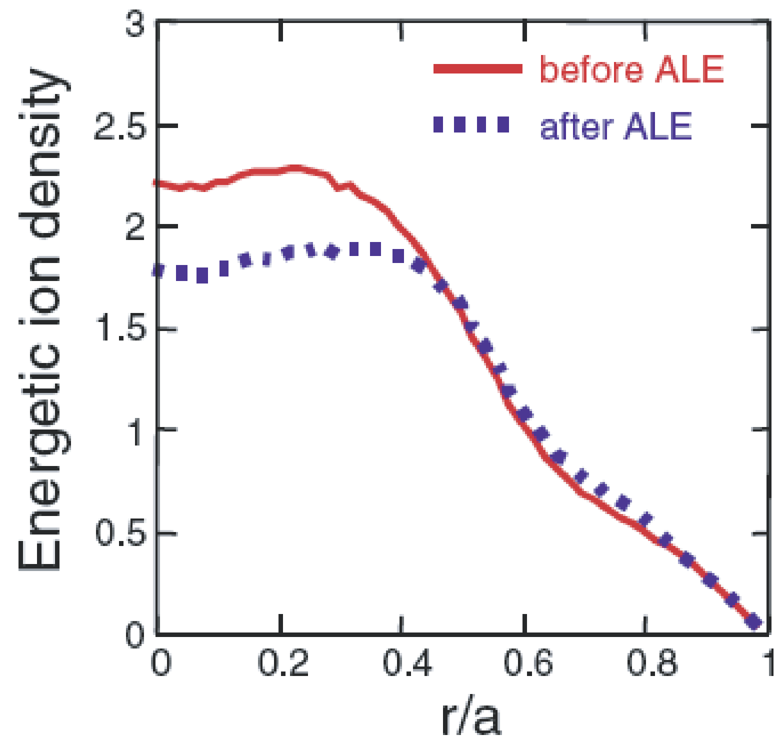
ALE = Abrupt Large amplitude Event

Courtesy of K. Shinohara and JT-60U

Fast ion transport: simulation and experiment

- Numerical simulations show fast ion radial redistributions, qualitatively similar to those by ALE on JT-60U.



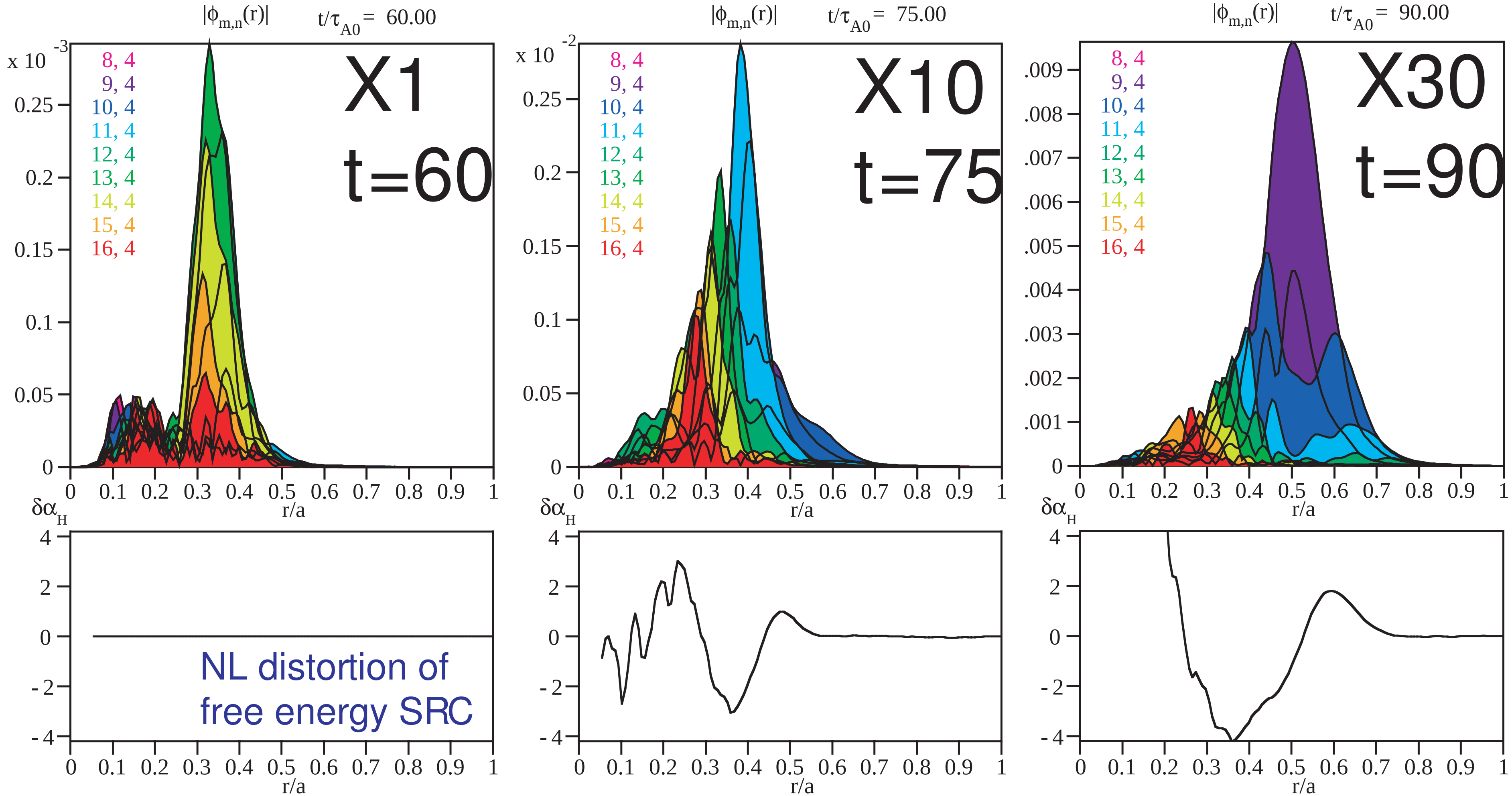


S. Briguglio et al POP 14, 055904, (2007)

K. Shinohara et al PPCF 46, S31 (2004)

Zonca et al. IAEA, (2002)

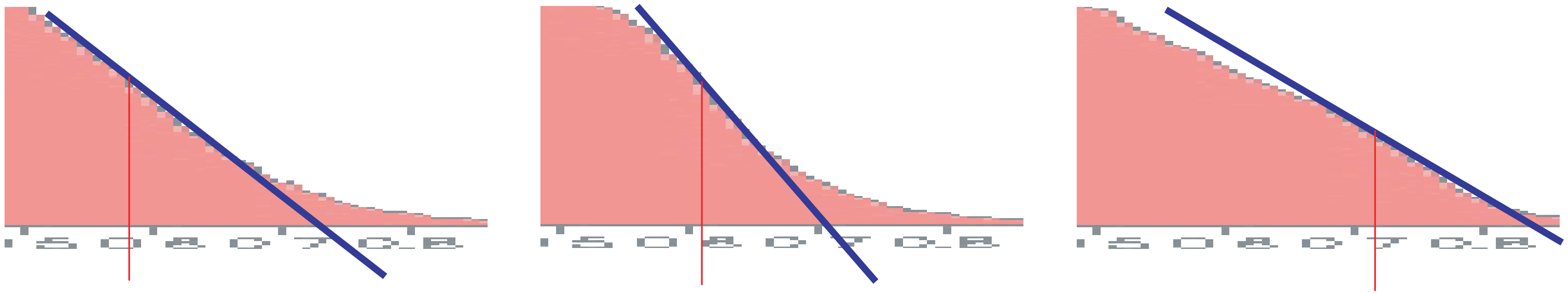
Avalanches and NL EPM dynamics

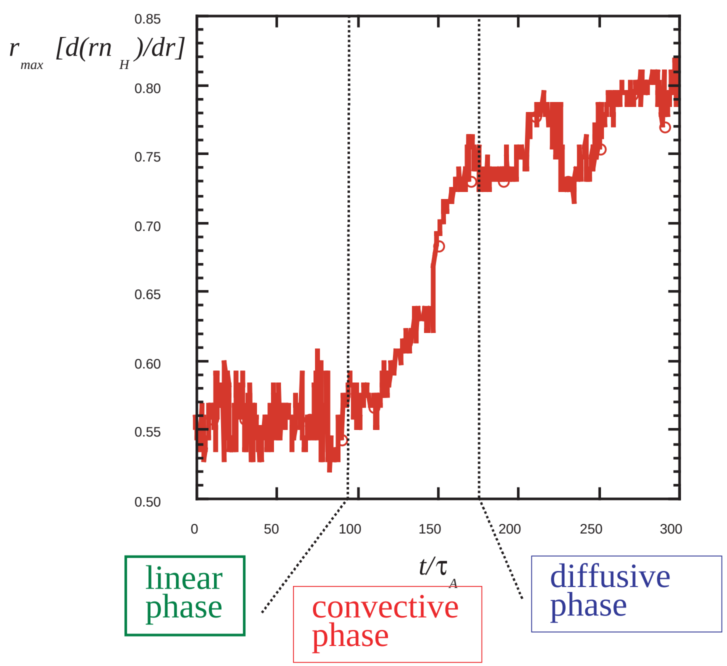


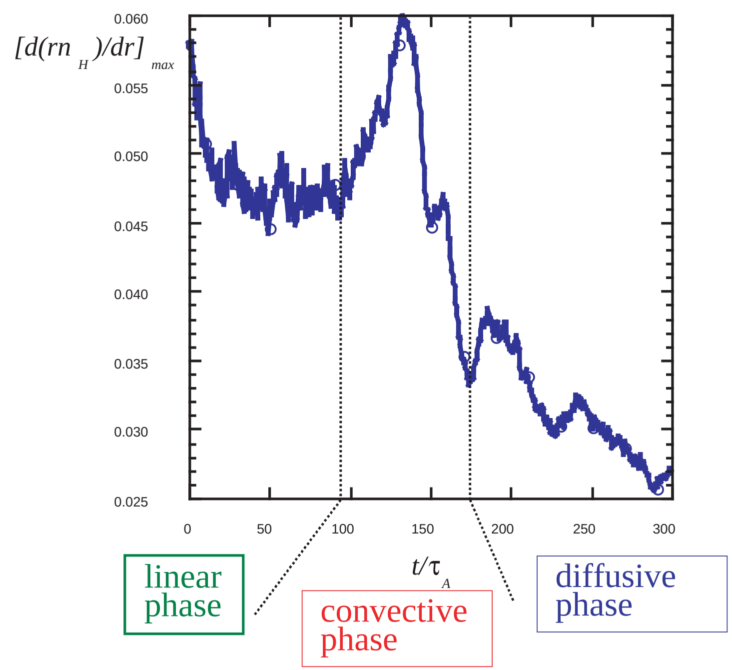
- Importance of toroidal geometry on wave-packet propagation and shape

Vlad et al. IAEA-TCM, (2003)

Propagation of the unstable front







- Gradient steepening and relaxation: spreading ... similar to turbulence

The form of nonlinear interactions in a torus

- ☐ Channels for nonlinear interactions can be described via the three degrees of freedom of mode structures: the toroidal mode number n, the parallel mode structure reflecting the radial width of a single poloidal harmonic m, and radial mode envelope $A(r) = \exp i \int \theta_k d(nq)$.

- ☐ Correspondingly, nonlinear interactions could occur via the following three channels: mode coupling between two n's, distortion of the parallel mode structure, and modulation of the radial envelope.
  - radial envelope modulations: ZF, GAM, zonal structures
  - mode coupling: spectral transfer (cascade) via 3-wave interactions

- ☐ Radial envelope modulation via generation of zonal flows dominates in ITG turbulence. Zonal structures (profile relaxation etc.) and/or GAM/ZF influence AE/EPM dynamics depending on the strength of mode drive.

- ☐ ETG turbulence is regulated by nonlinear toroidal mode couplings. What effect on Alfvénic turbulence?

Three-wave interactions and spectral transfer

- This is still an open problem, largely unexplored:
  - Alfvénic fluctuations in toroidal plasmas of fusion interest cover all scales, from thermal ion Larmor radius up to characteristic energetic ion orbit widths (meso-scale AE/EPM) and macro-scales (MHD modes).
  - All scales involved: no unique approach to investigate spectral transfer processes (local vs non-local in $\mathbf{k}$, anisotropy, density of states).
  - In realistic conditions, these dynamics are influenced by non-uniformities and toroidal geometries: wave-particle power exchange $\langle \mathbf{v} \cdot \delta \mathbf{E} \rangle = \mathbf{v_d} \cdot \langle \delta \mathbf{E} \rangle$; gyro-averaged forces $\langle \mathbf{v} \times \delta \mathbf{B} \rangle = -i \mathbf{v_d} \cdot \mathbf{k} \left\langle \delta \mathbf{A}_\parallel \right\rangle$
- Geometry and non-uniformity influence three-wave interactions (spectral transfer) via density of quasi-modes and scattering cross-section [Chen et al PPCF05] $\Rightarrow$ Filament-like structures ($|k_\parallel| qR \ll 1 \approx \mathrm{O}(\mathrm{n}^{-1/2})$) are naturally generated in toroidal systems.

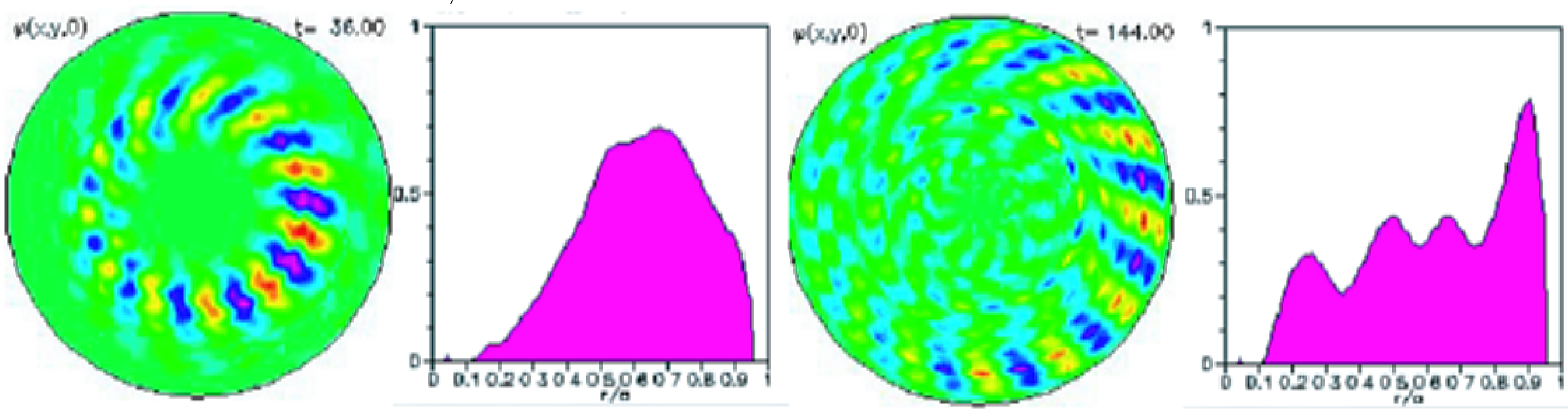
- Spectral transfer must be evaluated in competition with generation of ZF, GAM, zonal structures (e.g., phase-space holes and clumps if adiabatic processes dominate, which is not the general/most interesting case).
- Most relevant open issue: determine hierarchy of relevant non-linear time scales in realistic conditions, where cross-scale couplings are reproducing those expected to occur in plasmas of fusion interest.

Zonal Flows and Zonal Structures

- Very disparate space-time scales of AE/EPM, MHD modes and plasma turbulence: complex self-organized behaviors of burning plasmas will be likely dominated by their nonlinear interplay via zonal flows and fields [Chen and Zonca ASICTP08]:
  - Effects of different ZF and ZS (ω, k_r) spectra in cross/scale couplings
  - Peculiar roles of Alfvénic fluctuations in the acoustic frequency range: AITG, AE/EPM and MHD with similar frequencies
- Crucial role of toroidal geometry for Alfvénic fluctuations: fundamental importance of magnetic curvature couplings in both linear and nonlinear dynamics [Scott NJP05; Naulin et al POP05]
- Long time scale behaviors of zonal structures are important for the overall burning plasma performance: generators of NL (time varying) "equilibria"
- The corresponding stability determines the dynamics underlying the dissipation of zonal structures in collision-less plasmas and the nonlinear up-shift of thresholds for turbulent transport [Chen et al NF07].

Long time scale behaviors

- Depending on proximity to marginal stability, AE and EPM nonlinear evolutions can be predominantly affected by
  - spontaneous generation of zonal flows and fields [Chen et al NF01, Guzdar et al PRL01]
  - radial modulations in the fast ion profiles: for sufficiently strong fast ion drive, ZF effects are negligible $[(\beta_H/\beta_e)(R/L_{pH}) \gg \epsilon^{3/2}(T_H/q^2T_e)$; Zonca et al, Varenna00



- AITG and strongly driven MHD modes behave similarly

Structures of the low-frequency SAW spectrum

- Low-frequency Shear Alfvén Wave (SAW) gap: $\omega \sim \omega_{*i} \sim \omega_{ti}$; $\Lambda^2(\omega) = k_\parallel^2 v_A^2$

  $\Rightarrow$ (ideal MHD) accumulation point (at $\omega = 0$) shifted by thermal ion kinetic effects [Zonca et al PPCF96]

  $\Rightarrow$ new low-freq. gap! Kinetic Thermal Ion (KTI) gap [Chen NF07]
    - Diamagnetic drift: KBM [Biglari et al PRL91]
    - Thermal ion compressibility: BAE [Heidbrink et al PRL93]
    - ∇T_i and wave-part. resonances: AITG [Zonca POP99]

  $\Rightarrow$ unstable SAW accumulation point

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

  $\Rightarrow$ Excitation of BAE/EPM/AITG at all scales, form micro (thermal ions) to meso (fast ions)

- For physics analogy: BAE – GAM degeneracy [Zonca et al PPCF06; Chen et al NF07]. $\Rightarrow$ Implications on cross-scale couplings mediated by zonal structures [Chen and Zonca ASICTP08; Varenna08].

Nonlinear Dynamics: local vs. global processes

- Alfvénic fluctuation spectrum in burning plasma is dense and consists of mode with characteristic frequencies and radial locations [Chen NF07]. However, nonlinear dynamics has been investigated so far mostly for one single mode.

- Mode saturation via wave-particle trapping [Berk et al PFB90, PLA97] has been successfully applied to explain pitchfork splitting of TAE spectral lines [Fasoli et al PRL98]: local distortion of the fast ion distribution function because of quasi-linear wave-particle interactions.

- Negligible transport by AE is expected because of these processes, unless stochastization threshold is reached in phase space possibly via "domino effect" [Berk et al POP96].

- Such analyses generally assume proximity to marginal stability:
  - One single low amplitude wave, such that linear mode structures can be assumed and drop out of the problem: radial uniform problem
  - Finite background dissipation does not depend on the finite amplitude wave (no continuum damping)
  - Wave dispersiveness is set by the background plasma (no beam mode/EPM)
  - Frequency sweeping is absent or adiabatic (no mode-particle-pumping [White et al PF83])
- These properties delineate an analogy between single Alfvén Eigenmode behaviors in burning plasmas with those of Langmuir waves (1D beam-plasma problem). However they show a strong contrast between dynamics of beam-mode in 1D systems and Energetic Particle Modes in toroidal devices [Zonca IFTS Lecture Notes Spring 2010].
- Next: focus on the transition from weak to strong NL dynamic regime, where intrinsic EPM resonant nature plays a crucial role, with plasma non-uniformity and toroidal geometry. Control parameter is power density input: proximity to marginal stability does not hold.

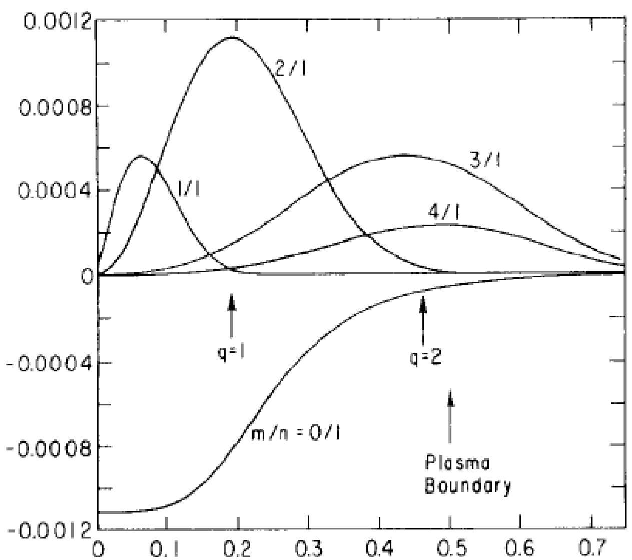
Mode-particle pumping (fishbone)

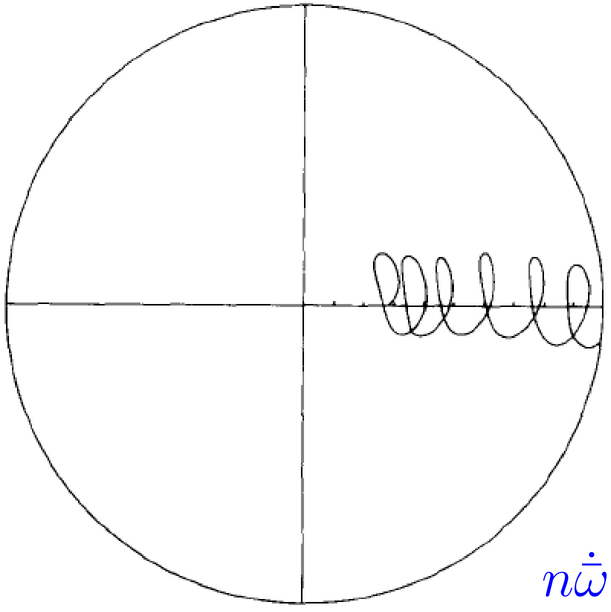
- Mode-particle pumping: (White et al., Phys. Fluids **26**, 2958, (1983))
  MHD $(\delta\phi, \delta A_\parallel)$ with $\delta\phi = \delta\phi_0(r)\sin(n\varphi - m\theta - \omega t + \psi)$

$$r \simeq r_0 + \frac{v_{d0}}{\omega_b}\theta_b \cos(\omega_b t) + \langle \Delta r \rangle \qquad \langle \dot{\Delta r} \rangle = \frac{c}{B}\frac{m}{r_0}\left[\frac{\ell\omega_b + (m/q)\bar{\omega}_d}{\ell\omega_b + n\bar{\omega}_d}\right]\delta\phi_0 J_\ell(m\theta_b)\cos\psi$$

$$\theta \simeq -\theta_b \sin(\omega_b t) + \langle \Delta\theta \rangle \qquad \dot{\psi} = \frac{\langle \Delta r \rangle}{r_0}(s-1)n\bar{\omega}_d$$

$$\omega = n\bar{\omega}_d + \ell\omega_b$$

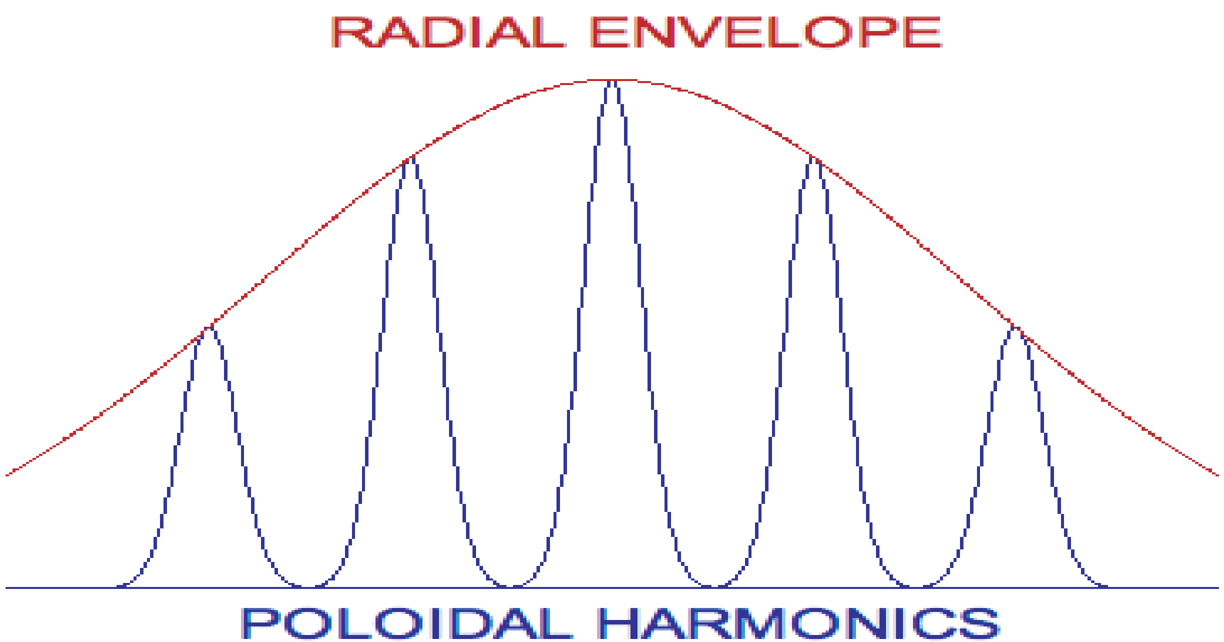




$$n\dot{\bar{\omega}}_d \approx \omega_B^2$$

Radial mode structures in toroidal geometry

- The notion of radial envelope: both linear and nonlinear interactions are affected by peculiar mode structures in toroidal geometry and by equilibrium non-uniformities



Transport, toroidal geometry, non-uniformities

- Energetic particle transport in toroidal systems has unique features that cannot be reproduced in simpler 1D geometries, except for special cases

- Conservation of Hamiltonian in extended phase-space $\Rightarrow$ $(\Delta r/L_p) \simeq (\omega_{*p}/\omega)(\Delta E/E)$; drift-wave turbulence tends to maximize ω_* consistently with finite orbit averaging; for fast ions $|\omega_{*p}/\omega| \gg 1$

- Wave particle de-correlations are set by radial non-uniformities: magnetic shear and toroidal mode number for the circulating particles; magnetic shear (not only) but no dependence on the mode number explicitly for trapped particles precession resonance (origin of different behavior of transports in ITG vs TEM turbulences)

- Either none or very limited/slow frequency chirping is allowed for Alfvénic modes (1D bump-on-tail paradigm): adiabatic hole-clump dynamics in phase-space near marginal stability [Berk et al PLA97, POP99; Lesur et al POP09] (strong drive case considered by [Vann et al PRL07])

- Unique feature of EPM/fishbones with large/fast frequency chirping: resonant frequency locking removes wave particle decorrelation by radial non-uniformities $\Rightarrow$ resonance de-tuning in velocity space and fast convective transports as consequence of coherent wave and particle nonlinear dynamics (nonlinear dispersiveness compensates changing frequency)

Nonlinear initial value problem for EPM

- Use the theoretical framework of the general fishbone-like dispersion relation: unified description for all Alfvénic modes in toroidal geometry [Chen and Zonca PPCF06, NF07]; focus on precession resonance for trapped particles with one monochromatic EPM with $\omega(t)$: $|\dot{\omega}| \ll |\gamma(t)\omega(t)|$ [Zonca et al NF05; Zonca IFTS Lecture Notes Spring 2010]

$$i\Lambda\left(\omega(t)+i\partial_t\right)A(r,t)=\left(\delta W_{f,MHD}+\delta W_{f,EP}+\delta W_{k,EPT}\right)A(r,t)$$

$$\delta W_{k,EPT}=\mathcal{I}\circ\int_{-\infty}^{\infty}\frac{k_\theta}{\omega_c}\frac{\overline{\omega}_{dk}\partial\hat{F}_0(\omega)/\partial r}{\overline{\omega}_{dk}-\omega(t)-\omega}e^{-i\omega t}d\omega \qquad \delta W_{f,EP}=-\mathcal{I}\circ\frac{k_\theta}{\omega_c}\frac{\partial F_0}{\partial r}\frac{\bar{J}_L^2}{\bar{J}^2}$$

$$\mathcal{I}\equiv\frac{2\pi^2e^2}{Mc^2}\frac{q}{|s|}R_0B_0\sum_{v_\parallel/|v_\parallel|=\pm1}\int_0^\infty\mathcal{E}d\mathcal{E}\int d\lambda\frac{\overline{\omega}_{dk}}{k_\theta^2}\tau_b\bar{J}^2$$

$$\bar{J}^2\equiv\int_{-\infty}^{\infty}J_0^2(\lambda_{Lk})J_0^2(\lambda_{dk})\left|\delta\phi_c(\theta,\theta_k)\right|^2d\theta \qquad \bar{J}_L^2\equiv\int_{-\infty}^{\infty}J_0^2(\lambda_{Lk})\left|\delta\phi_c(\theta,\theta_k)\right|^2d\theta$$

- This problem is already in the suitable nonlinear form via $\hat{F}_0$

- Within this approach, it is possible to systematically generate standard NL equations in the form (expand wave-packet propagation about envelope ray trajectories):

$$\Big\{ \overbrace{\omega^{-1}\partial_t - \frac{\gamma}{\omega}}^{\text{drive/damping}} - \underbrace{\frac{\xi}{nq'\theta_k}\partial_r}_{\text{group vel.}} + \overbrace{i(\lambda+\xi)}^{\text{potential well}} + \underbrace{\mathrm{i}\frac{\lambda}{(nq'\theta_k)^2}\partial_r^2}_{\text{(de)focusing}} \Big\} A(r,t) \quad = \quad \text{NL TERMS}$$

- θ_k solution of $D_R(r,\omega,\theta_k) = 0$ and

$$\lambda = \left(\frac{\theta_k^2}{2}\right)\frac{\partial^2 D_R/\partial\theta_k^2}{\omega\partial D_R/\partial\omega}\,; \quad \xi = \frac{\theta_k(\partial D_R/\partial\theta_k) - \theta_k^2(\partial^2 D_R/\partial\theta_k^2)}{\omega\partial D_R/\partial\omega}\,; \quad \gamma = \frac{-D_I}{\partial D_R/\partial\omega}$$

- Equations admit the well-known local limit, which is readily recovered.

The renormalized $\hat{F}_0$ expression

- The F_0 expression is obtained from the solution of the nonlinear GKE [Frieman and Chen PF82] with a source term S (collisions are added trivially; note that only trapped particles are considered for simplicity, $\bar{v}_{\parallel} = 0$).

$$\frac{\partial F_0}{\partial t} = S - \frac{c}{B_0}\frac{i}{r}\frac{\partial}{\partial r}\left(\delta K_{-k} J_{0k} \delta\phi_k - \delta K_k J_{0-k} \delta\phi_{-k}\right)$$

- Decompose fluctuating particle responses into adiabatic and non-adiabatic

$$\delta F_k = \frac{e}{m}\delta\phi_k \frac{\partial}{\partial v^2/2} F_0 + \sum_{\mathbf{k}_\perp} \exp\left(-\mathrm{i}\mathbf{k}_\perp \cdot \mathbf{v} \times \mathbf{b}/\omega_c\right) \overline{\delta H}_k$$

$$\overline{\delta H}_k = \delta K_k - \frac{e}{m}\frac{QF_0}{\omega_k} J_{0k} \delta\psi_k \qquad \delta A_{\parallel k} \equiv -\mathrm{i}\left(\frac{c}{\omega}\right) \mathbf{b} \cdot \nabla \delta\psi_k$$

- Definition: $QF_0 = (\omega \partial_{\mathcal{E}} + \hat{\omega}_*)F_0$, $\hat{\omega}_* F_0 = (mc/eB)(\mathbf{k} \times \mathbf{b}) \cdot \nabla \mathbf{F_0}$.

- Solve the problem in the Laplace transform space; $F_0(t) = \int_{-\infty}^{\infty} e^{-i\omega t}\hat{F}_0(\omega)d\omega,\ \hat{F}_0(\omega) = (2\pi)^{-1}\int_0^{\infty} e^{i\omega t}F_0(t)dt.$

$$\delta\hat{K}_k(\omega) = \int_{-\infty}^{\infty}\frac{e}{m}\frac{\bar{\omega}_{dk}}{\bar{\omega}_{dk}-\omega}\frac{Q_{k,x}}{x}\hat{F}_0(\omega-x)J_{0k}J_{0dk}^2\delta\phi_k(x)dx$$

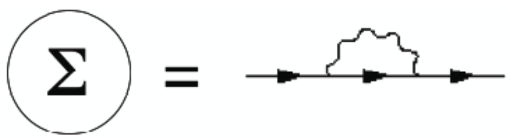
$$\hat{F}_0(\omega) = \frac{i}{\omega}\hat{S}(\omega)+\frac{i}{2\pi\omega}F_0(0)-\frac{ck_\theta}{\omega B_0}\frac{\partial}{\partial r}\int_{-\infty}^{\infty}\left[J_{0k}\delta\phi_k(x)\delta K_{-k}(\omega-x)-J_{0-k}\delta\phi_{-k}(x)\delta K_k(\omega-x)\right]dx$$

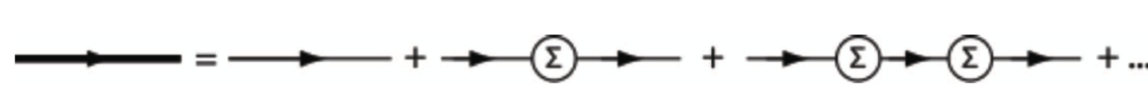
- Assuming an implicit summation on k

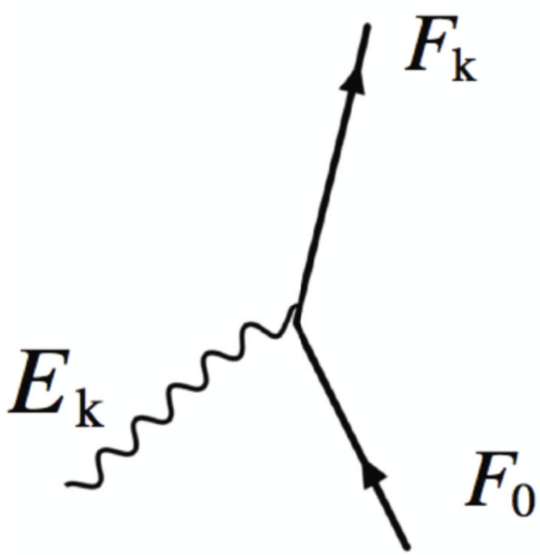
$$\hat{F}_0(\omega) = \frac{i}{\omega}\hat{S}(\omega)+\frac{i}{2\pi\omega}F_0(0)-\frac{ck_\theta}{\omega B_0}\frac{e}{m}\frac{\partial}{\partial r}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}J_{0k}^2J_{0dk}^2\left[\delta\phi_k(x)\frac{\bar{\omega}_{d-k}}{\bar{\omega}_{d-k}+x-\omega}\frac{Q_{-k,x'}}{x'}\right.$$

$$\left.\times\,\hat{F}_0(\omega-x-x')\delta\phi_{-k}(x')-\delta\phi_{-k}(x)\frac{\bar{\omega}_{dk}}{\bar{\omega}_{dk}+x-\omega}\frac{Q_{k,x'}}{x'}\hat{F}_0(\omega-x-x')\delta\phi_k(x')\right]dxdx'$$

- This solution is valid for strong distortions of the equilibrium distribution function and is the analogue of the Dyson equation ($G = G_0 + G_0 \Sigma G$, with G_0/G the bare/dressed propagators), as noted, e.g., by [Al'tshul' and Karpman 65].







- The description does not include power spectrum generation and spatial bunching and accurate treatment of phase mixing on scales much longer than the wave-particle trapping time. Not a limitation for EPM nonlinear dynamics ⇒ convective amplification of unstable front.

- Monochromatic EPM: reasonable assumption, since EPM spectrum is peaked for optimizing resonance condition. $\delta\phi(t) = \delta\bar{\phi}(\tau)\exp(-i\omega(\tau)t)$, $|\dot{\omega}(t)| \ll |\gamma(t)\omega(t)|$.

$$\delta\hat{\phi}_k(\omega) = \frac{i\delta\bar{\phi}_k(\tau)}{2\pi(\omega-\omega(\tau))} \qquad \delta\hat{\phi}_{-k}(\omega) = \frac{i\delta\bar{\phi}_{-k}(\tau)}{2\pi(\omega+\omega^*(\tau))}$$

$$\hat{F}_0(\omega) = \frac{i}{\omega}\hat{S}(\omega) + \frac{i}{\omega}\mathrm{St}\hat{F}_0(\omega) + \frac{i}{2\pi\omega}F_0(0) - \frac{ck_\theta}{\omega B_0}\frac{e}{m}\frac{\partial}{\partial r}J_{0k}^2 J_{0dk}^2\left[\frac{\bar{\omega}_{dk}}{\bar{\omega}_{dk}+\omega-\omega(\tau)}\frac{Q^*_{k,\omega(\tau)}}{\omega(\tau)^*} - \frac{\bar{\omega}_{dk}}{\omega+\omega^*(\tau)-\bar{\omega}_{dk}}\frac{Q_{k,\omega(\tau)}}{\omega(\tau)}\right]\hat{F}_0(\omega-2i\gamma(\tau))|\delta\bar{\phi}_k(\tau)|^2$$

- For evanescent drive and flat envelope, this problem is reduced to the wave-particle trapping and to [Berk et al PLA97, POP99] for $\omega_B t \ll 1$.

- For increasing drive, EPM mode structures play a crucial role: particles are convected out efficiently since - with frequency locking - wave-particle resonances are decorrelated only in velocity space. $(nqs)^{-1} \lesssim (\gamma/\omega)(\omega_*/\omega) \lesssim (L_{pH}/nqr)^{1/2}$.

The EPM avalanche and convective EP transport

- Assume isotropic slowing-down and EPM NL dynamics dominated by precession resonance, $(\beta_H/\beta_e)(R/L_{pH}) \gg \epsilon^{3/2}(T_H/q^2T_e)$ [Zonca et al NF05].

$$[D_R(\omega,\theta_k;s,\alpha)+iD_I(\omega,\theta_k;s,\alpha)]\,\partial_t A = \frac{3\pi\epsilon^{1/2}}{4\sqrt{2}}\alpha_H \bar{J}^2\left[1+\frac{\omega}{\bar{\omega}_{dF}}\ln\left(\frac{\bar{\omega}_{dF}}{\omega}-1\right)\right.$$

$$\left.+i\pi\frac{\omega}{\bar{\omega}_{dF}}\right]\partial_t A + \underbrace{i\pi\frac{\omega}{\bar{\omega}_{dF}}\bar{J}^2 A\frac{3\pi\epsilon^{1/2}}{4\sqrt{2}}k_\theta^2\rho_H^2\frac{T_H}{m_H}\partial_r^2\partial_t^{-1}\left(\alpha_H\bar{J}^2|A|^2\right)} \ .$$

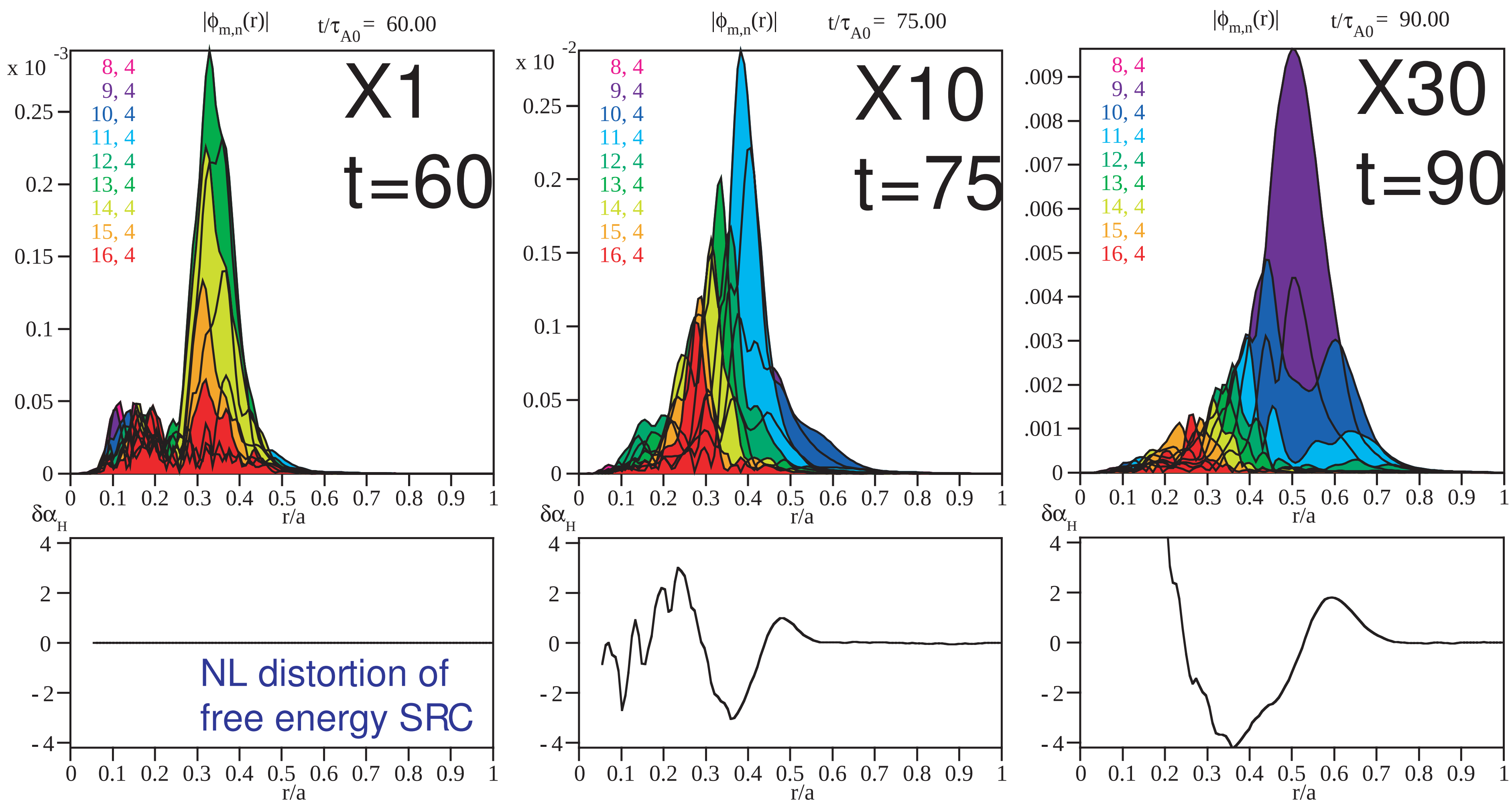
DECREASES DRIVE@ MAX $|A|$

INCREASES DRIVE NEARBY

- Assume $\alpha_H = \alpha_{H0}\exp(-x^2/L_p^2) \simeq \alpha_{H0}(1-x^2/L_p^2)$, with $x=(r-r_0)$. EPM structure has characteristic linear radial envelope width $\Delta \approx (L_p/k_\theta)^{1/2}$ and is nonlinearly displaced to maximize the drive as

$$(x_0/L_p) = \gamma_L^{-1}k_\theta\rho_H\left(T_H/M_H\right)^{1/2}(|A|/W_0) \ , \qquad W_0 = \text{NL EPMwidth}$$

Zonca et al. IAEA, (2002)



- Importance of toroidal geometry on wave-packet propagation and shape

Crucial points and Summary

- ☐ Fluctuation induced fast particle transport in toroidal plasmas of fusion interest involves both micro- and meso-scales phenomena, as well as macro-scale MHD.
- ☐ Micro-turbulence induced transport of energetic particles is well described by quasi-linear theories, while meso-scale fluctuations exhibit both coherent and incoherent non-linear behaviors, corresponding to convective and diffusive transport events.
- ☐ Given a dense spectrum of Alfvénic fluctuations, spectral transfers (cascade) are strongly affected by non-uniformities and toroidal geometries. Meanwhile, three-wave couplings are in competition with zonal structure formations: determining an hierarchy of nonlinear time scales in realistic conditions remains an open problem.

- There is a relationship of MHD and shear Alfvén waves in the kinetic thermal ion frequency gap with micro-turbulence, Zonal Flows and Geodesic Acoustic Modes, which has importance in determining long time scale dynamic behaviors in burning plasmas.
- When drive is sufficiently strong, coherent nonlinear wave-particle interactions are the dominant processes, which determine energetic particle transport as avalanche phenomena, characterized by convective amplification of the unstable front and gradient steepening and relaxation, where plasma non-uniformities, mode structures and toroidal geometries are crucial elements.

Grazie – 謝謝您