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Nonlinear dynamics and complex behaviors in magnetized plasmas of fusion interest

F. Zonca
E.N.E.A., Centro Ricerche Energia Frascati, Italy

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

Nonlinear dynamics and complex behaviors in magnetized plasmas of fusion interest *

Fulvio Zonca

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

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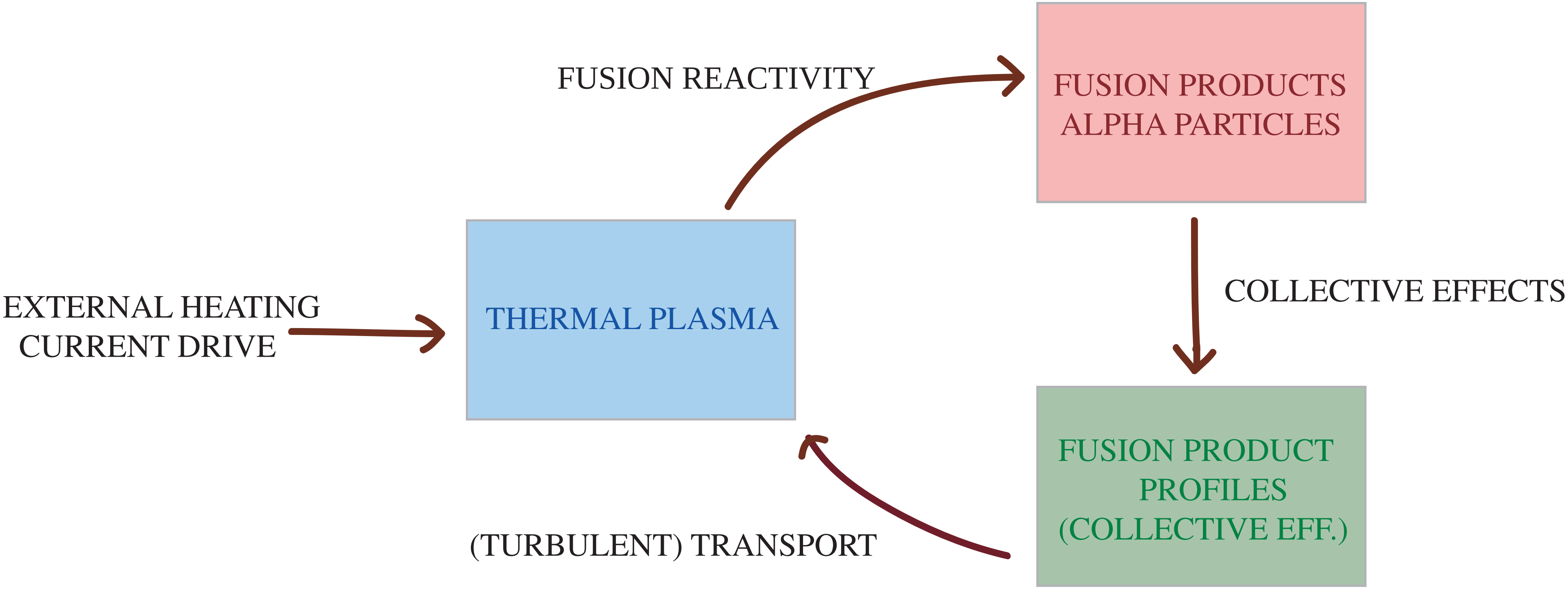
Nonlinear Dynamics of Burning Plasmas I

☐ A burning plasma is a complex self-organized system where among the crucial processes to understand there are (turbulent) transport and fast ion/fusion product induced collective effects.


FUSION REACTIVITY

FUSION PRODUCTS
ALPHA PARTICLES

EXTERNAL HEATING
CURRENT DRIVE

THERMAL PLASMA

COLLECTIVE EFFECTS

FUSION PRODUCT
PROFILES
(COLLECTIVE EFF.)

(TURBULENT) TRANSPORT

Nonlinear Dynamics of Burning Plasmas II

- Reactor relevant conditions require fast ion (MeV energies) and charged fusion products good confinement:
  - Identification of burning plasma stability boundaries with respect to energetic ion collective mode excitations and their nonlinear dynamic behaviors above the stability thresholds
  - Obvious impact on the operation-space boundaries, since collective losses may lead to significant wall loading and damaging of plasma facing materials in addition to degrading fusion performance
- Mutual interactions between collective modes and energetic ion dynamics with drift wave turbulence and turbulent transport should not deteriorate the thermonuclear efficiency:
  - MeV ion energy tails introduce a dominant electron heating and different weighting of the electron driven micro-turbulence w.r.t. present experiments
  - They also generate long time-scale nonlinear behaviors typical of self-organized complex systems

The roles of simulation and theory

☐ These phenomena can be analyzed, at least in part, in present day experiments and provide nice examples of mutual positive feedbacks between theory, simulation and experiment.

☐ In a burning plasma, however, unique features not reproducible in existing experiments are:

- energetic ion power density profiles and characteristic wavelengths of the collective modes
- local power balance dominated by electron heating (fast ions) and self-organization of radial profiles of the relevant quantities: consequence on turbulence spectra and turbulent transport

☐ Crucial roles of predictive capabilities based on numerical simulations as well as of fundamental theories for developing simplified yet relevant models, needed for insights into the basic processes

☐ Importance of using existing and future experimental evidences for modeling verification and validation

Outline

☐ Collective behaviors and fast ion transport:

- The shear Alfvén fluctuation spectrum: Alfvén Eigenmodes and resonant modes
- Fast ion transport: diffusion and avalanches
- Open issues in fast ion transport studies

☐ Mutual interactions between collective modes and energetic ion dynamics with drift wave turbulence and turbulent transport

☐ Examples of broader applications of fundamental physics in fusion science

☐ Additional material: lecture notes from ICTP Autumn College on Plasma Physics, Oct. 13 - Nov. 7 2003 (available for distribution)

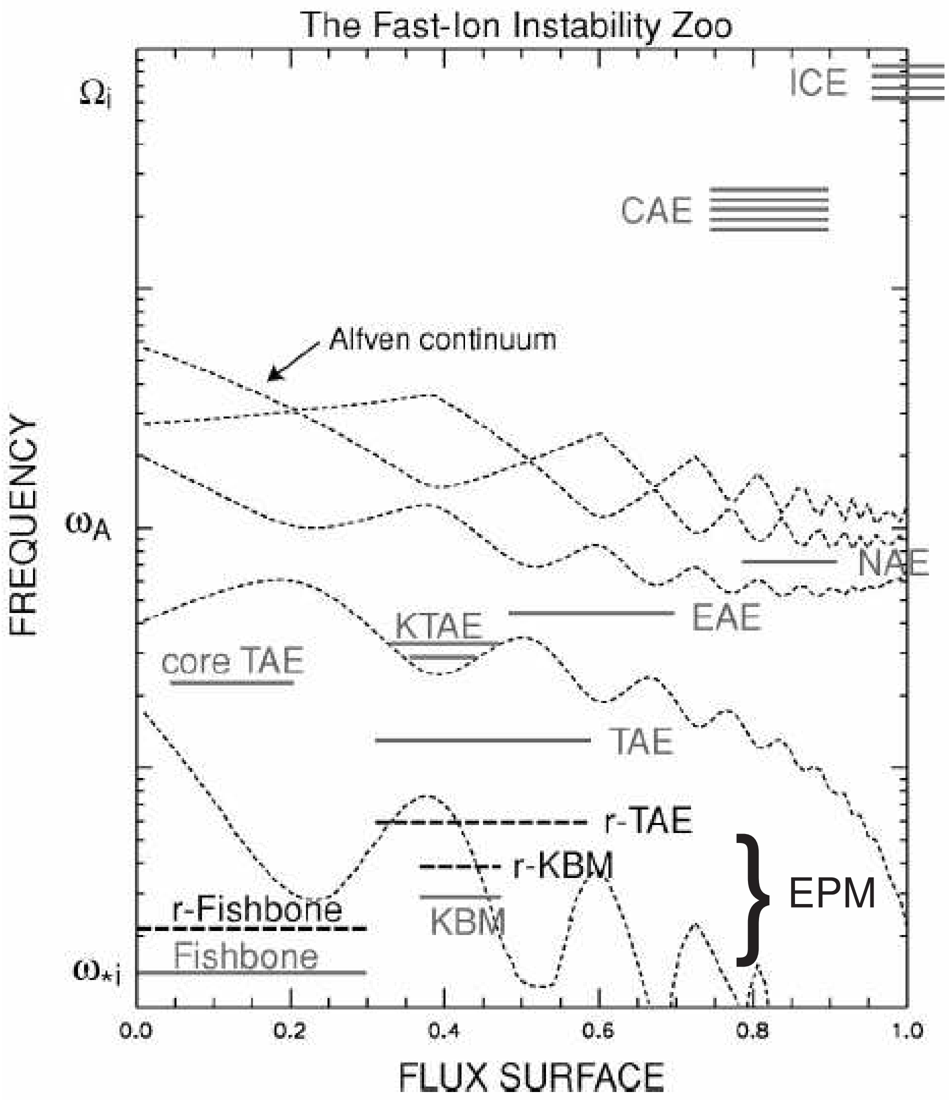
- Role of resonant vs non-resonant wave-particle interactions in electromagnetic turbulence
- Collective effects and self-consistent energetic particle dynamics in burning plasmas

Collective behaviors and fast ion transport

The role of shear Alfvén waves

- Collective behaviors due to energetic ions in burning plasmas: shear Alfvén (SA) waves play a crucial role:
  - Resonant wave particle interaction of ≈ MeV ions with SA inst. due to $v_E \approx v_A$ $(k_\parallel v_A \approx \omega_E)$
  - Group velocity is along B-field lines $(\omega = k_\parallel v_A)$: particles stay in resonance
- Toroidal geometry plays a crucial role: SA waves propagate along B as in a 1D lattice and sample periodic potential structures with influence on SA spectrum and linear as well as non-linear dispersion
- Focus on non-linear dynamics and fast ion transport: conclusions largely apply to MHD modes

Shear Alfvén spectrum: continuum with gaps



W.W. Heidbrink, Phys. Plasmas **9**, 2113, (2002)

- Frequency gaps are due to lattice symmetry breaking
- Linear theory reasonably well understood: few technical aspects need to be refined for more realistic comparisons with EXP
- Unified description: discrete gap modes vs. resonant (driven) continuum modes.
- Alfvén Eigenmodes (AE): weakly damped gap modes excited by fast ions; fixed frequency
- Energetic Particle Modes (EPM): fast ions drive overcomes continuum damping; resonant particle characteristic frequency
- Nonlinear dynamics and fast ion transport: reflect different nature of AE and EPM

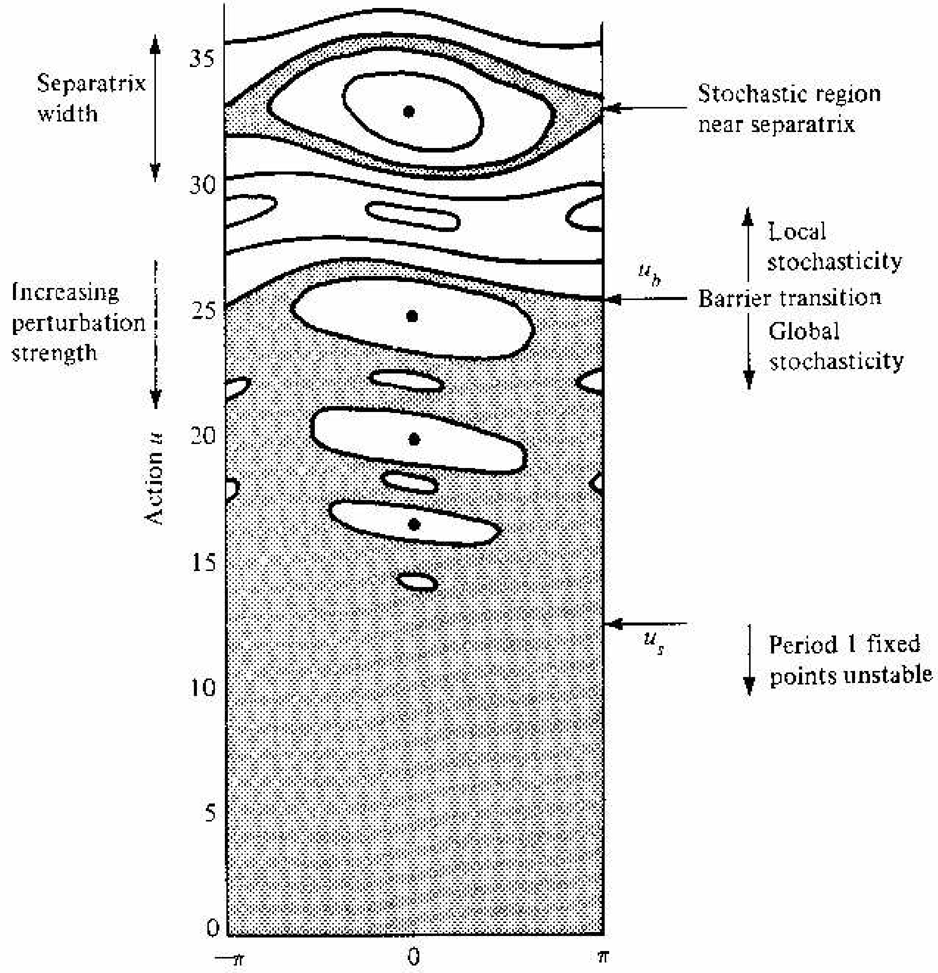
Fast ion transports in burning plasmas

☐ AE 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).

Phase space structures: fast ion resonant interactions with AE

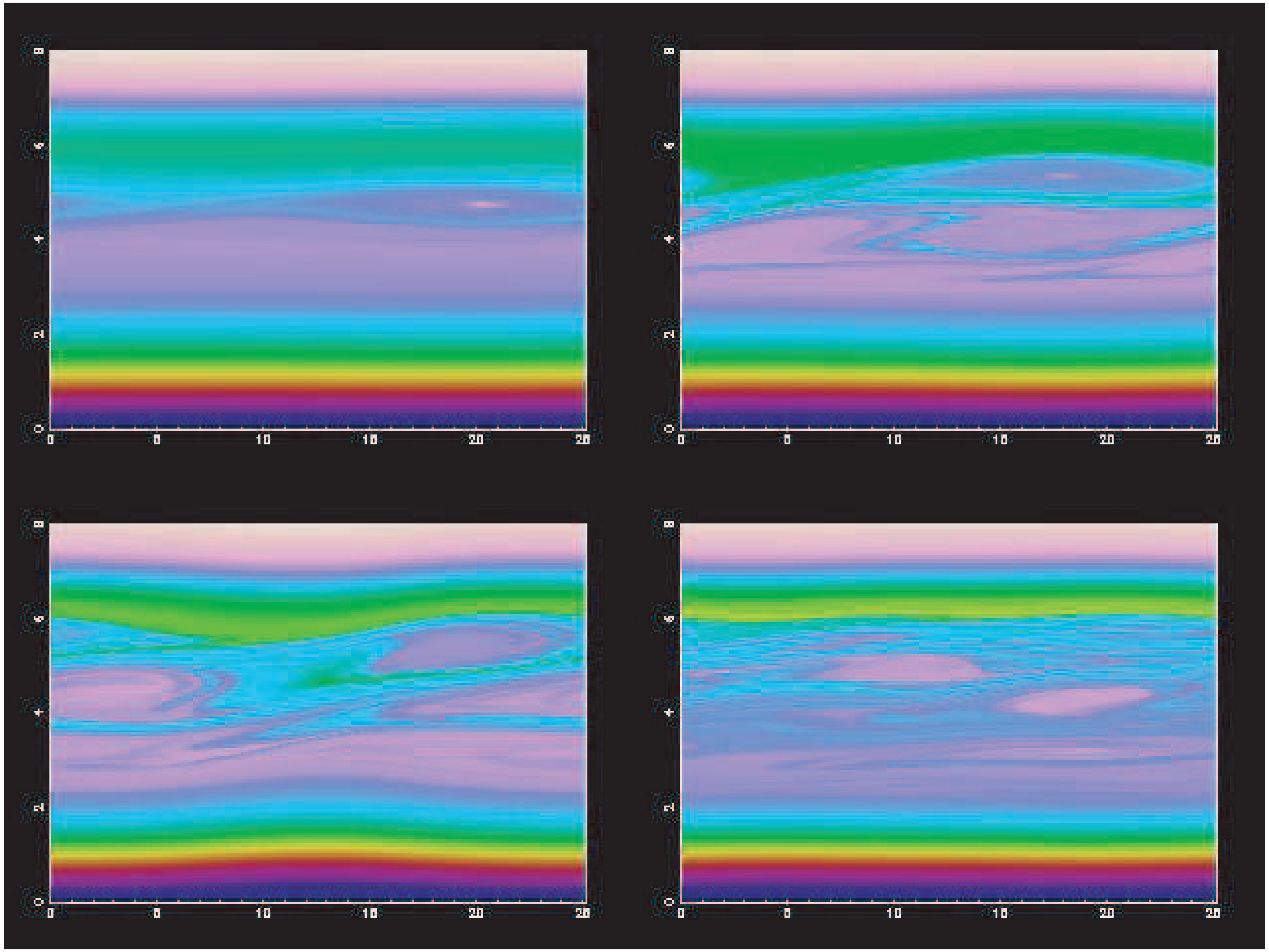
D.J. Sigmar, *et al.* 1992, *PFB* **4**, 1506 ; C.T. Hsu and D.J. Sigmar 1992, *PFB* **4**, 1492

- ☐ Transient losses ≈ $\delta B_r/B$: resonant drift motion across the orbit-loss boundaries in phase space
- ☐ Diffusive losses ≈ $(\delta B_r/B)^2$ above a stochastic threshold, due to stochastic diffusion in phase space across orbit-loss b.
- ☐ 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" (H.L. Berk, *et al.* 1996, *PoP* **3**, 1827)
- ☐ SOC models for transport event and related PDF?



Lichtenberg & Lieberman 1983, Sp.-Ver. NY

Simulation results: strongly unstable 1D system



☐ Creation of phase space structures changes the distribution function thereby permitting otherwise disallowed modes to grow (R.G.L. Vann, *et al.* 2005 Intl. Sherwood Conf.)

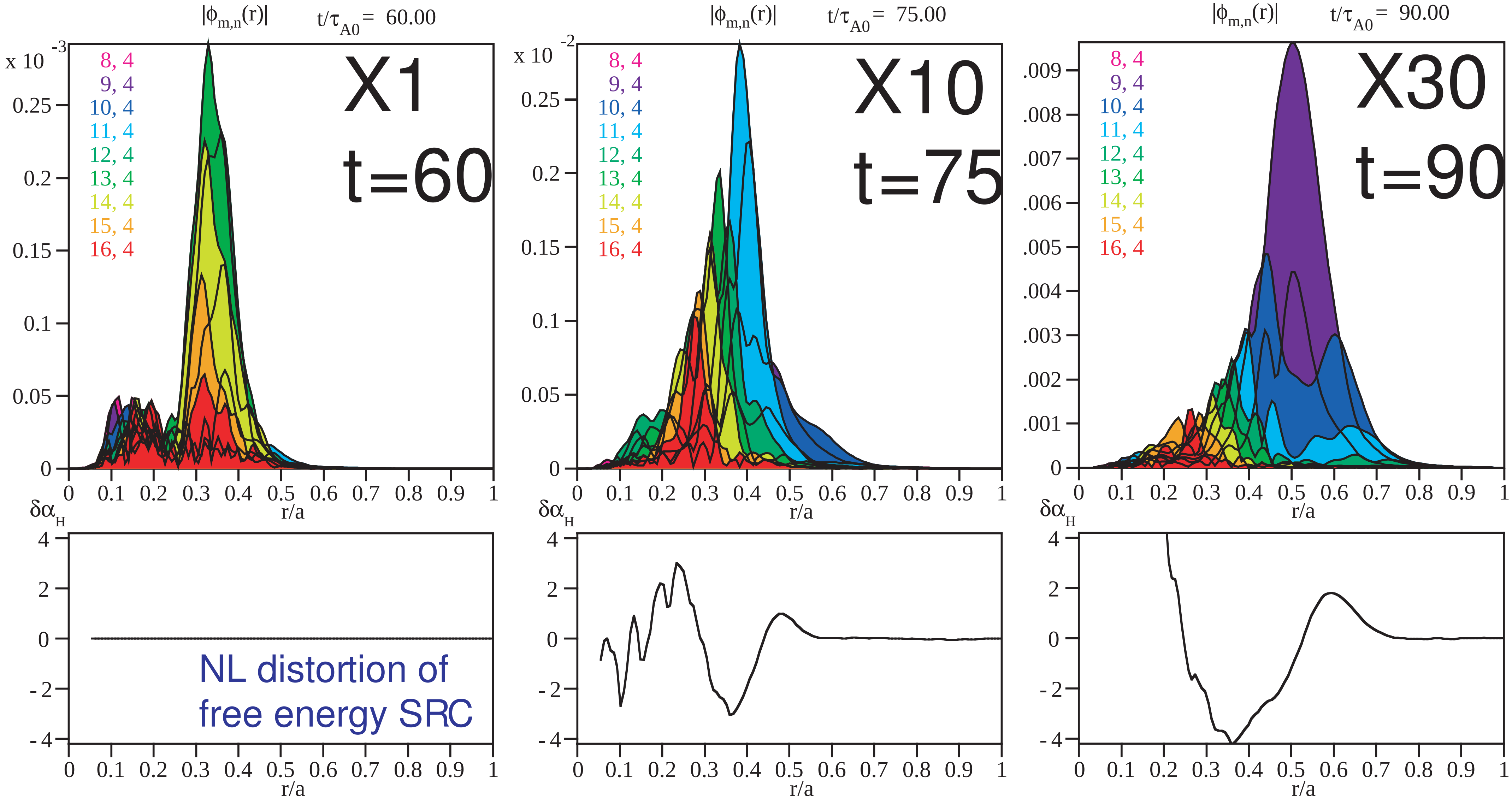
Fast ion transports in burning plasmas

- ☐ AE 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).

- ☐ 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).

Zonca et al. IAEA, (2002)

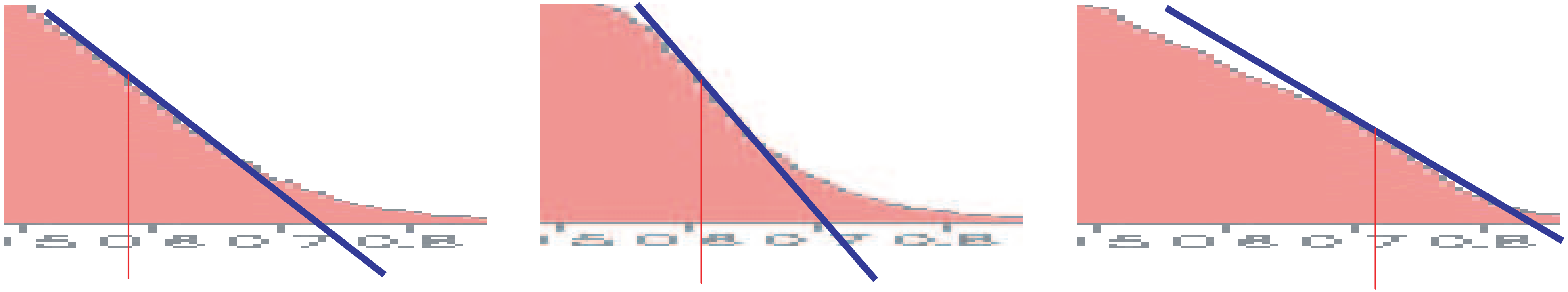
Avalanches and NL EPM dynamics

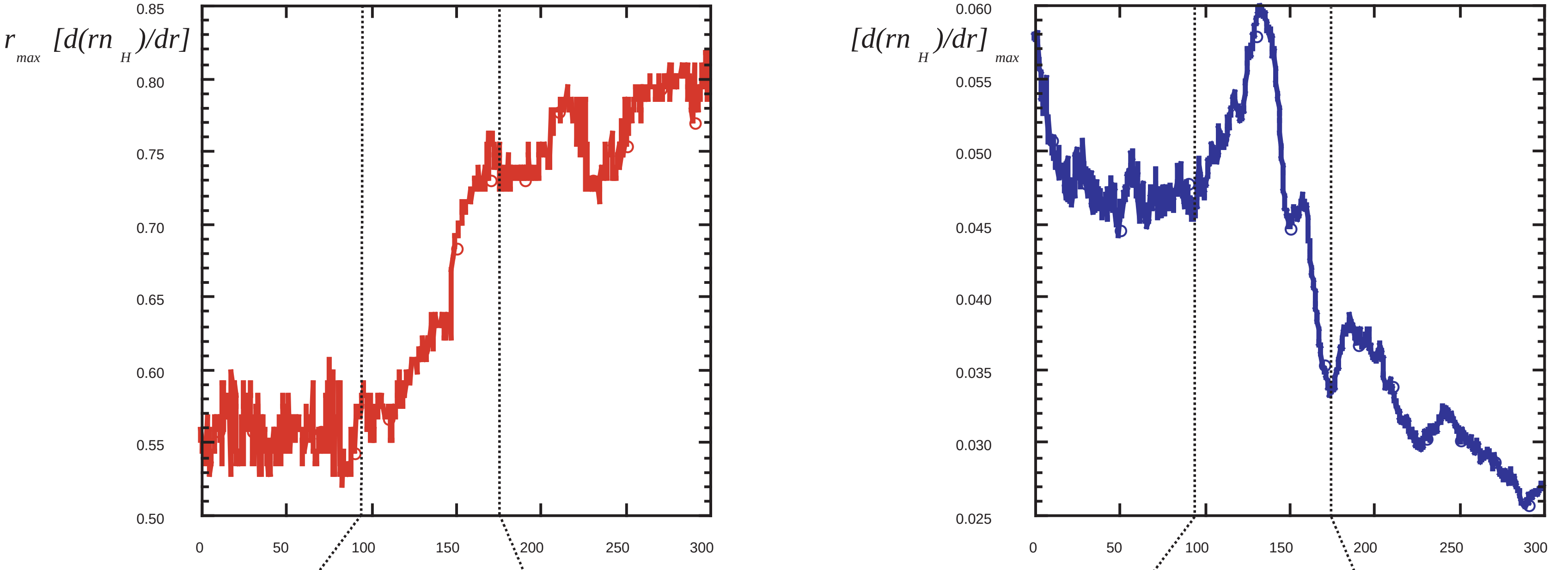


☐ Importance of toroidal geometry on wave-packet propagation and shape

Vlad et al. IAEA-TCM, (2003)

Propagation of the unstable front





linear phase

convective phase

diffusive phase

linear phase

convective phase

diffusive phase

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

Fast ion transports in burning plasmas

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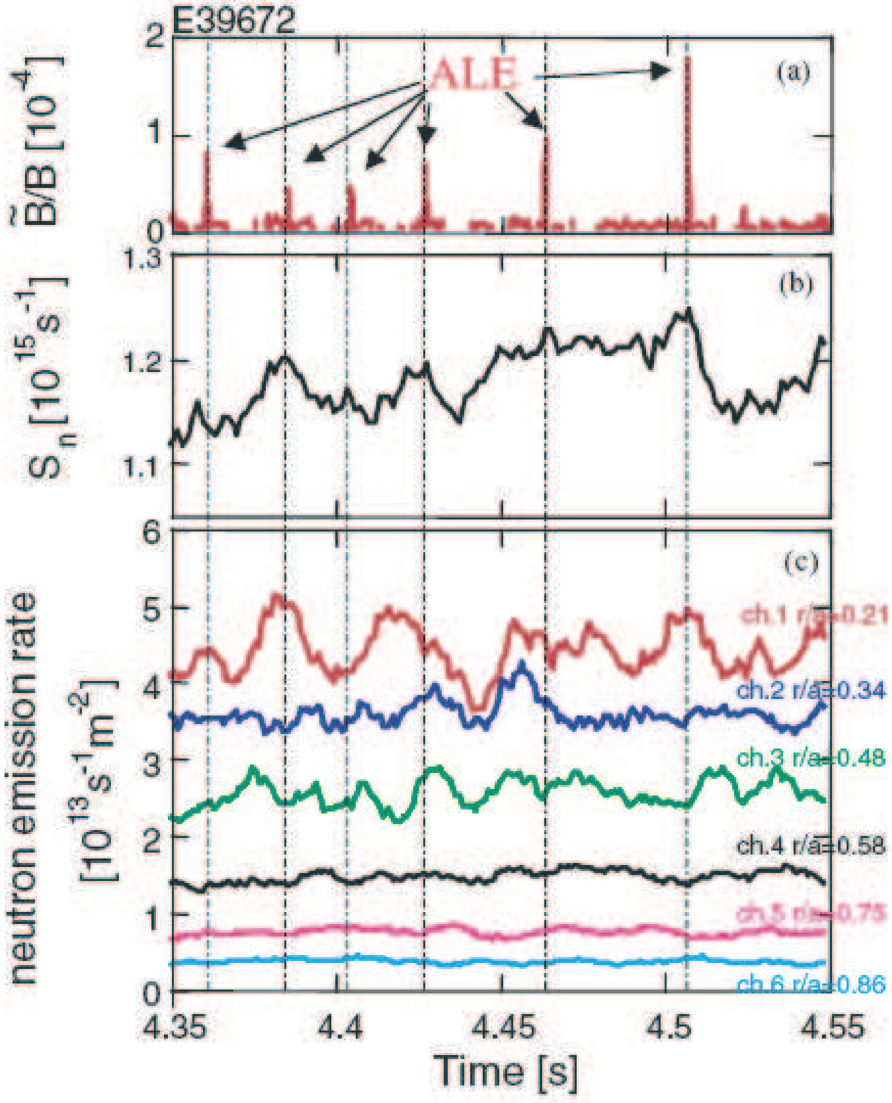
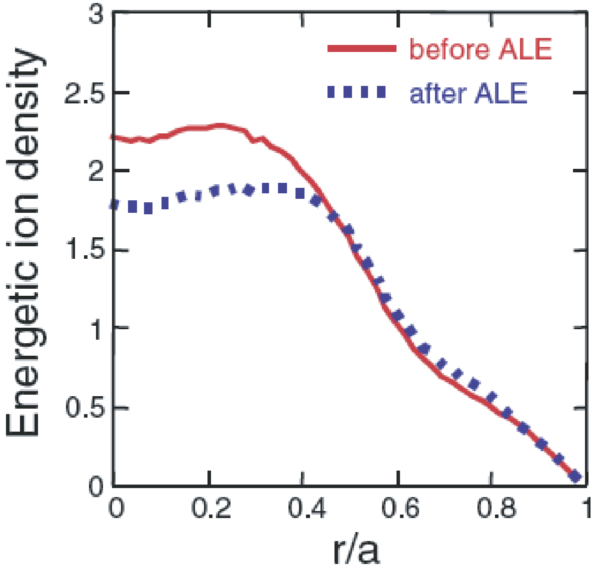
☐ Nonlinear Dynamics of Burning Plasmas: energetic ion transport in burning plasmas has two components:

- slow diffusive processes due to weakly unstable AEs and a residual component possibly due to plasma turbulence (Vlad *et al.* PPCF **47** 1015 (2005); Estrada-Mila *et al.*, Phys. Plasmas **13**, 112303, (2006)).
- 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 (K. Shinohara *etal* PPCF 46, S31 (2004))

Abrupt Large amplitude Events (ALE) in JT60-U





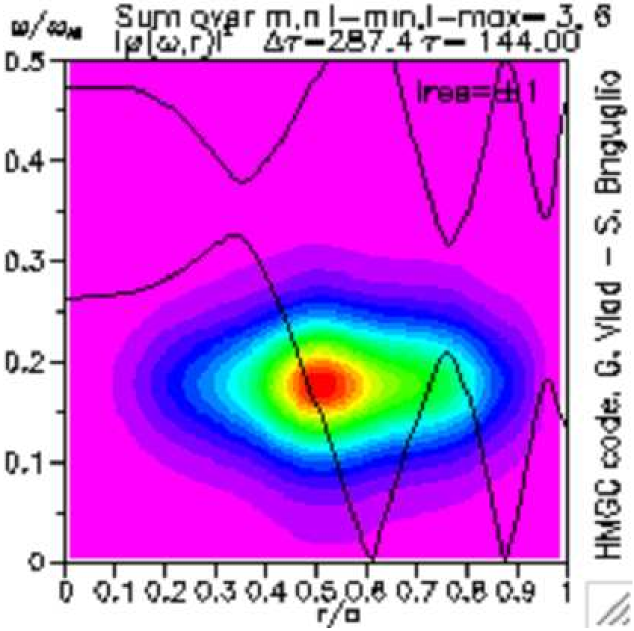
Courtesy of M. Ishikawa, K. Shinohara and JT60-U

K. Shinohara *etal* PPCF 46, S31 (2004)

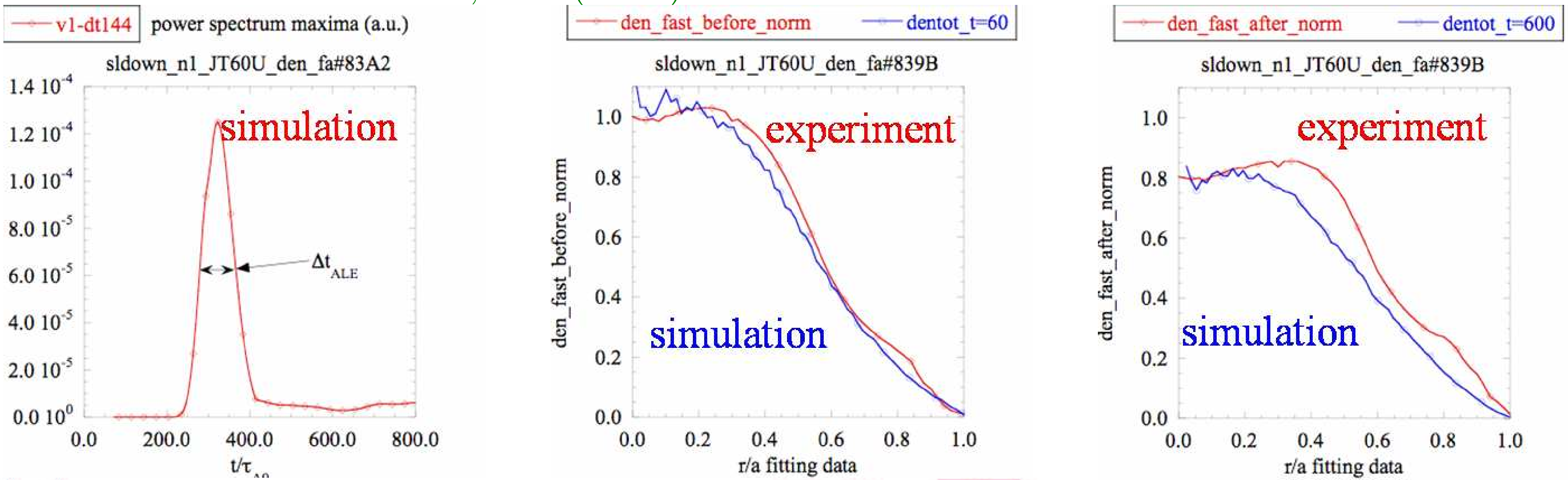
Fast ion transport: 3D simulation and experiment

S.Briguglio,G.Fogaccia,G.Vlad *et al*,EPS⊕IAEA⊕APS 2006

- Abrupt Large amplitude Events (ALE) in JT60-U:
  - $n = 1$ mode, $\beta_{H0} = 8\pi P_{H0}/B^2 \approx 3\%$;
  - linear growth rate $\gamma \approx 0.106\tau_{A0}^{-1}$;
  - half width of the pulse $\Delta t_{\rm ALE} \approx 64.5\mu s$;
  - experimental range $\Delta t_{\rm ALE} \approx 50 \div 200\mu s$;
  - energetic particle profiles compare well before and after ALE burst



K. Shinohara *etal* PPCF 46, S31 (2004)



Some open issues for fast ion transport

☐ Single mode vs. multi-mode nonlinear dynamics:

- dense spectrum of modes of characteristic frequency and location
- coherent vs. incoherent wave-particle interaction
- structure formation in phase space

☐ Wave-particle resonances ⇒ nonlinear phase-space dynamics of charged particles ⇒ trapping, stochastic motion; etc.

☐ Nonlinear dynamics of Energetic Particle Modes:

- importance of rare but large and potentially dangerous transport events
- coherent non-linear wave-particle interactions

Fast ion transport: some broader applications

A.V. Milovanov et al., (2006)

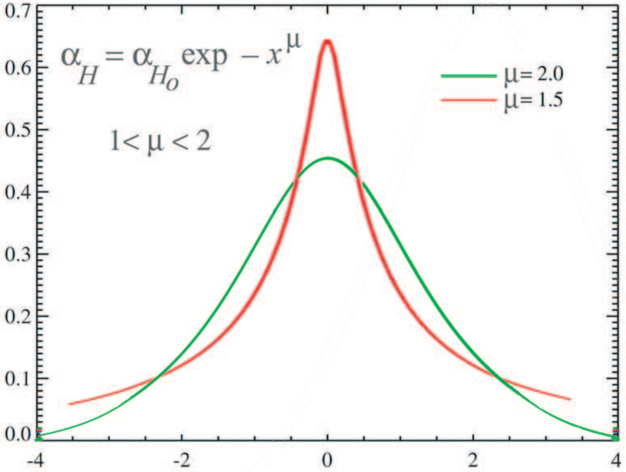
☐ Convective amplification of the EPM wave-packet and ballistic particle transport in Avalanche process is described by the complex Ginzburg-Landau equation (GLE)

$$\partial_\xi^2 A_n = i\frac{\gamma_L}{D}\left(\frac{\Delta\gamma_L}{\gamma_L} + \frac{L_{NL}^2}{\gamma_L}\partial_\xi^2\left(\gamma_L\left|A_n\right|^2\right)\right)A_n + \frac{\Delta\omega}{D}A_n$$

$$\xi = r - v_{gr}t$$

$$\gamma_L \propto \alpha_H = -R_0 q^2 (d\beta_H/dr)$$

☐ For Gaussian source function $\alpha_H = \alpha_{H0}\exp[-(\xi-\xi_0)^2]$, the GLE reduces to its canonical form; for generalized stretched Gaussian distribution, i.e., $\alpha_H = \alpha_{H0}\exp[-|\xi-\xi_0|^\mu]$ $(1 < \mu < 2)$, the GLE is rewritten in terms of fractional derivative operators:



$$\nabla^2 A = q^2 A - p^2 A \nabla^{2-\mu}|A|^2$$

Fractional derivative Riesz Operator

$$\nabla^{2-\mu}|A|^2 = \frac{1}{\Gamma(1-\mu)}\nabla\int_{-\infty}^{x}\frac{|A|^2(x_0)}{(x-x_0)^{2-\mu}}dx_0$$

☐ The fractional derivative GLE incorporates the key features of non-Gaussianity and long-range dependence in thresholded nonlinear dynamical systems

Mutual interactions of collective modes with drift wave turbulence

Physics issues behind fluctuations non-linear interactions

☐ Interaction between collective modes and thermal plasma turbulence:

- collective modes due to energetic particles
- plasma turbulence due to thermal components

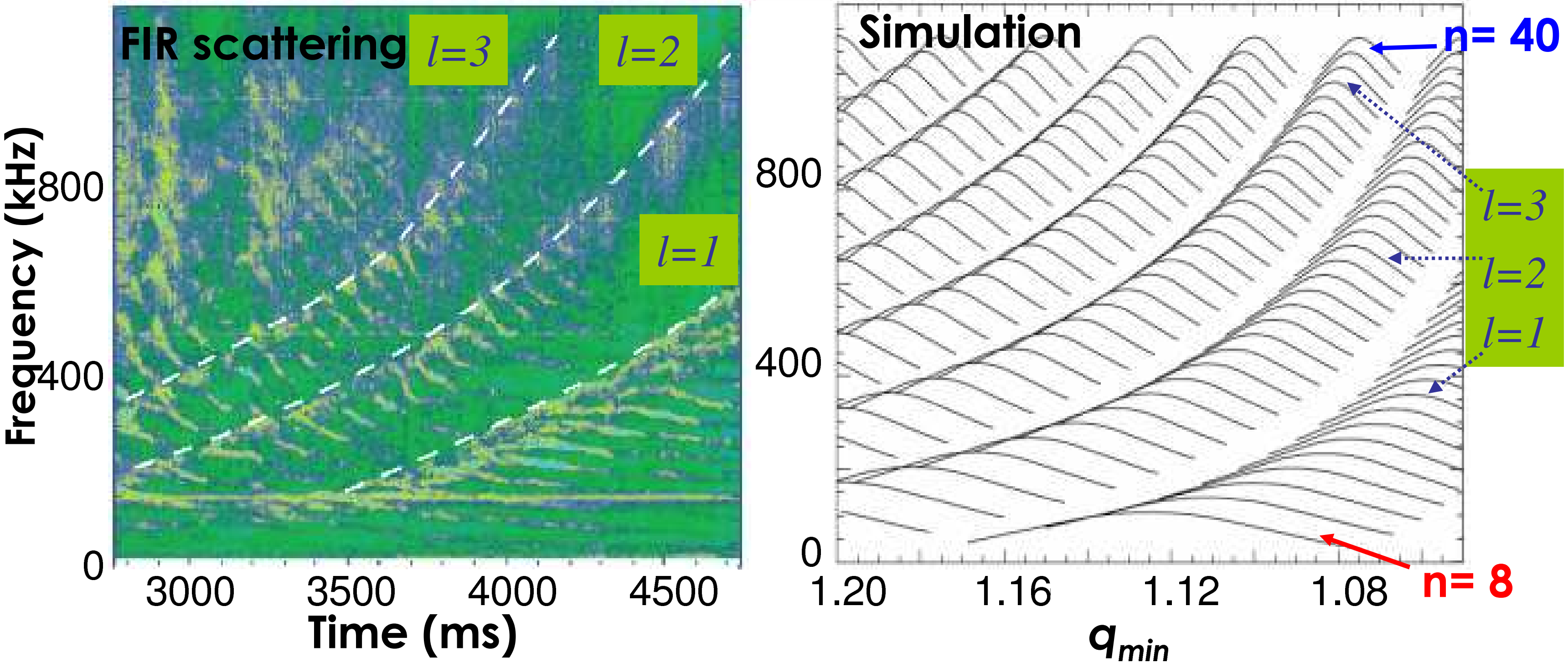
☐ Intrinsic separation of spatial scales (orbit size) in the free energy source: interaction occurs

- if the time scales become comparable such as for Alfvén ITG (e.m. ITG)
- if mediated by the 3rd entities such as zonal structures: zonal flows, fields, corrugations of radial profiles

Mutual interactions of collective modes with DW turbulence

- E.m. plasma turbulence: theory predicts excitation of Alfénic fluctuations in a wide range of mode numbers near the low frequency accumulation point of s.A. continuum, $\omega \simeq (7/4 + T_e/T_i)^{1/2}(2T_i/m_i)^{1/2}/R$ (F. Zonca, L. Chen, *et al.* 96, *PPCF* **38**, 2011; ... 99, *PoP* **6**, 1917):
  - by energetic ions at long wavelength: finite Beta AE (BAE)/EPM
  - by thermal ions at short wavelength: Alfvén ITG
- Magnetic flutter: may be relevant for electron transport (B.D. Scott 2005,*NJP* **7**, 92; V. Naulin , *et al.* 2005, *PoP* **12**, 052515)
- Recent observations on DIII-D confirm these predictions (R. Nazikian, *et al.* 06, *PRL* **96**, 105006)

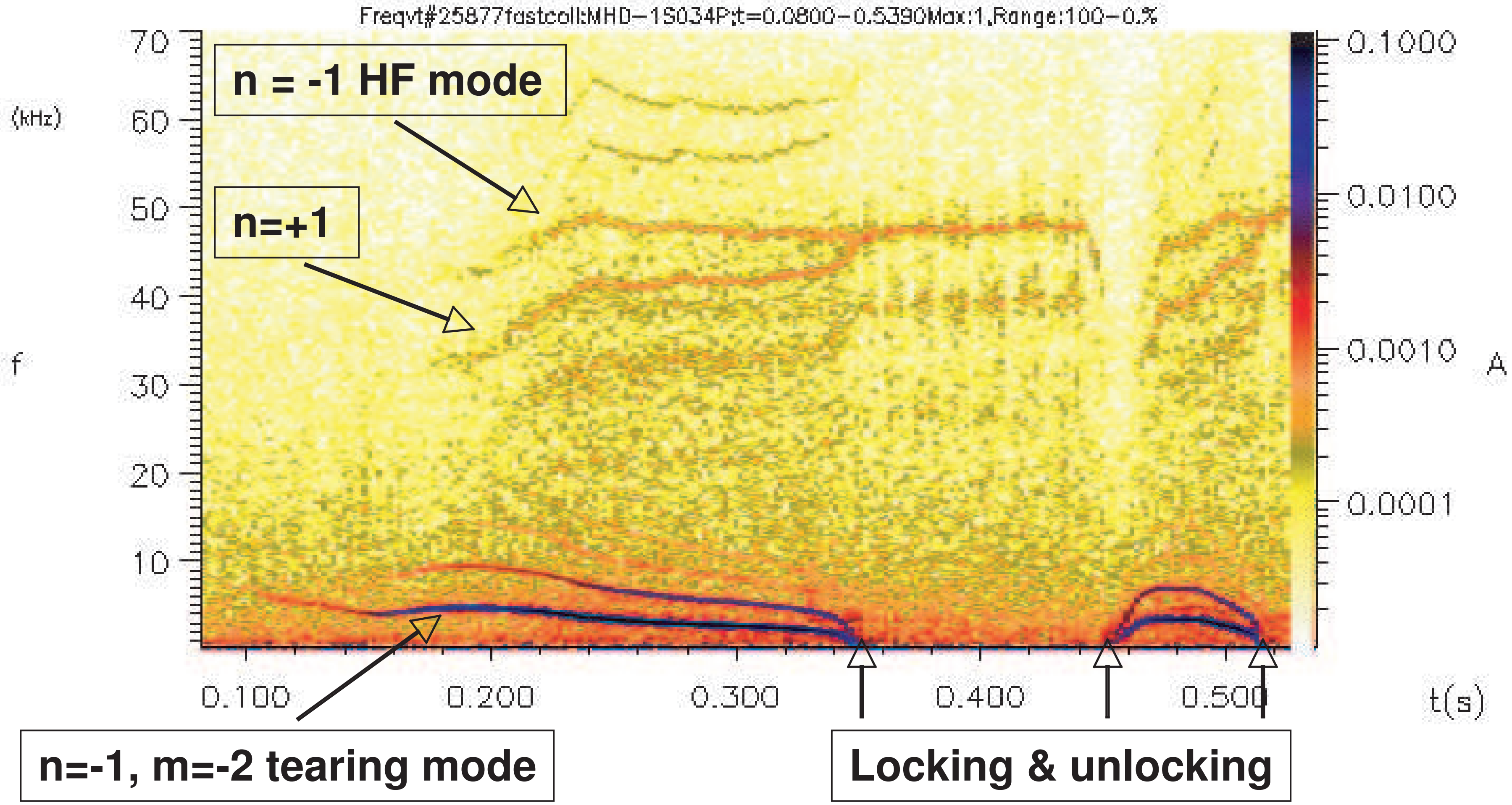
A “Sea of Core Localized Alfvén Eigenmodes” Observed in DIII-D Quiescent Double Barrier (QDB) plasmas



- **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.* 06, *PRL* **96**, 105006

- ☐ The same modes are excited by a large amplitude magnetic island on FTU (P. Buratti, *et al.* 2005, *NF* **45** 1446; S. Annibaldi, EPS 2006, O2.016).



n = -1 HF mode

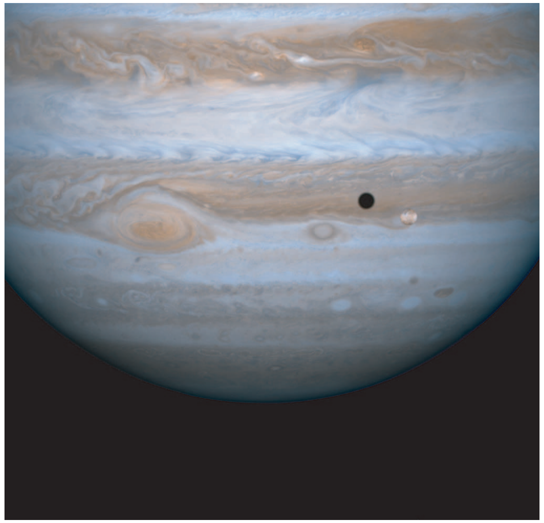
n=+1

n=-1, m=-2 tearing mode

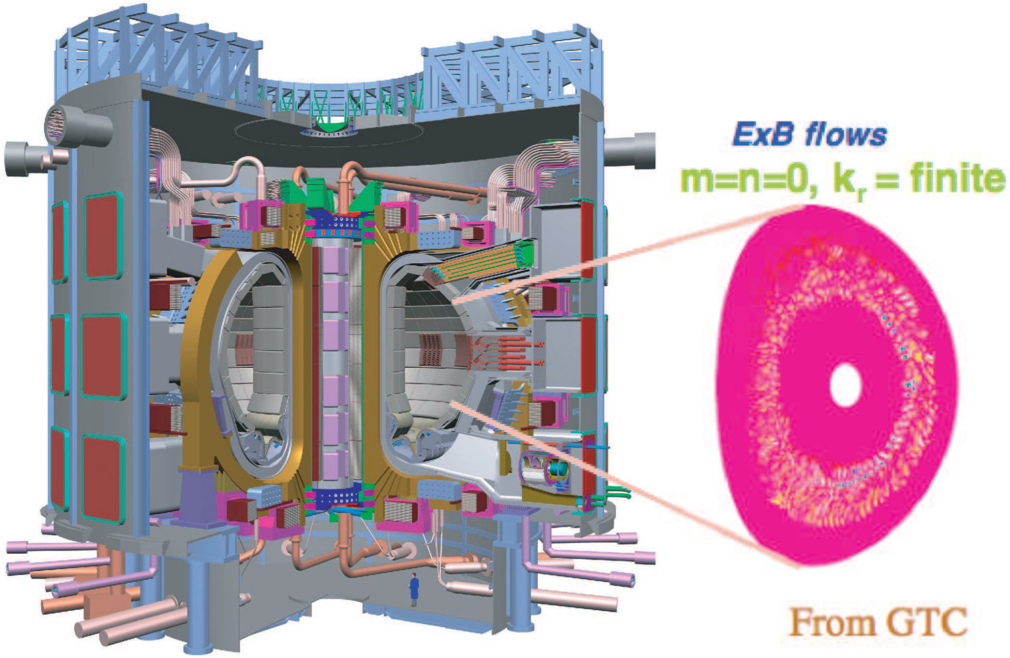
Locking & unlocking

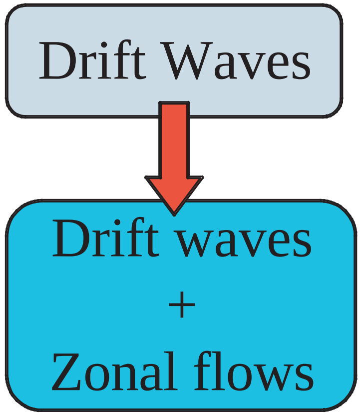
P. Smeulders, *et al.* 2002, *ECA* **26B**, D5.016

Zonal Flows are common in plasmas



Zonal Flows on Jupiter





Drift Waves

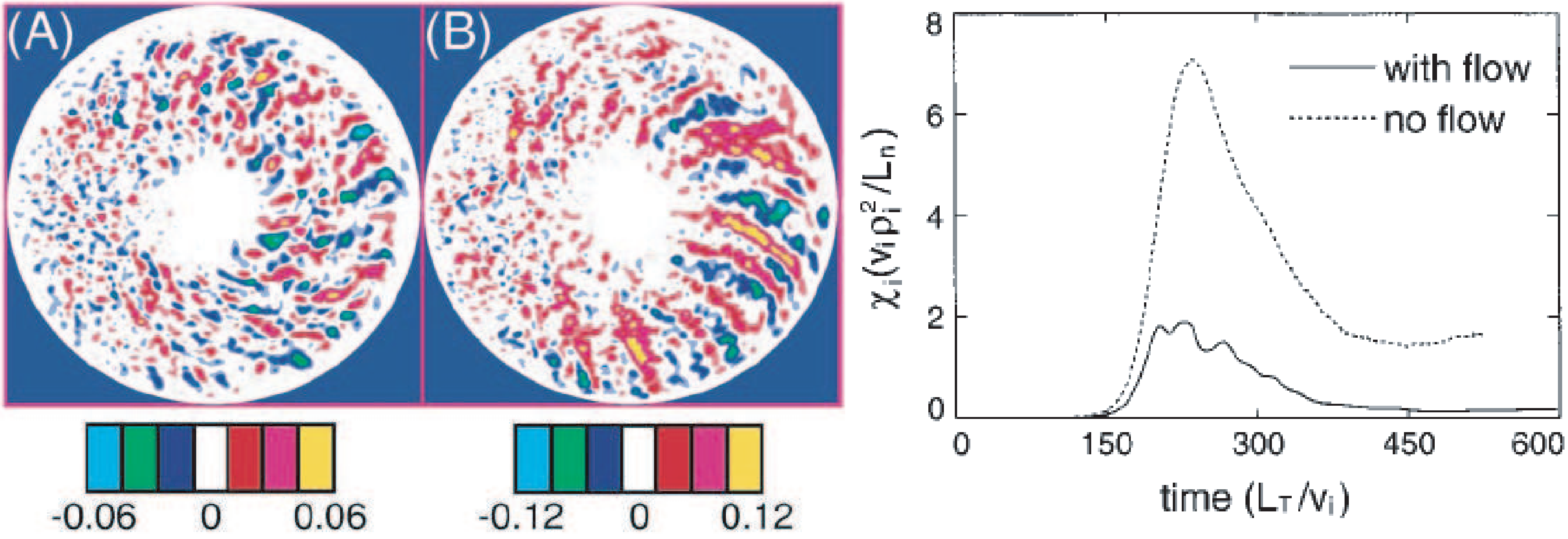
Drift waves
+
Zonal flows

Paradigm Change
P.H. Diamond, *et al.* 2005
PPCF **47**, R35

ZFs peculiarities

- No direct radial transport
- No linear instability
- Turbulence driven

Zonal Flows regulate turbulence: effect on transport



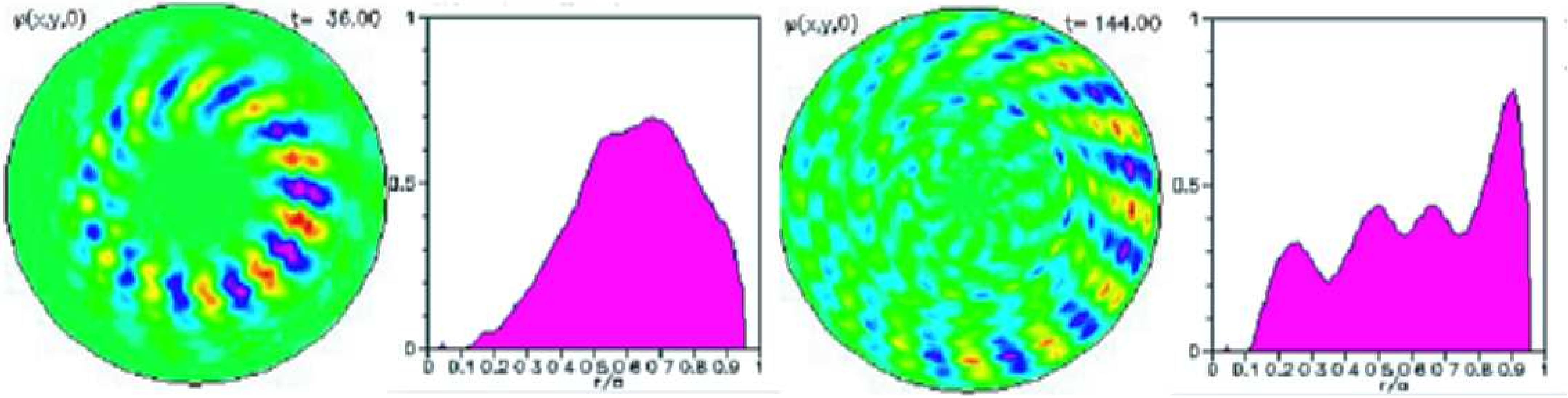
Z. Lin, *et al.* 1998, *Science* **281**, 1835

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 (L. Chen, *et al.* 2001, *NF* **41**, 747; P.N. Guzdar, *et al.* 2001, *PRL* **87**, 015001)
- radial modulations in the fast ion profiles (F. Zonca, *et al.* 2000, *Theory of Fusion Plasmas*, 17)

EPM NL dynamics (F. Zonca, *et al.* 2000, *Theory of Fusion Plasmas*, 17)



☐ AITG and strongly driven MHD modes behave similarly

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
- Crucial role of toroidal geometry for Alfvénic fluctuations: fundamental importance of magnetic curvature couplings in both linear and nonlinear dynamics (B.D. Scott 2005,*NJP* **7**, 92; V. Naulin , *et al.* 2005, *PoP* **12**, 052515)
- Long time scale behaviors of zonal structures are important for the overall burning plasma performance: generators of nonlinear 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 (L. Chen, *et al.* IAEA 2006, 2007 *NF* **47**, 886)
- Impact on burning plasma performance

Conclusions

- Burning plasmas are complex self-organized systems, whose investigation requires a conceptual step in the analysis of magnetically confined plasmas.
- Integrated numerical simulations are crucial to investigate these new physics; while fundamental theories provide the conceptual framework and the necessary insights.
- Verification against experimental observations in present day machines is a necessary step for the validation of physical models and numerical codes for reliable extrapolations to burning plasmas.
- Lack of understanding of some complex burning plasma behaviors can be likely filled in by increasingly complicated and more realistic modeling of plasma conditions as computing performances improve.
- However, some other unexplained behaviors may be just indications of fundamental conceptual problems: mutual positive feedbacks between theory, simulation and experiment will be necessary.
- Burning plasma physics is an exciting and challenging field: many examples of fundamental problems with broader applications and implications.