ENERGETIC PARTICLES AND BURNING PLASMA PHYSICS

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REFERENCES

- A. Ödblom, B. N. Breizman, S. E. Sharapov, T. C. Hender, and V. P. Pastukhov, *Nonlinear magnetohydrodynamical effects in precessional fishbone oscillations*, Phys. Plasmas **9**, 155 (2002)
- Y. Todo, H. L. Berk, and B. N. Breizman, *Simulation of intermittent beam ion loss in a Tokamak Fusion Test Reactor experiment*, Phys. Plasmas **10**, 2888 (2003)
- B. N. Breizman, H. L. Berk, and M. S. Pekker, *Theory of Alfvén eigenmodes in shear reversed plasmas*, Phys. Plasmas **10**, 3649 (2003)
- B. N. Breizman, *Selected issues in energetic particle theory*, 8th IAEA Technical Committee Meeting on Energetic Particles in Magnetic Confinement Systems (October 2003, San Diego)

INTRODUCTION

- **Alpha particles in a burning plasma can have an affect on:**
    - Stability: fishbone, TAE
    - Transport: particle loss, wall heat loading
    - Heating and current drive
    - Edge physics: transport barrier
    - Burn dynamics: He ash, thermal stability

- **Hence the need for integrated simulation, coupled with theory-based modeling, of alpha particle physics in a burning plasma**

ISSUES FOR ALPHA THEORY/SIMULATION

- **Predictive capabilities:**
  - Limitations of linear theory/simulations
  - Near-threshold nonlinear regimes (soft/hard)

- **Alfvén Cascade modes (example of soft nonlinear response)**
  - Interpretation in reversed-shear scenarios
  - Mysteries that remain to be explained

- **Fishbone modes (example of hard nonlinear response)**
  - Interplay of fluid (continuum) and kinetic (wave-particle) resonances

- **Convective and diffusive scenarios for global transport**
  - Transport barriers for energetic/alpha particles

PREDICTIVE CAPABILITIES

LIMITATIONS OF LINEAR THEORY/SIMULATION

"ROBUST"

- **Mode frequencies**
  - Robust (for perturbative modes)
  - Easy to measure experimentally
- **Mode structure**
  - Robust, experimentally measurable, and useful in nonlinear theory (for perturbative modes)

"LESS ROBUST"

- **Growth rate**
  - Energetic particle drive can be reliably calculated
  - Useful as parameter in near-threshold weakly nonlinear theory
  - However, full nonlinear effects may cause it to change significantly
- **Damping rates**
  - Except for collisional damping, the damping rates from the background plasma (e.g., ion Landau damping, radiative damping, continuum damping) are exponentially sensitive to parameter/profile details
  - Exp'tally measurable (for reverse determination of parameters)

UTILITY OF LINEAR THEORY/SIMULATION

- **Study the phase space for fast particles in the presence of linearly unstable modes, to find resonance overlap conditions for global diffusion**
  - Note: Possible partial depletion of phase space (“holes” in distribution)
- **Study the sensitivity of instability boundaries to the variation of plasma parameters**
  - Difficult to do globally; instead analyze selected modes for trends
- **Study whether unstable modes can be suppressed over a radial interval that is sufficiently broad to create a transport barrier for energetic particles**
- **Assess edge effects (e.g., boundary conditions for the modes, particle orbits, etc.)**

NEAR-THRESHOLD NONLINEAR REGIMES

- **Why study the nonlinear response near the threshold?**
  - Typically, macroscopic plasma parameters evolve slowly compared to the instability growth time scale
  - Perturbation technique is adequate near the instability threshold

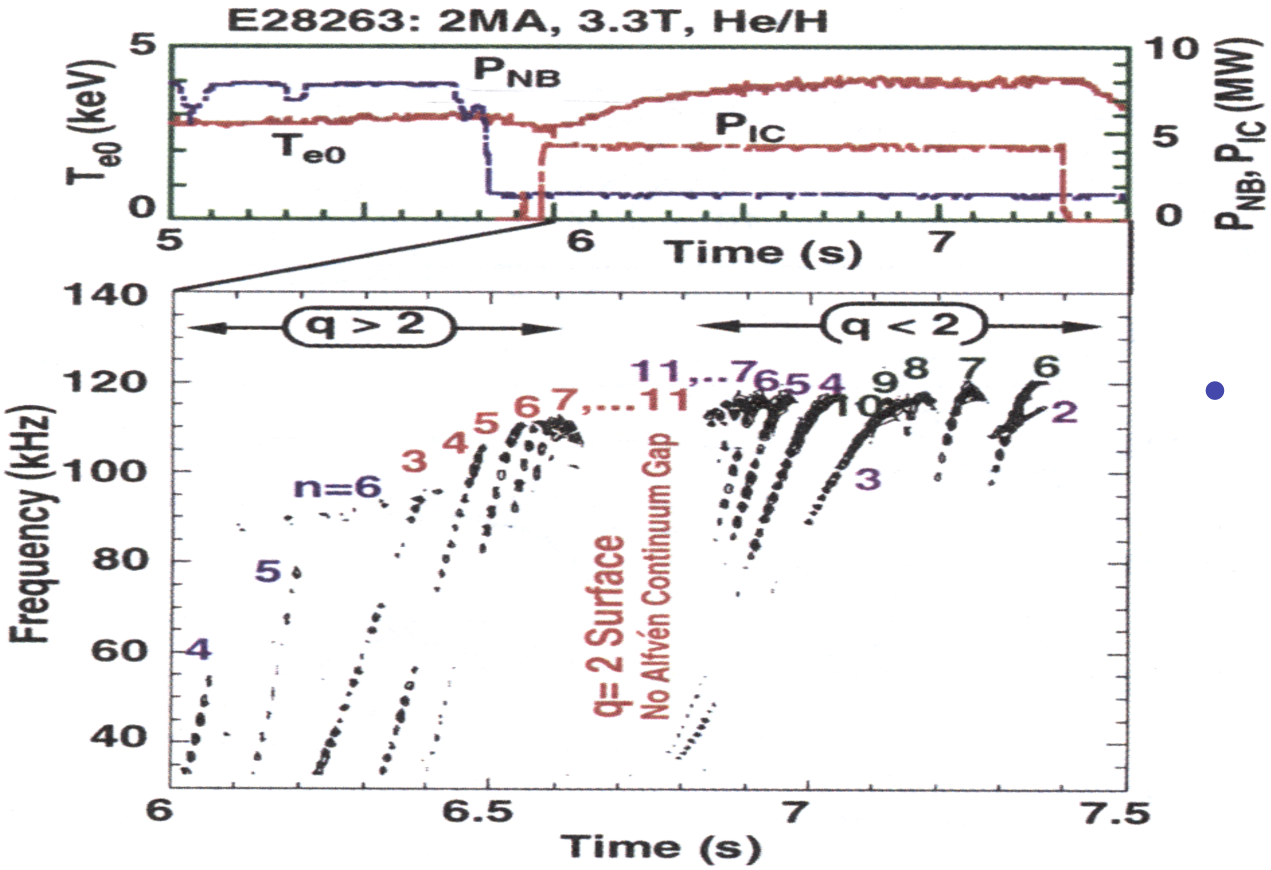
- **Single-mode case:**
  - Identification of the soft and hard nonlinear regimes is crucial to determining whether an unstable system will remain at marginal stability
  - Bifurcations at single-mode saturation can be analyzed
  - The formation of long-lived coherent nonlinear structure is possible

- **Multi-mode case:**
  - Multi-mode scenarios with marginal stability (and possibly transport barriers) are interesting
  - Resonance overlap can indicate hard nonlinear regime

ALFVEN CASCADES

(example of soft nonlinear response)

OBSERVATION OF ALFVEN CASCADES

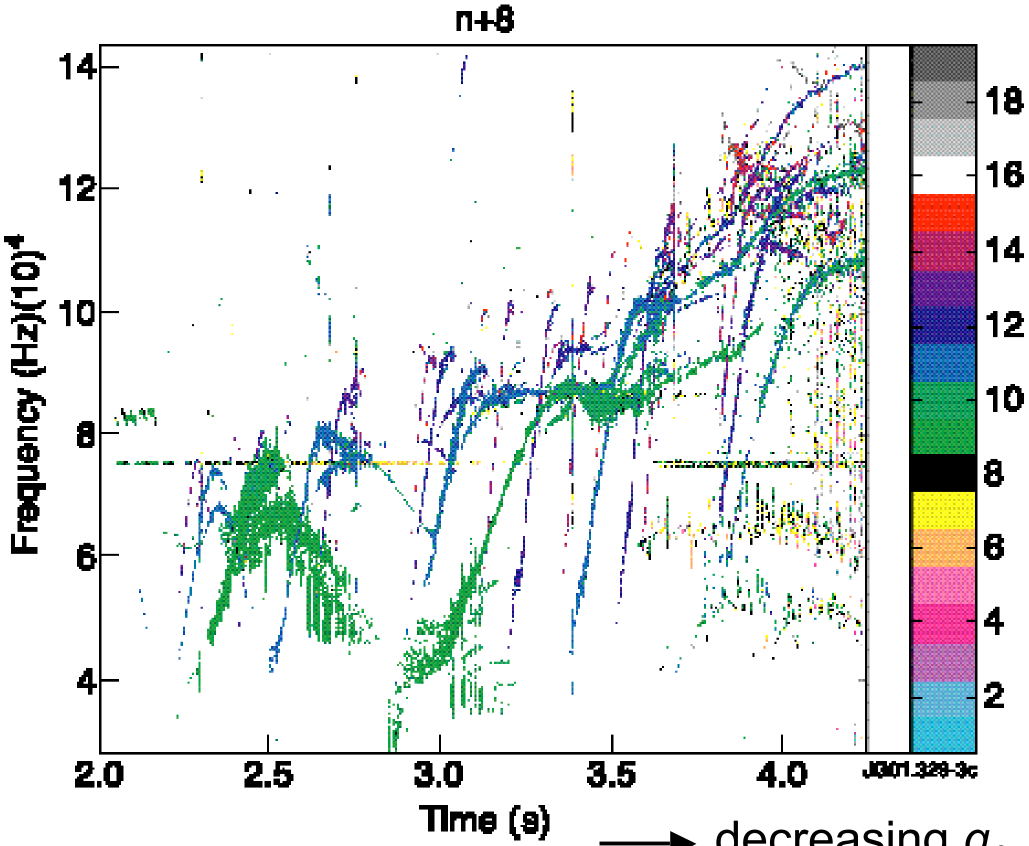


H. Kimura et al., Nuclear Fusion **38**, 1303 (1998)

→ decreasing q

- **First seen in JT-60U**
  - Fukuyama simulation of “Reversed Shear Induced Alfvén Eigenmodes”

FEATURES OF ALFVEN CASCADES



→ decreasing q_0

S. Sharapov and IFS/JET teams,
Phys Lett A **289**, 127 (2001)

- **Characteristics:**
  - Occur in reversed shear plasmas at zero-shear location $q(r) = q_0$
  - Frequency initially below TAE gap and sweeps upward (usually never downward) as safety factor decreases in time
  - Frequency signals are quasi-periodic for a large number of n-values (typically, n=1–6)
  - Higher-n modes recur more frequently and have more rapid frequency sweeping $(\partial f/\partial t \quad n)$
  - Sometimes the frequency merges into the TAE gap
  - Modes are suppressed at low frequencies

TRANSITION OF ALFVEN CASCADES TO TAES

Mode structure (m, m-1)

Mode tail near continuum resonance (magnified)

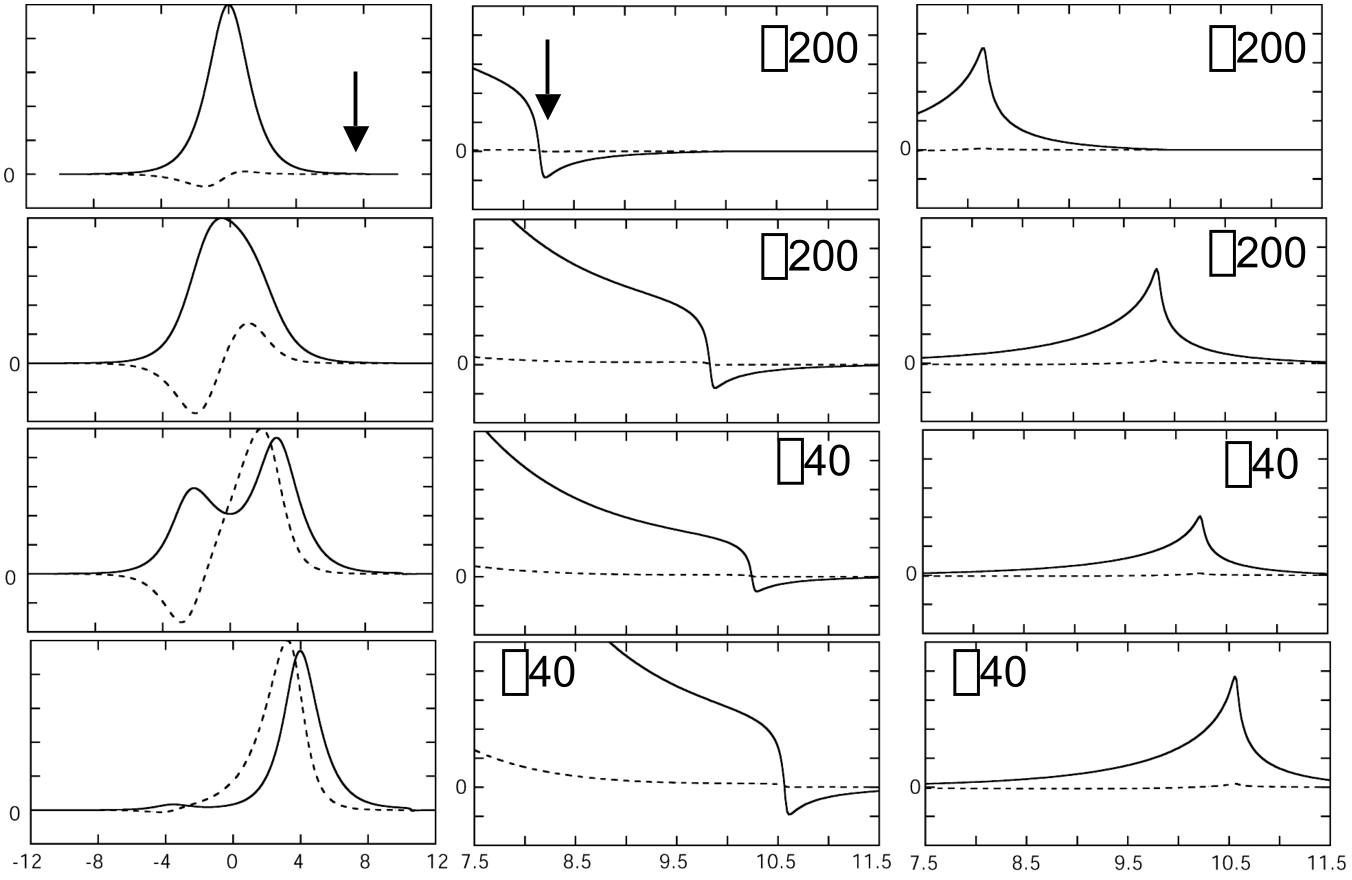
q_0=2.915
Cascade structure

q_0=2.875

Approach TAE gap

q_0=2.860

q_0=2.840
TAE structure



Re (□$_m$)

Im (□$_m$)

Breizman, Berk, et al., PoP (2003)

CONTINUUM DAMPING FOR CASCADE MODES

- **Cascade eigenmode equation (with *εx⁴* continuum damping terms):**

$$\frac{d}{dx}\left[(S+i\delta)+x^2-i\epsilon x^4\right]\frac{d}{dx}\phi_m-\left[(S+i\delta)+x^2-Q\frac{\Omega}{2(m-nq_0)}-i\epsilon x^4\right]\phi_m=0$$

$$(S+i\delta)\equiv\frac{\Omega(\Omega+i\gamma)-4(m-nq_0)^2}{4(m-nq_0)}\frac{mq_0}{r_0^2q_0''}\qquad \epsilon\equiv\frac{1}{4(m-nq_0)}\frac{r_0^2q_0''}{mq_0}<<1$$

Energetic particle contribution: $Q\equiv-\frac{4\pi e}{cB}\frac{q_0^2}{q_0''}V_A\frac{R}{r_0}\frac{d}{dr}\left\langle n_{\text{fast ion}}\right\rangle$

- **Damping rate grows exponentially as *q₀* approaches rational surface:**

$$\text{Im}\,\Omega \quad \exp\left(-\frac{2}{\sqrt{\epsilon}}\right)$$

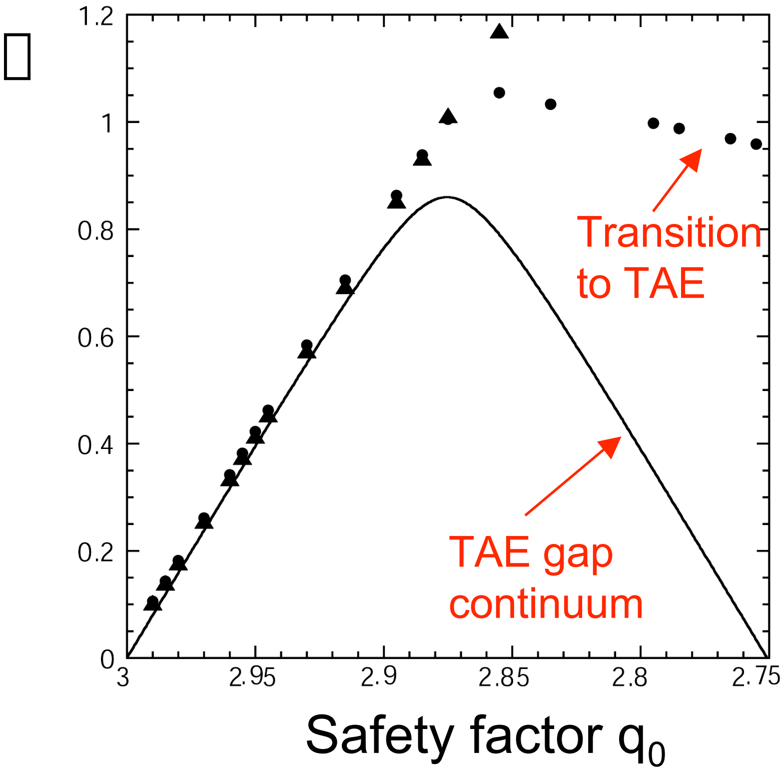
- **Low frequency limit:** $\Omega_{\min}=2Q\frac{r_0^2q_0''}{mq_0}\longrightarrow\Omega_{\min}=-\frac{\omega_{ci}}{m}\frac{r_0}{n}\frac{d}{dr}\left\langle n_{\text{fast ion}}\right\rangle$

Breizman et al., APS/DPP Conference (2003)

CASCADE FREQUENCY AND DAMPING RATE

▲ = single poloidal harmonic (m = 12)
● = two coupled poloidal harmonics (m = 11, m = 12)

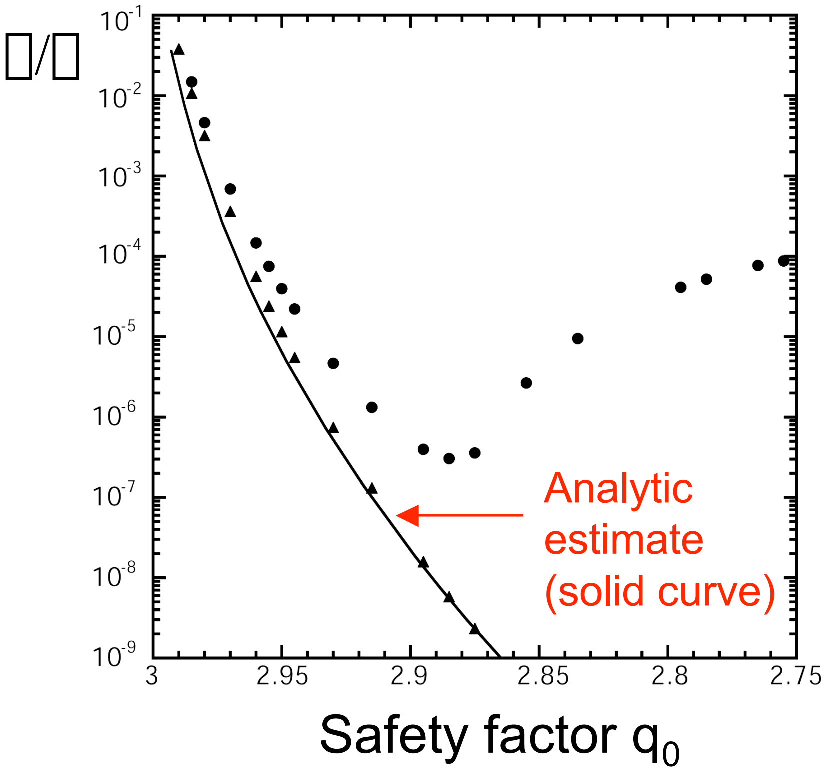
Frequency



Transition to TAE

TAE gap continuum

Damping rate

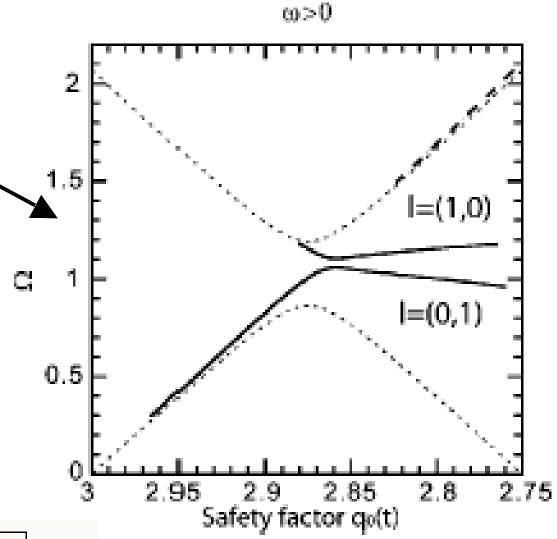


Analytic estimate (solid curve)

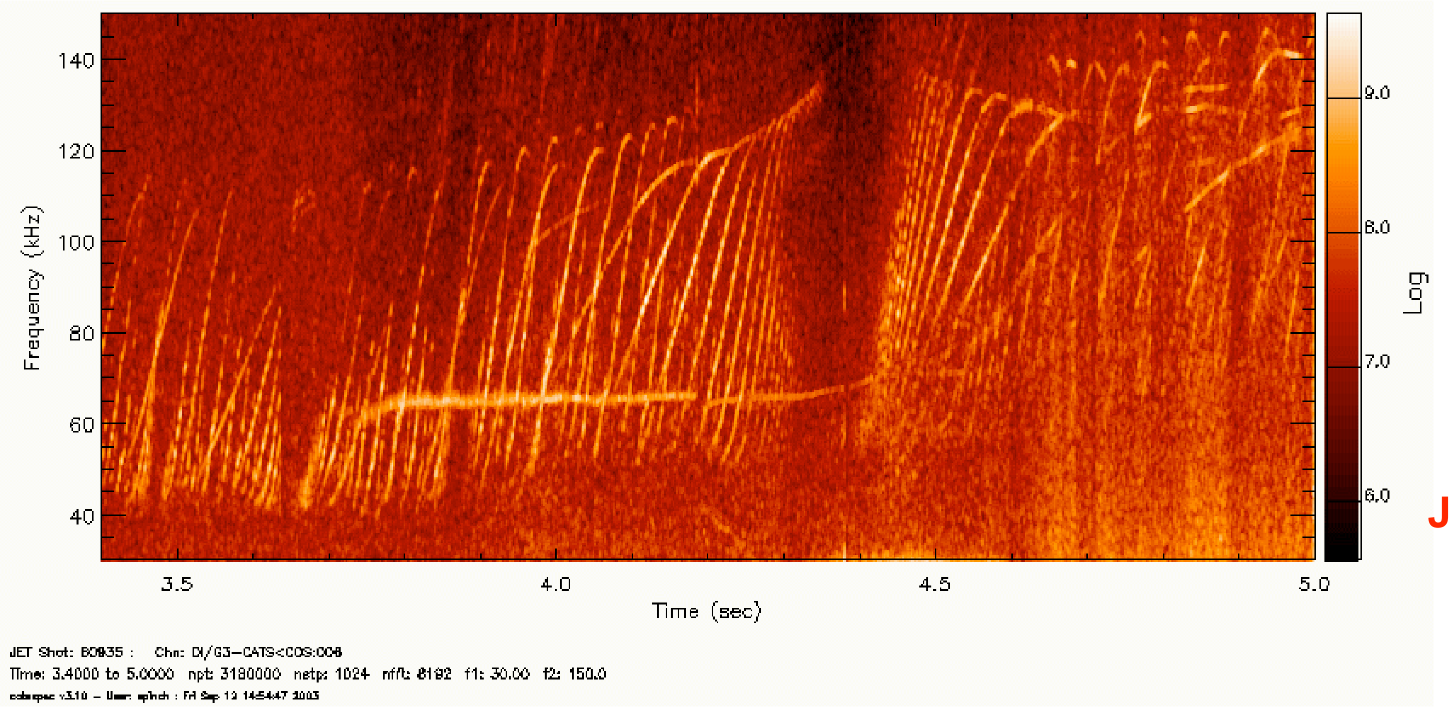
Breizman et al., APS/DPP Conference (2003)

PARTIALLY EXPLAINED FEATURES

- **Transition from Alfvén Cascades to TAEs**
  - But why not continue after turn over?
- **Suppression of Cascades at low frequency:**
  - Continuum damping for moderate m (radiative damping at high m)
  - Coupling to acoustic modes & ion Landau damping?
  - Low-freq cutoff could provide a diagnostic tool



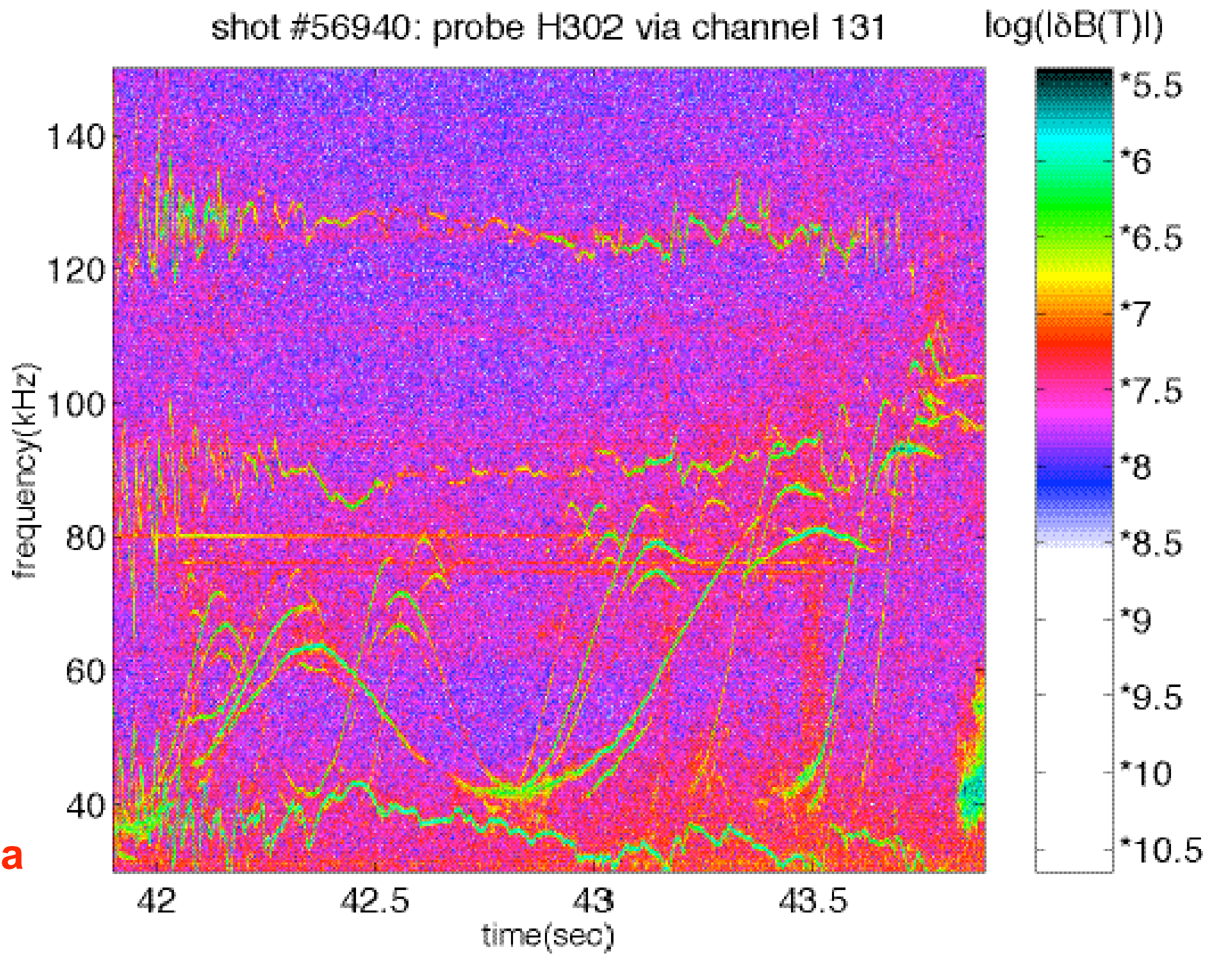
Breizman, Berk, et al. Phys Plasmas (2003)



JET data

UNEXPLAINED CASCADE FEATURES

- Frequency “rolling”
- Mode enhancement at low frequencies

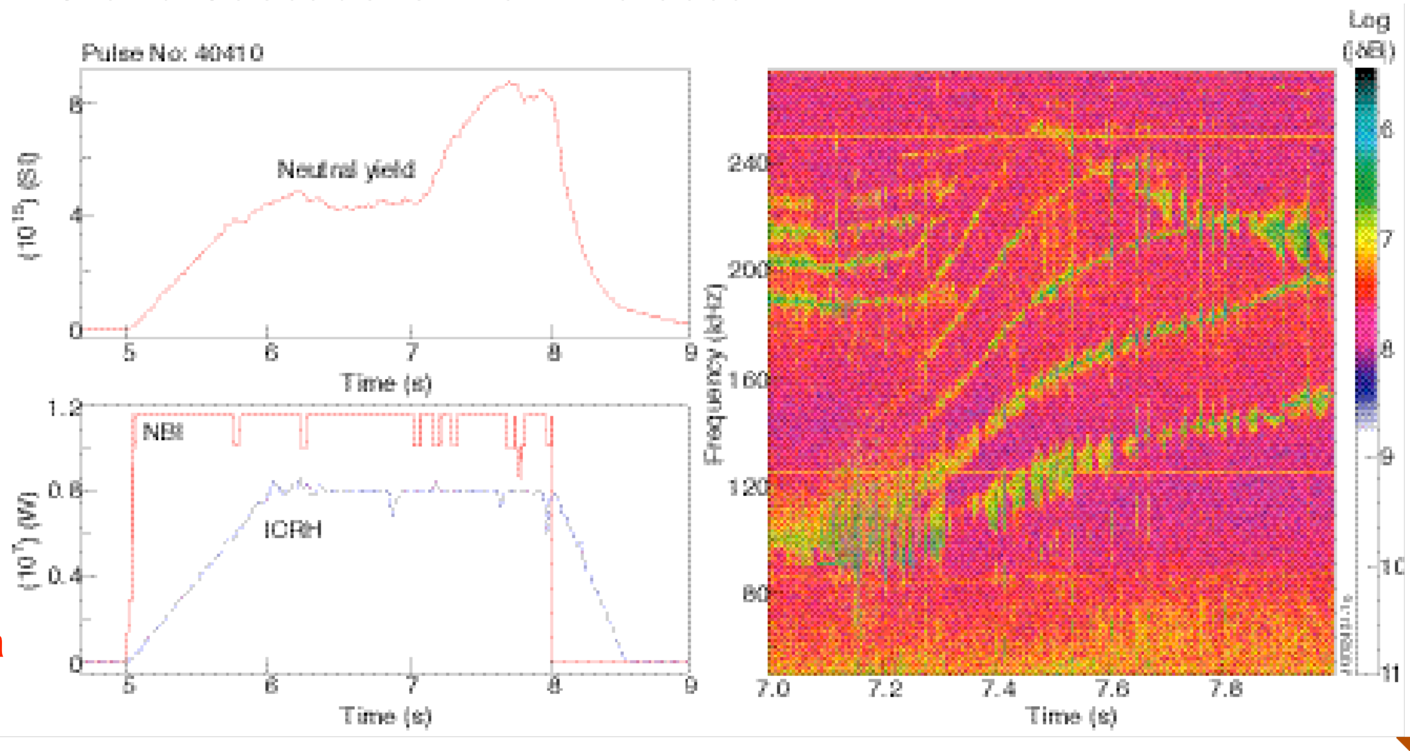


JET data

Sharapov, IAEA TCM on Energetic Particles (2003)

ALFVEN CASCADES AS ITB DIAGNOSTIC

- **ITB triggering event**
  - "Grand Cascade" (many simultaneous n-modes) occurrence is coincident with ITB formation (when q_{min} passes through integer value)
  - Already being used on JET as a diagnostic to monitor q_{min}
  - Proposal to create ITB by application of main heating shortly before a Grand Cascade is known to occur



JET data

E. H. Joffrin et al., IAEA (2002), EX/P1-13

FISHBONES

(example of hard nonlinear response)

FISHBONE ONSET

- **Linear responses from kinetic (wave-particle) and fluid (continuum) resonances are in balance at instability threshold; however, their nonlinear responses differ significantly.**

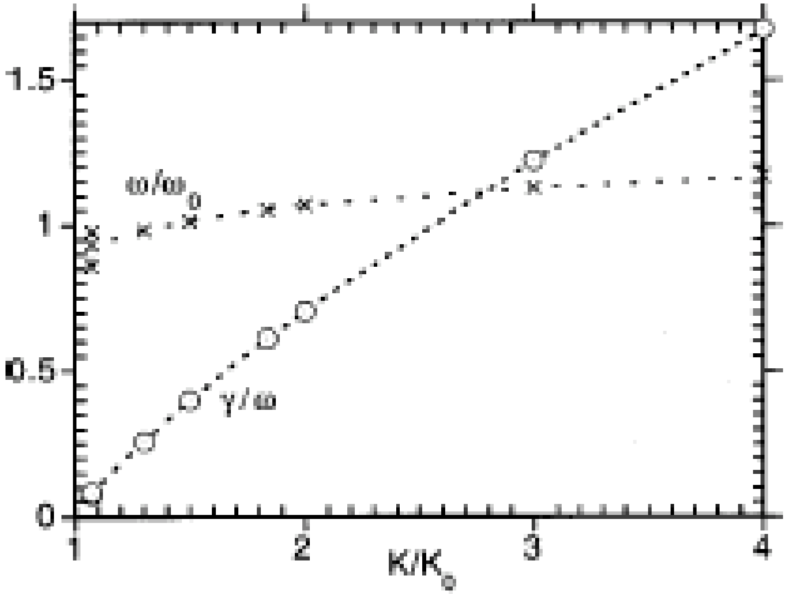
- **Questions:**
  - Which resonance produces the dominant nonlinear response?
  - Is this resonance stabilizing or destabilizing?

- **Approach:**
  - Analyze the nonlinear regime near the instability threshold
  - Perform hybrid kinetic-MHD simulations to study strong nonlinearity

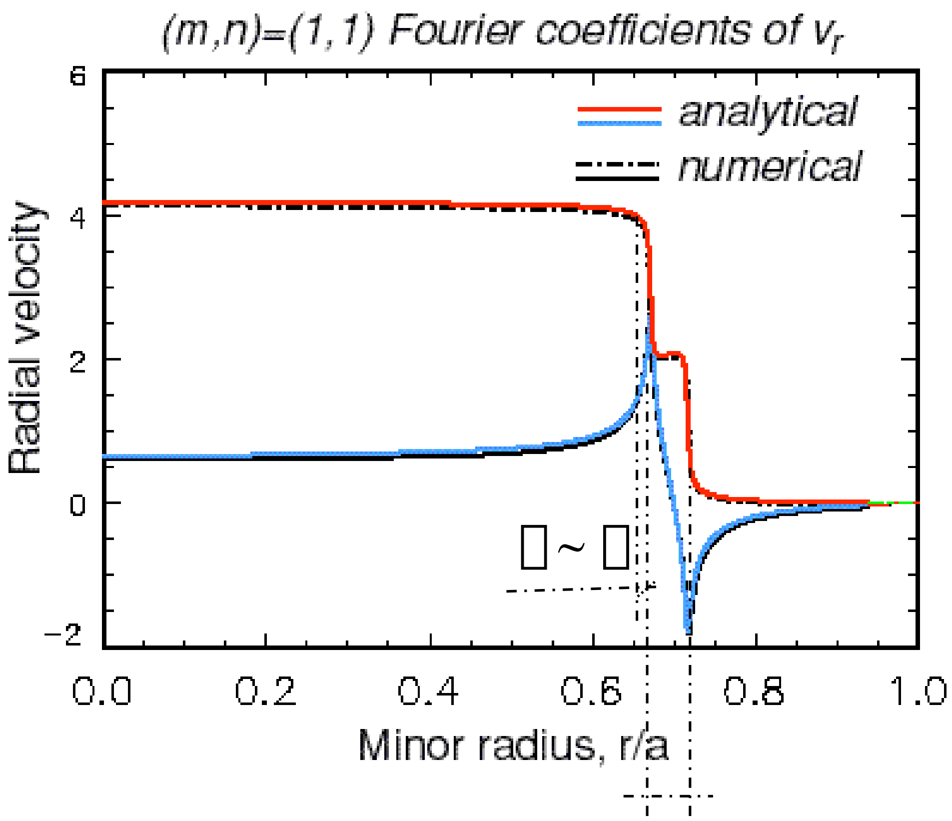
LINEAR NEAR-THRESHOLD MODE

Double resonance layer at □ = ± □(r)

Frequency □ and growth rate □



Energetic ion drive



□ = r□□$_A$s$^{□1}$

A. Odblom et al., Phys Plasmas (2002)

EARLY NONLINEAR DYNAMICS

- **Weak MHD nonlinearity of the q = 1 surface destabilizes fishbone perturbations**
  - Near threshold, fluid nonlinearity dominates over kinetic nonlinearity
  - As mode grows, q profile is flattened locally (near q=1) □ continuum damping reduced □ explosive growth is triggered

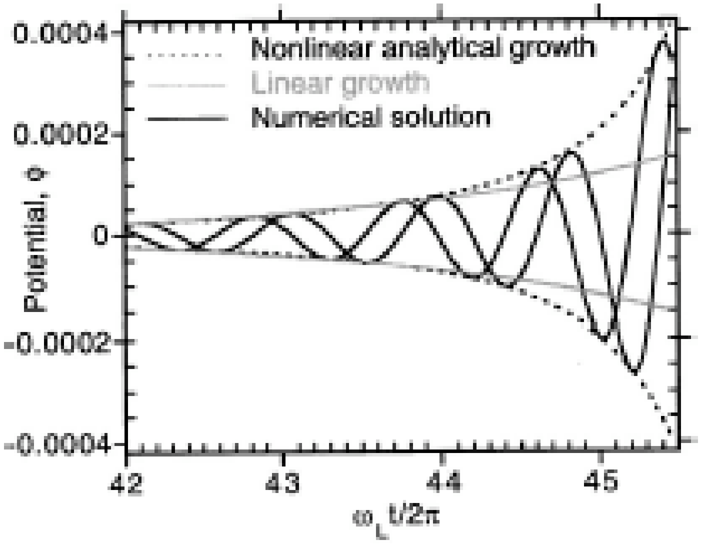


FIG. 4. The $m=1$ amplitude evolution in the numerical solution (solid black), and as predicted by the explosive analytical envelope (dashed), in contrast to a linear growth (solid gray), for a mode near the instability threshold, $\gamma/\omega \sim 8\%$, with $m=0-8$, $\eta=0=\nu$, $T/\tau_A=40$.

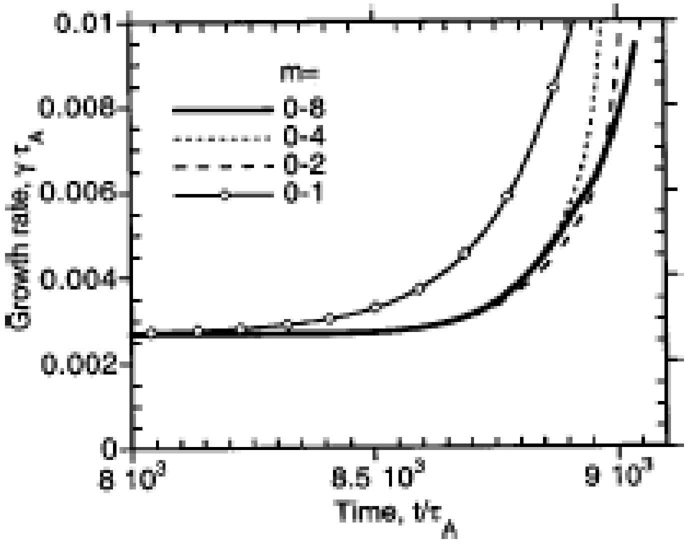


FIG. 5. The nonlinear growth rate evolution of the $m=1$ radial velocity amplitude, $\gamma=\partial \ln|V_r|/\partial t$, for a mode near the instability threshold, $\gamma/\omega \sim 8\%$, and its dependence on the numerical spectral resolution: $m=0-8$ (thick solid), $m=0-4$ (short dashed), $m=0-2$ (long dashed), $m=0-1$ (solid with markers). Here, $T/\tau_A=40$.

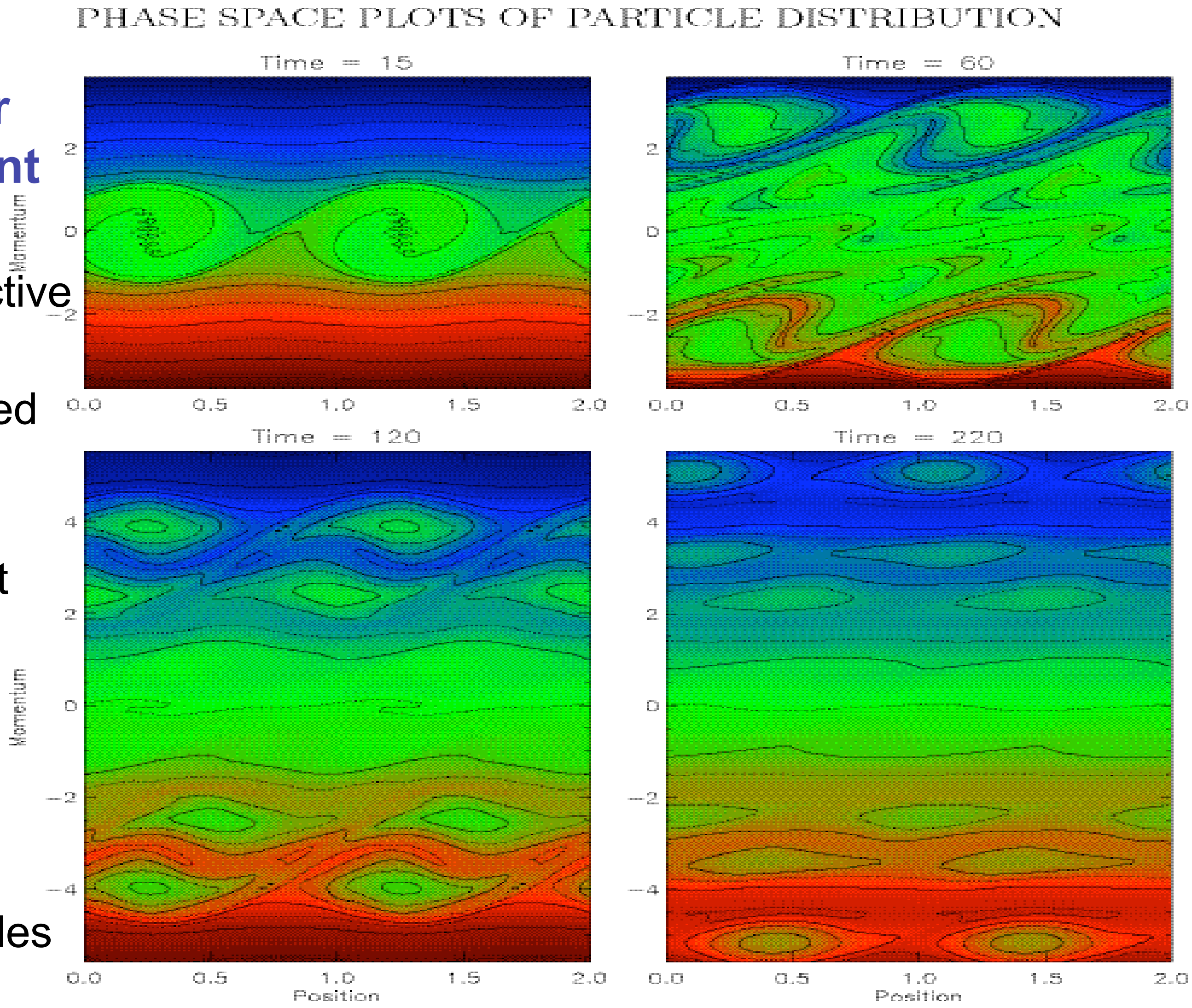
UNEXPLAINED FISHBONE FEATURES

- **Transition from explosive growth to slowly growing MHD structure (i.e., island near q=1 surface)**
- **Modification of fast particle distribution**
- **Mode saturation and decay**
- **Quantitative simulation of frequency sweeping**
  - Frequency change during explosive phase suggests mode will slow down and saturate
- **Burst repetition rate in presence of injection**
  - Need to include sources/sinks/collisions

CONVECTIVE AND DIFFUSIVE TRANSPORT

CONVECTIVE TRANSPORT IN PHASE SPACE

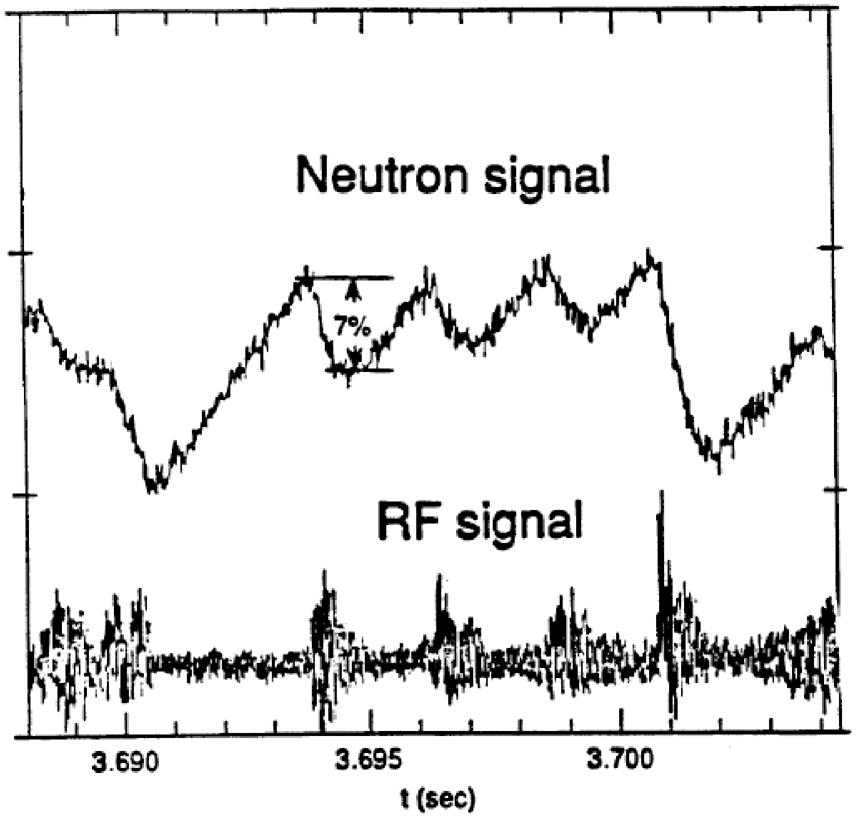
- **Explosive behavior can lead to coherent structures**
  - Can cause convective transport
  - Single mode: limited extent
  - Multiple modes: extended transport (“avalanche”)
- **Not simulated for fishbone**
  - Indication from another example (single mode): “holes and clumps”



Petviashvili, Berk, Breizman (1998)

INTERMITTENT LOSSES OF FAST IONS

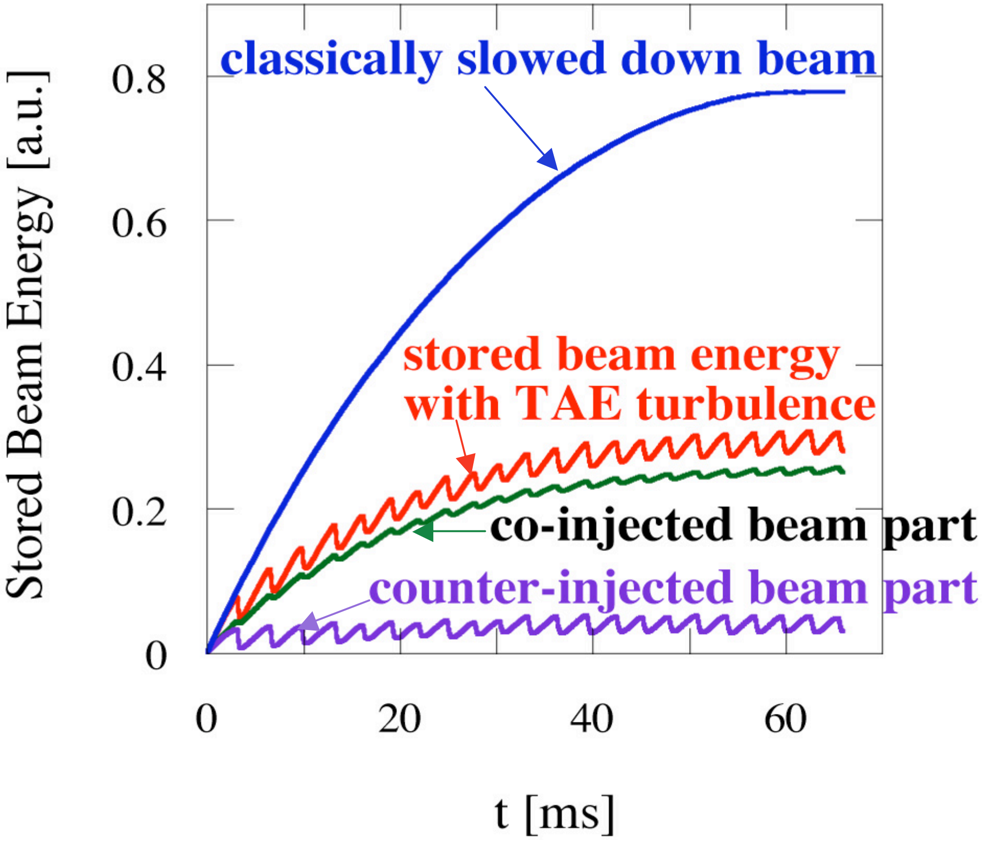
- **Experiments show both benign and deleterious effects**
- **Rapid losses in early TAE experiments:**
  - Wong (TFTR)
  - Heidbrink (DIII-D)
- **Simulation of rapid loss:**
  - Todo, Berk, and Breizman, Phys. Plasmas (2003)
  - Multiple modes (n=1, 2, 3)



K.L. Wong et al., PRL (1991)

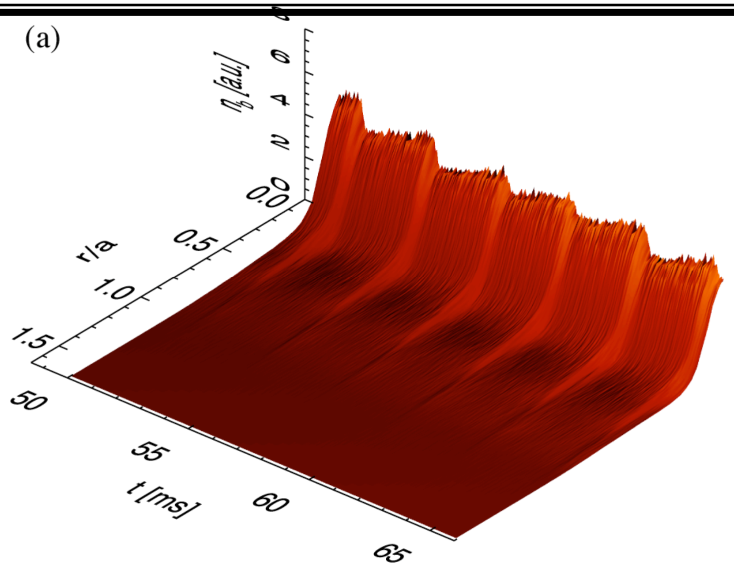
SIMULATION OF INTERMITTENT LOSSES

- **Simulations reproduce NBI beam ion loss in TFTR**
- **Synchronized TAE bursts:**
  - At 2.9 ms time intervals (cf. 2.2 ms in experiments)
  - Beam energy 10% modulation per burst (cf. 7% in experiment)
- **TAE activity reduces stored beam energy wrt to that for classical slowing-down ions**
  - 40% for co-injected ions
  - Larger reduction (by 88%) for counter-injected beam ions (due to orbit position wrt limiter)

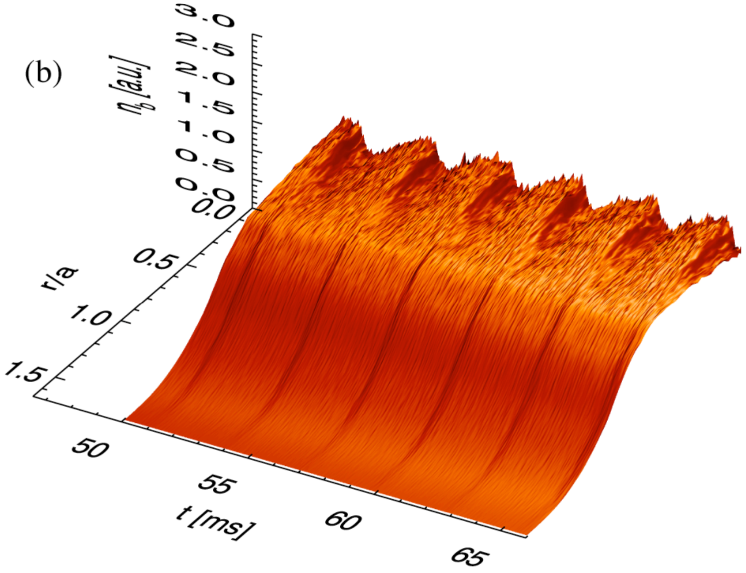


Y. Todo et al., Phys Plasmas (2003)

TEMPORAL RELAXATION OF RADIAL PROFILE



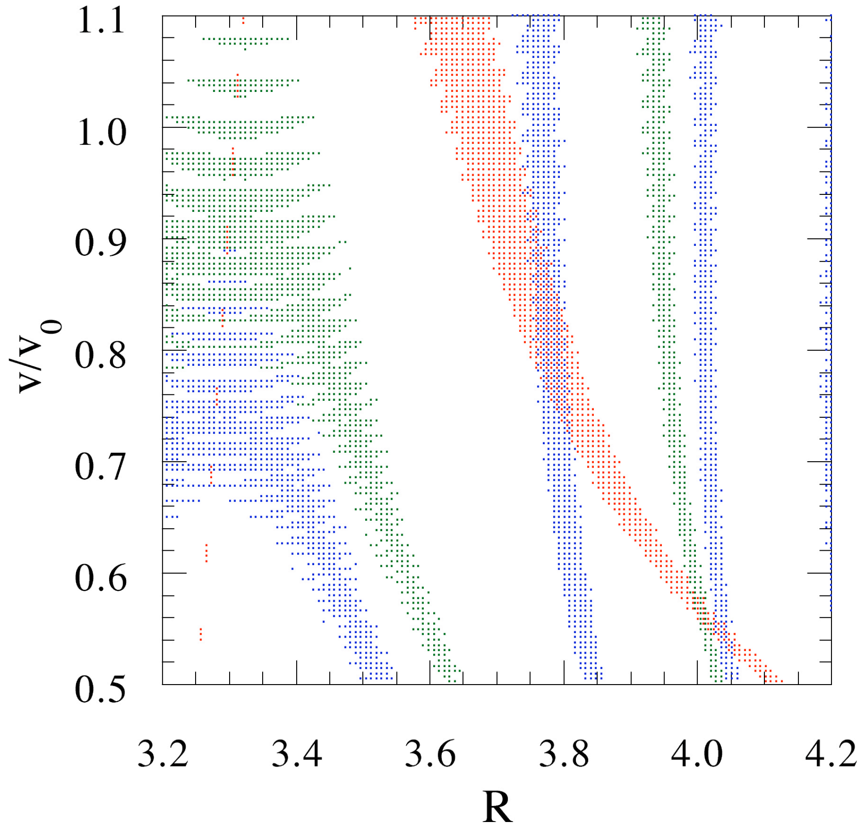
- **Counter-injected beam ions:**
  - Confined only near plasma axis



- **Co-injected beam ions:**
  - Well confined
  - Pressure gradient periodically collapses at criticality
  - Large pressure gradient is sustained toward plasma edge

Y. Todo et al., PoP (2003)

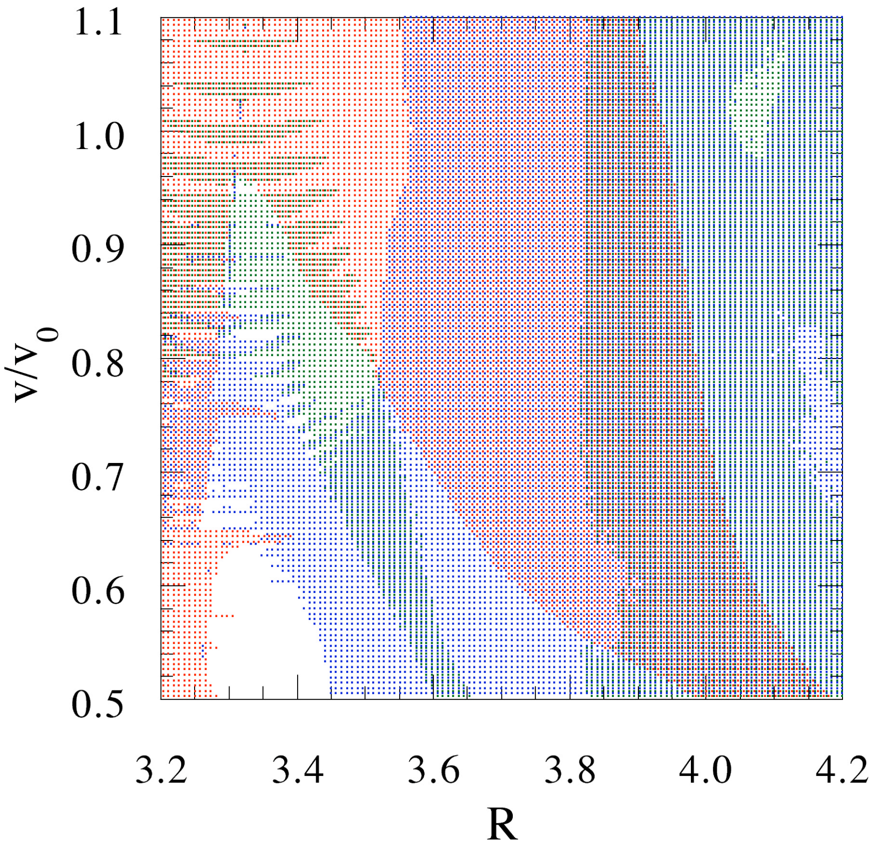
PHASE SPACE RESONANCES



For low amplitude modes:

□B/B = 1.5 X 10^{-4}

n=1, n=2, n=3



At mode saturation:

□B/B = 1.5 X 10^{-2}

n=1, n=2, n=3

ISSUES IN MODELING DIFFUSIVE TRANSPORT

- **Reconciliation of mode saturation levels with experimental data**
  - Simulations (Y. Todo) reproduce experimental behavior for repetition rate and accumulation level
  - However, saturation amplitude is larger than exp'tal measurements
- **Edge effects in fast particle transport**
  - Sufficient to suppress modes locally near the edge
  - Need better description of edge plasma parameters
- **Transport barriers for marginally stable profiles**
- **Resonance overlap in 3D**
  - Different behavior: (1) strong beam anisotropy, (3) fewer resonances

SUMMARY

MODELING ISSUES FOR FURTHER STUDY

- **Diagnostic applications of benign modes**
  - Obtain q_{min} without saturation information
- **Quantitative interpretation of exp'tal data for nonlinearly saturated isolated modes (TAE, Cascade, high-frequency modes, etc.)**
  - What determines saturation level
- **Transport barriers for energetic particles in presence of many unstable modes**
- **Parameter window for fast particle confinement in fusion devices**
  - Predict range for safe operation
- **Intermittent strong bursts versus stochastic diffusive transport**
  - Many modes (quasilinear-like scenario)
- **Full lifecycle of fishbones and EPMs, starting from instability threshold**
  - So far, described only the initial phase
- **Fast nonlinear frequency sweeping**
  - Multi-mode case
- **Interplay of kinetic and fluid resonances**

MODELING/SIMULATION METHODOLOGY

- **Highlight puzzles/discrepancies of fundamental importance**
- **Identify key physics ingredients qualitatively/analytically**
- **Develop self-consistent reduced theory-based models/codes:**
  - To capture and simulate essential physics
  - To perform broad parameter scans
- **Develop advanced techniques for large-scale simulations**
- **Use reduced models/codes to validate large codes**
- **Apply large codes:**
  - To quantitatively model present-day experiments
  - To predictively extrapolate to reactor conditions
- **Attain ultimate goal of integrated simulations**