

Transition From Weak to Strong Energetic Ion Transport in Burning Plasmas

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Vilamoura, Portugal, November 1–6 2004

20th IAEA Fusion Energy Conference



Background

- A burning plasma is a self-organized system, where collective effects associated with fast ions (MeV energies) and charged fusion products may alter their confinement properties and even prevent the achievement of ignition.

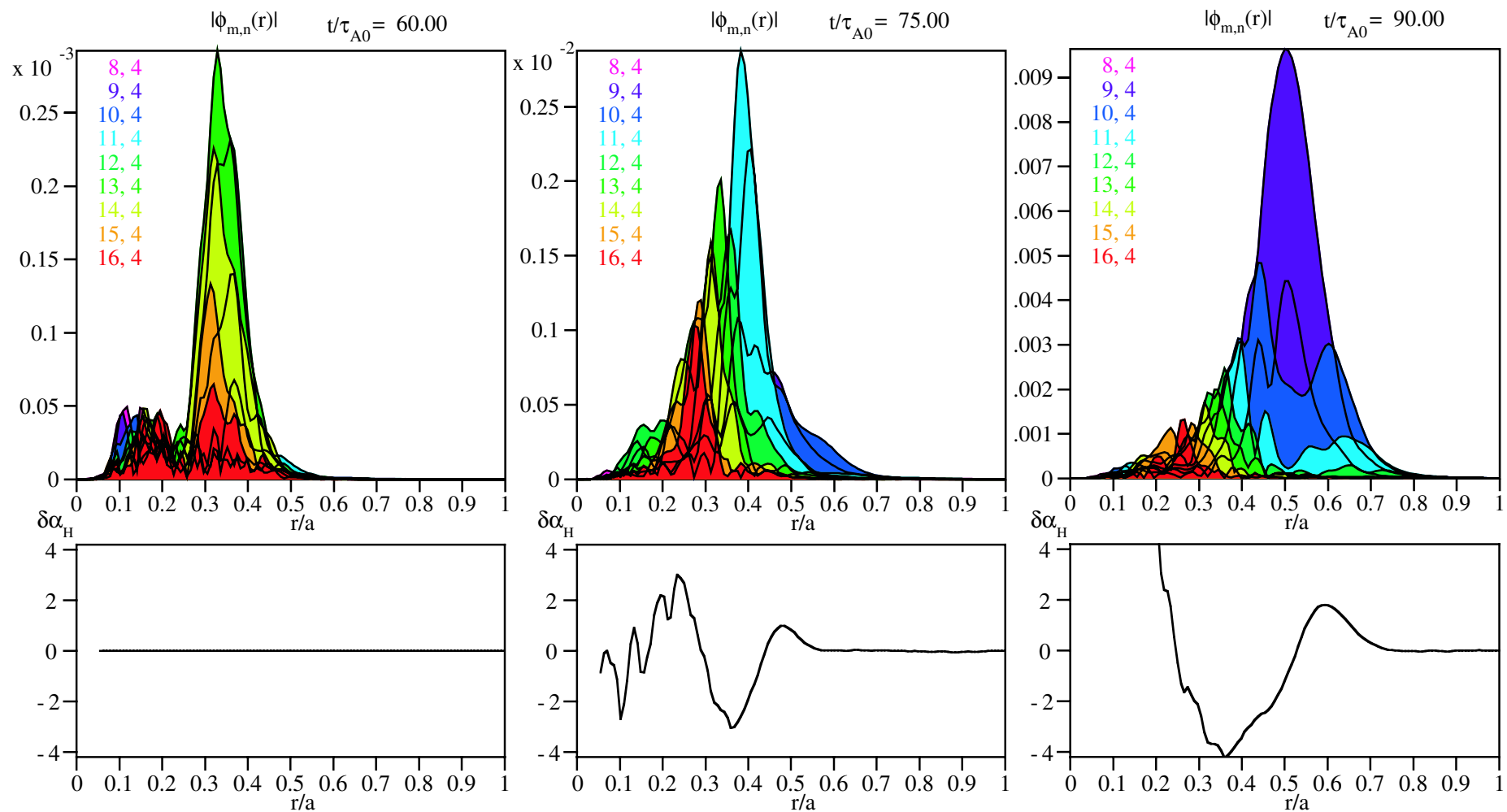


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Avalanches and NL EPM dynamics (IAEA 02)



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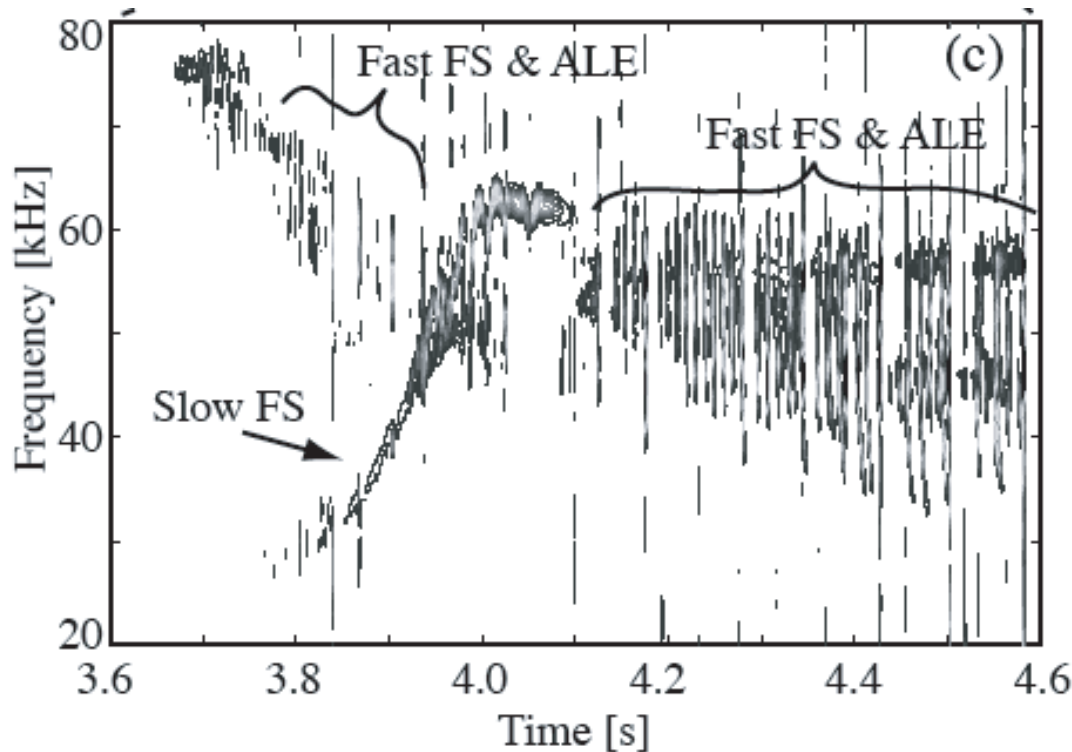


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- Observations on JT-60U (and other tokamaks) have confirmed macroscopic and rapid energetic particle radial redistributions in connection with the so called Abrupt Large amplitude Events (ALE) (K. Shinohara, NF 01).

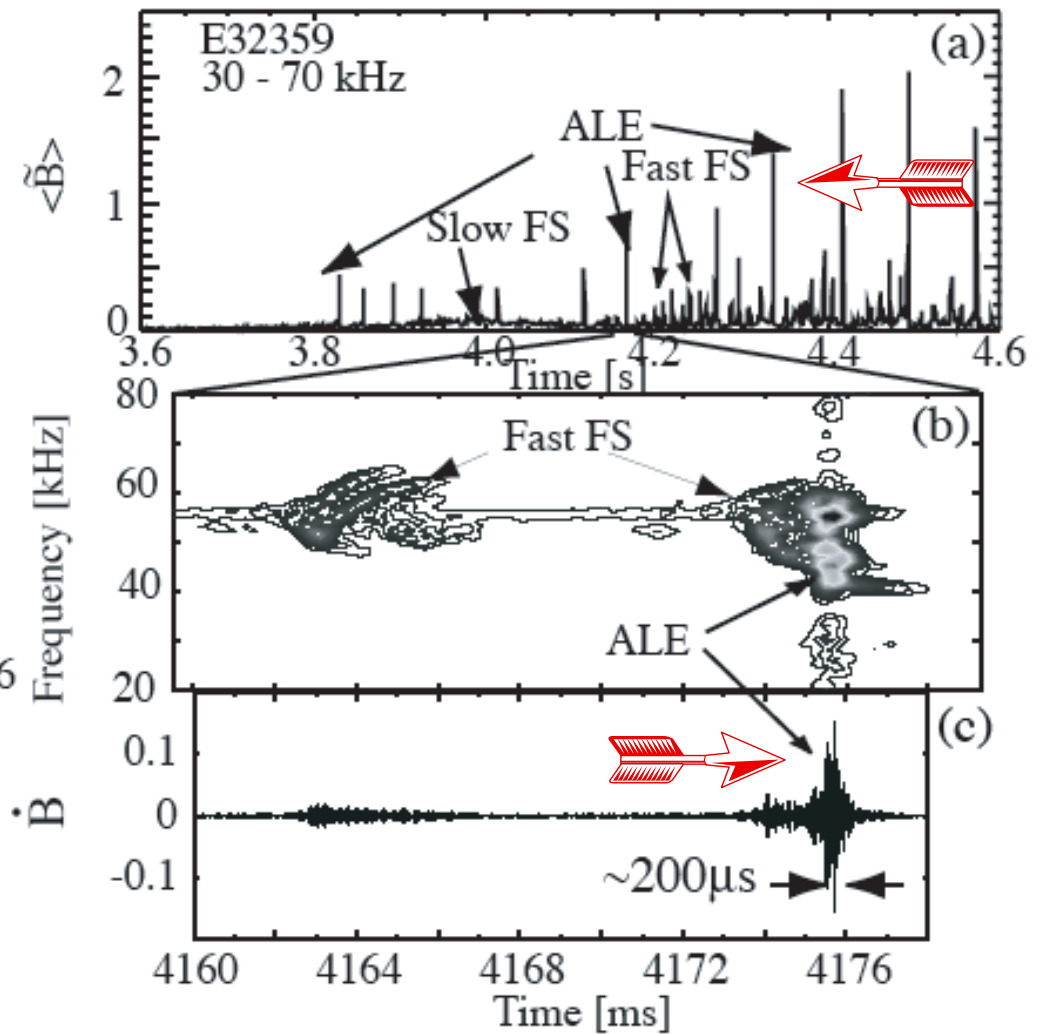


ALE on JT-60U (K. Shinohara, *et al.*, Nucl. Fus. 41, 603, (2001))



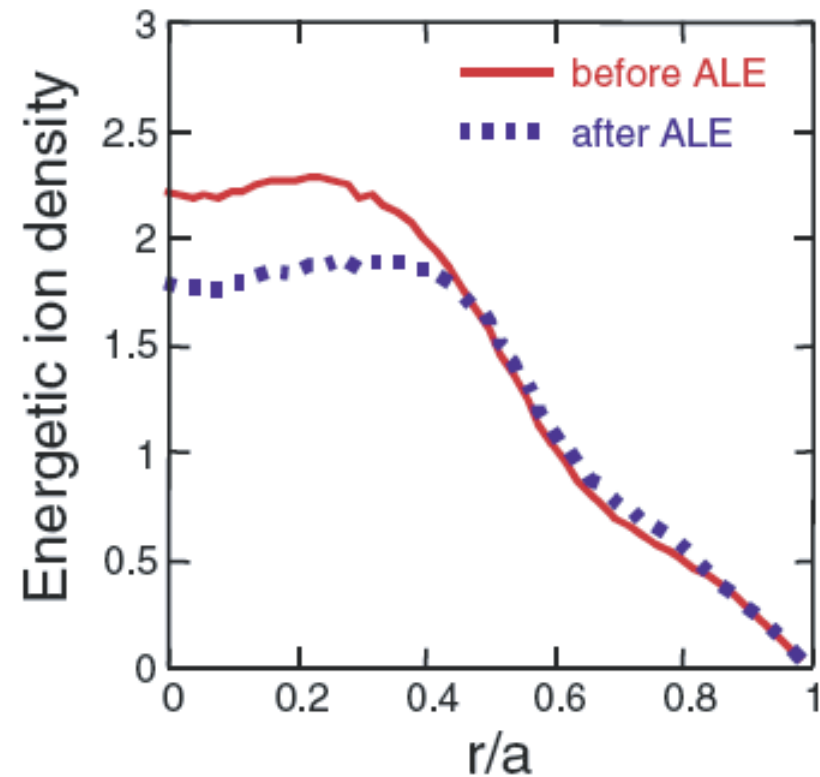
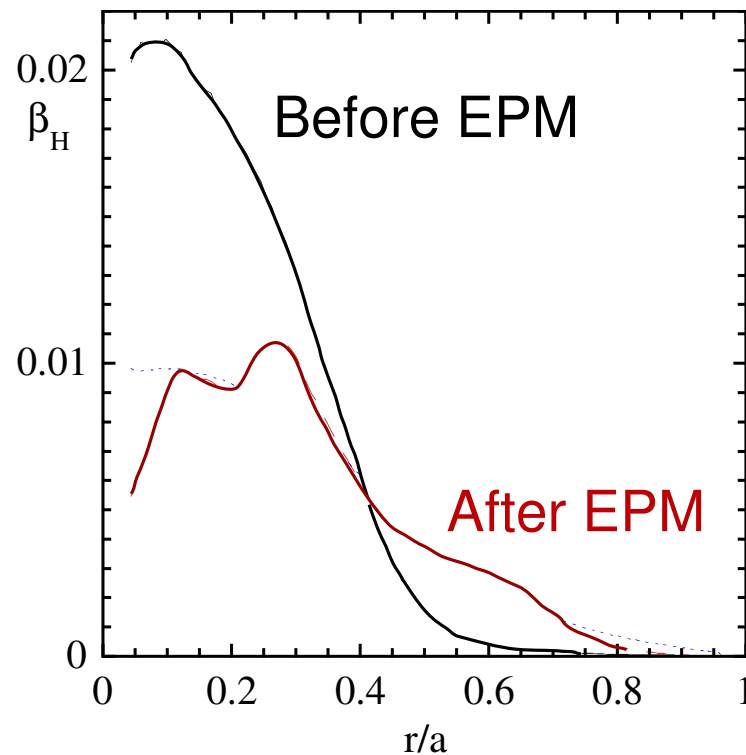
ALE = Abrupt Large amplitude Event

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.



G. Vlad *et al.*, EPS02, ECA 26B, P-4.088, (2002).

K. Shinohara *etal* PPCF 46, S31 (2004)
 Courtesy of M. Ishikawa and JT-60U



Issues arising

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- Applications to plasma equilibria given a priori. High B-field, low fast-ion energy density operations are favored. Applications to ITER indicate fairly benign behaviors except for the reversed shear operations. Hybrid scenario is optimal $\Rightarrow$ G. Vlad *et al.*, IT/P3-31 in Thursday Poster Session.



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- Therefore, it is crucial to theoretically assess the potential impact of fusion product avalanches on burning plasma operation in the perspective of direct comparisons with experimental evidence.
- Simulation, Theory and Experiment are equally important.



Nonlinear Dynamics: local vs. global processes

- Mode saturation via wave-particle trapping (H.L. Berk *et al.* PFB 90, PPR 97) has been successfully applied to explain pitchfork splitting of TAE spectral lines (A. Fasoli *et al.* PRL 98): local distortion of the fast ion distribution function because of quasi-linear wave-particle interactions.



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- Compton scattering off the thermal ions (T.S. Hahm and L. Chen PRL 95): locally enhance the mode damping via nonlinear wave-particle interactions
- Mode-mode couplings generating a nonlinear frequency shift which may enhance the interaction with the Alfvén continuous spectrum (Zonca *et al.* PRL 95 and Chen *et al.* PPCF 98): locally enhance the mode damping via nonlinear wave-wave interactions.



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- EPM is a resonant mode (L. Chen PoP 94), which is localized where the drive is strongest: global readjustments in the energetic particle drive is expected to be important as well.



Nonlinear Dynamics of a single- n coherent EPM

- NL dynamics of a single- n coherent EPM: neglect local phenomena and consider only global NL EPM dynamics. Consistency check *a posteriori*.
- Treat hot particle distribution consisting of a background plus a perturbation on meso time and space scales: the background is frozen in time.



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- Treat hot particle distribution consisting of a background plus a perturbation on meso time and space scales: the background is frozen in time.
- The modification in the energetic particle distribution function in the presence of finite amplitude fluctuations is derived in the framework of nonlinear Gyrokinetics
- The non-adiabatic fast ion response – $\overline{\delta H_k}$ – is obtained from the NL gyrokinetic equation (Frieman & Chen PF 82). For details see TH/5-1 in Friday Poster Session.



Initial value radial envelope problem

- Using both time scale separation, $\omega = \omega_0 + i\partial_t$ as well as spacial scale separation, $\theta_k \Rightarrow (-i/nq')\partial_r$ with ∂_r acting on $A(r, t)$ only, the initial value radial envelope problem **meso time and space scales** becomes:

$$\underbrace{[D_R(\omega, \theta_k; s, \alpha) + iD_I(\omega, \theta_k; s, \alpha)] A_0}_{\text{LINEAR DISPERSION}} = \underbrace{\delta W_{KT} A_0}_{\text{LIN.} \oplus \text{NL EN. PART. RESP.}},$$

- $e_H \delta \phi / T_H = A(r, t) = A_0(r, t) \exp(-i\omega_0 t)$, with $|\omega_0^{-1} \partial_t \ln A_0(r, t)| \ll 1$



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- Nonlinear ($n = 0, m = 0$) distortion to the hot particle distribution on **meso time and space scales**: for details see TH/5-1 in Friday Poster Session.

$$\frac{\partial}{\partial t} H_z = 2k_\theta^2 \rho_H^2 \frac{\omega_{cH}}{k_\theta} \frac{T_H}{m_H} \frac{\partial}{\partial r} \left[\text{Im} \left(\frac{Q F_0}{\omega} \frac{\bar{\omega}_d}{\bar{\omega}_d - \omega} \right) \Gamma^2 |A|^2 \right]_H.$$



- Assume isotropic slowing-down and EPM NL dynamics dominated by precession resonance.

$$[D_R(\omega, \theta_k; s, \alpha) + iD_I(\omega, \theta_k; s, \alpha)] \partial_t A_0 = \frac{3\pi\epsilon^{1/2}}{4\sqrt{2}} \alpha_H \left[1 + \frac{\omega}{\bar{\omega}_{dF}} \ln \left(\frac{\bar{\omega}_{dF}}{\omega} - 1 \right) + i\pi \frac{\omega}{\bar{\omega}_{dF}} \right] \partial_t A_0 + i\pi \frac{\omega}{\bar{\omega}_{dF}} A_0 \frac{3\pi\epsilon^{1/2}}{4\sqrt{2}} k_\theta^2 \rho_H^2 \frac{T_H}{m_H} \partial_r^2 \partial_t^{-1} (\alpha_H |A_0|^2) .$$



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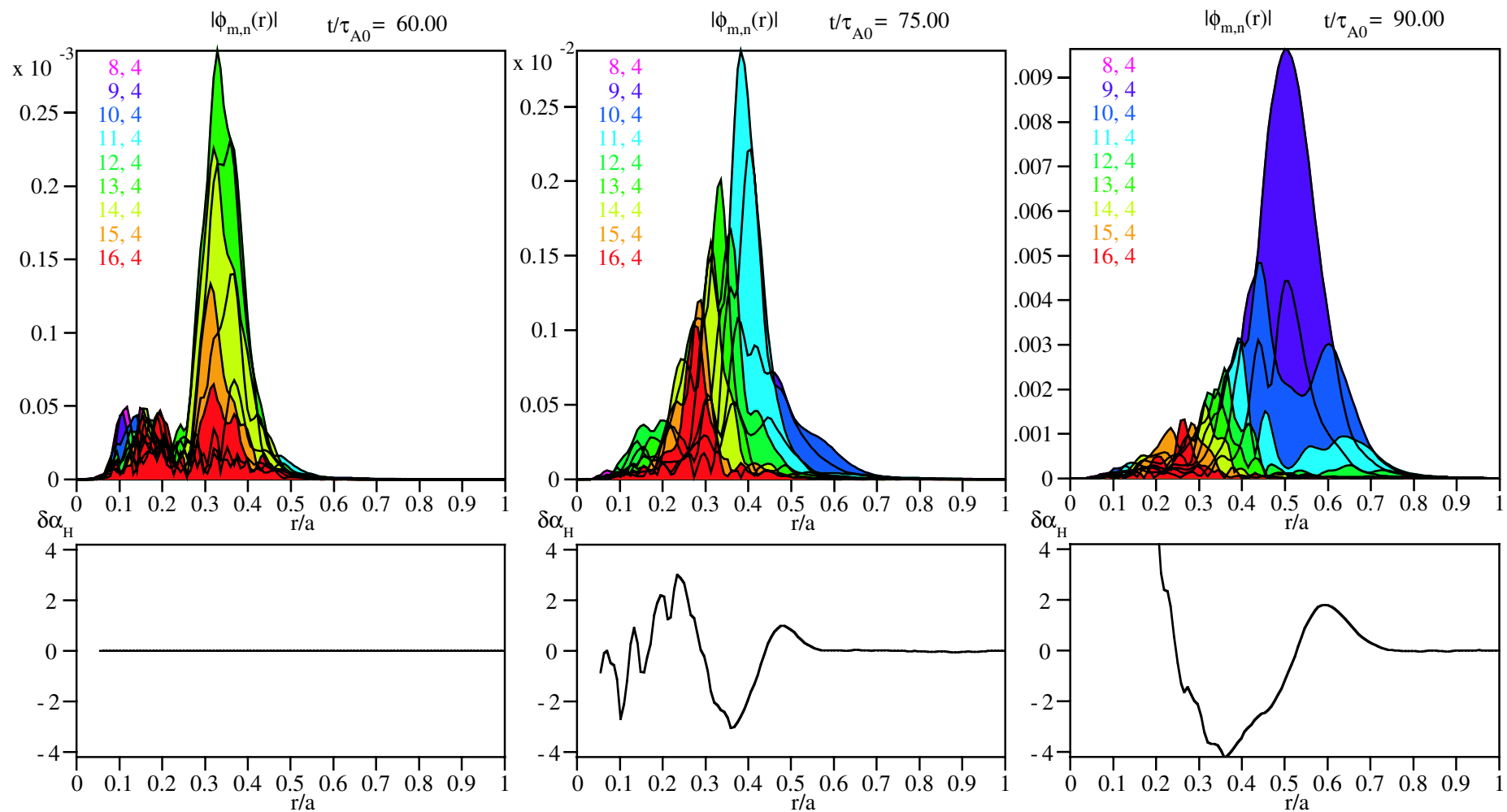
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DECREASES DRIVE@ MAX $|A_0|$

INCREASES DRIVE NEARBY

- Assume localized fast ion drive, $\alpha_H = -R_0 q^2 \beta'_H = \alpha_{H0} \exp(-x^2/L_p^2) \simeq \alpha_{H0}(1 - x^2/L_p^2)$, with $x = (r - r_0)$.

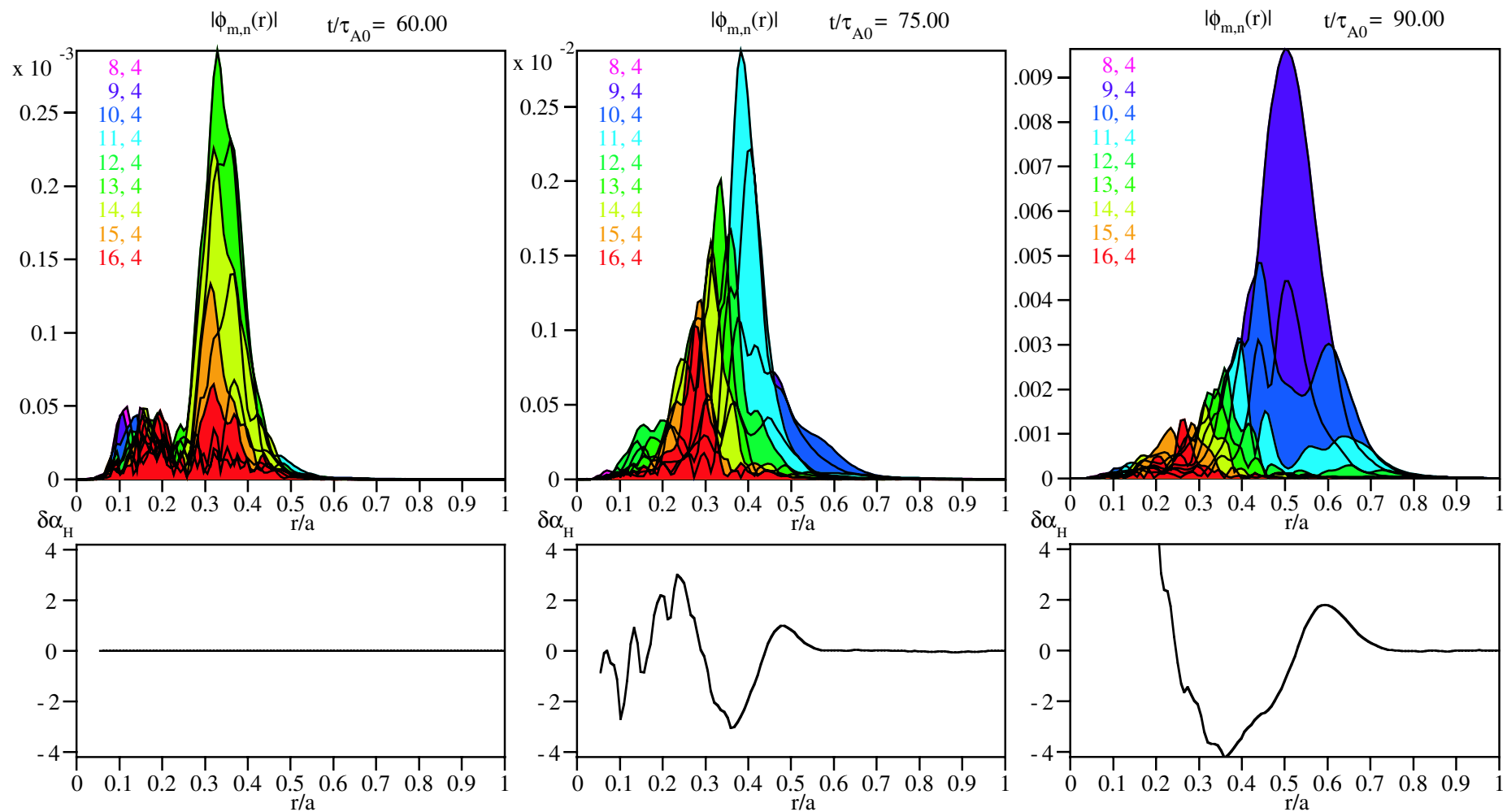
- In order to maximize the drive the EPM radial structure is nonlinearly displaced by

$$(x_0/L_p) = \gamma_L^{-1} k_\theta \rho_H (T_H/M_H)^{1/2} (|A_0|/W_0) ,$$

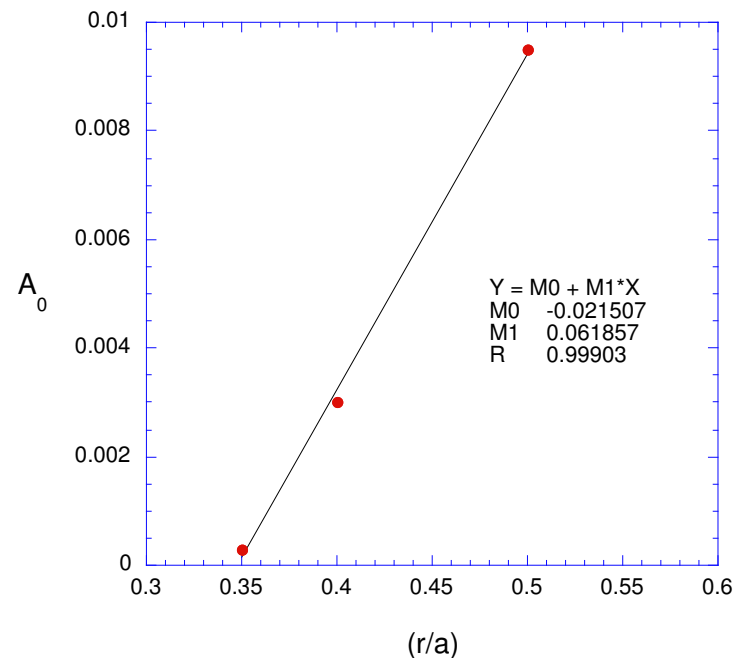
- x_0 is the radial position of the max EPM amplitude and W_0 indicating the typical EPM radial width in the NL regime



Avalanches and NL EPM dynamics (IAEA 02)



- During convective amplification, radial position of unstable front scales linearly with EPM amplitude.

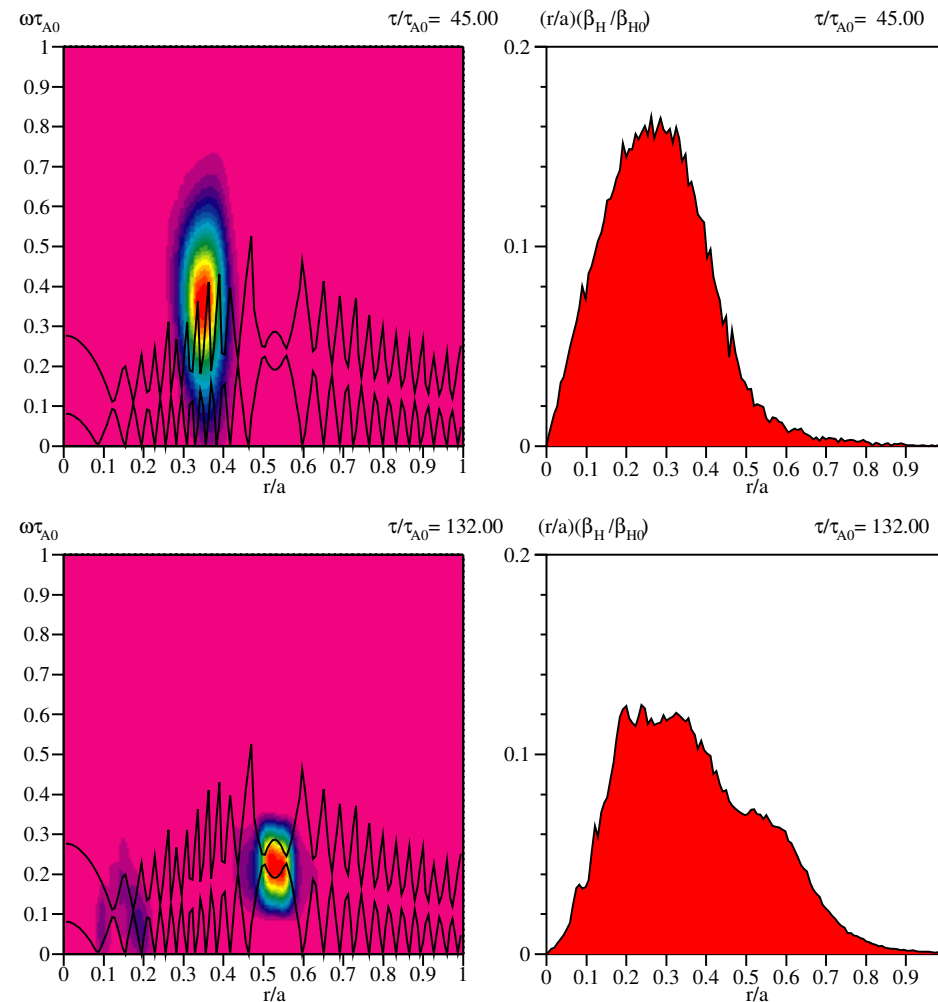


- Real frequency chirping accompanies convective EPM amplification in order to keep $\omega \propto \bar{\omega}_d$

$$\Delta\omega = s \bar{\omega}_{dF}|_{x_0} (x_0/r) (\omega_0 / \bar{\omega}_{dF}|_{x=0}) \quad .$$



Avalanches and transport in NL EPM dynamics



Threshold conditions for Avalanches

- Consistency check for neglecting wave particle trapping: based on the displacement $\bar{x}_0$ of the avalanche front when trapping becomes important
- Threshold for weak avalanche, or avalanche onset: $\bar{x}_0 \gtrsim |nq'|^{-1}$.

$$1 \gg \frac{\gamma_L}{k_\theta \rho_H (T_H/m_H)^{1/2} R_0^{-1}} \gtrsim (k_\theta L_p)^{-1/2} ,$$



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- Strong avalanche condition: $\bar{x}_0 \gtrsim W_0$, the characteristic NL EPM width.

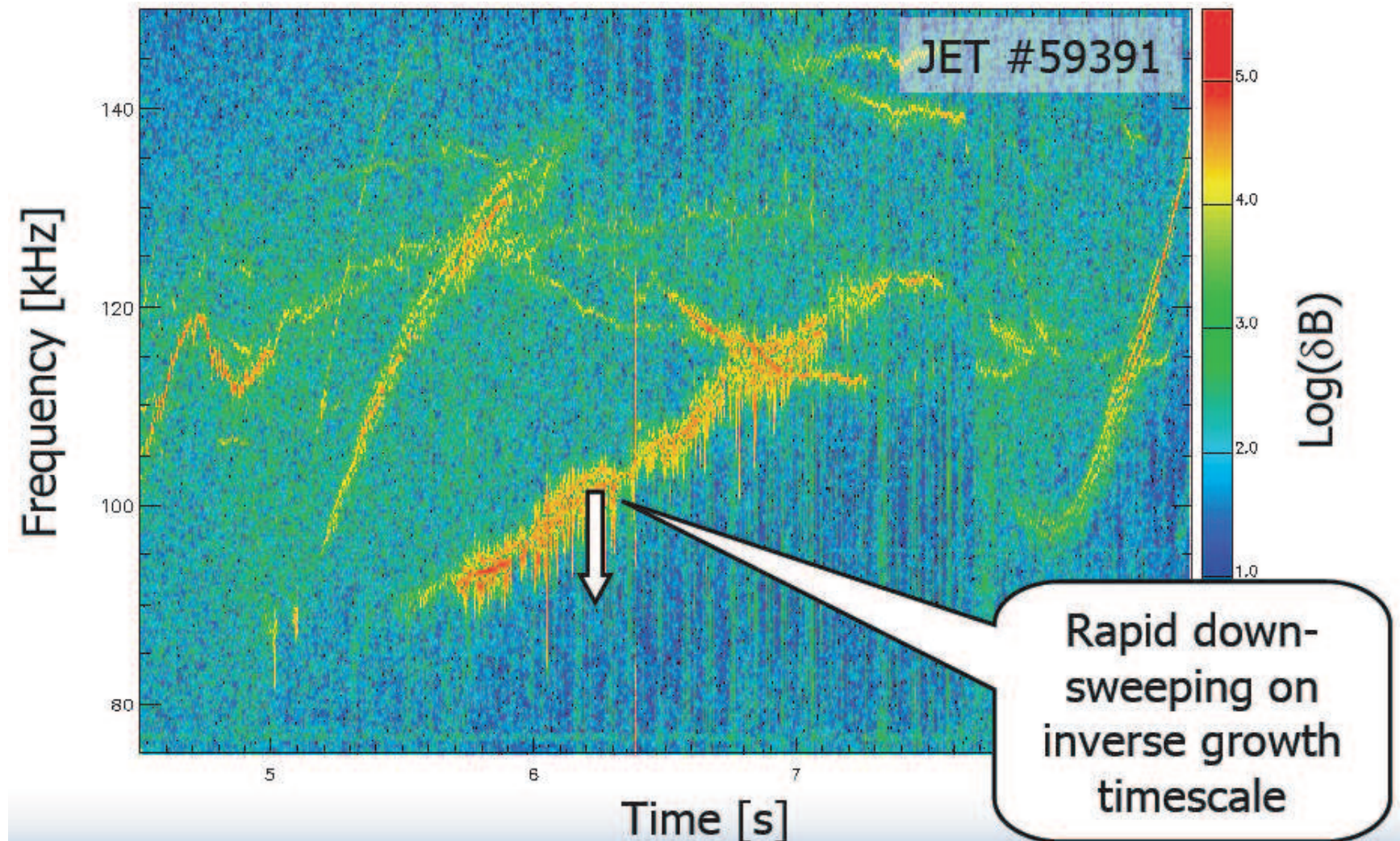
$$1 \gg \frac{\gamma_L}{k_\theta \rho_H (T_H/m_H)^{1/2} R_0^{-1}} \gtrsim W_0^2 / \Delta^2 . \quad \Delta \approx (L_p/k_\theta)^{1/2}$$

- $W_0^2 / \Delta^2 \ll 1$, due to the short scale of the nonlinear distortion: onset for EPM induced avalanches is close to the linear excitation threshold.
- If neither of these conditions is satisfied, EPM will saturate either via wave-particle trapping or other local phenomena.



Possible EPMS during Alfvén Cascades in JET

Courtesy of S.D. Pinches and JET-EFDA



Simon Pinches, 31st EPS Conference on Plasma Physics, London, 2004



Conclusions

- Numerical simulations and theoretical analyses demonstrate ballistic fast ion transport above the EPM linear excitation threshold.
- Nonlinear mode dynamics is an avalanche process: *i.e.* the radial propagation of an unstable front.
- Threshold conditions for the avalanche onset are given: typical values are close to the linear excitation threshold.
- Good qualitative agreement of numerical simulations with local theoretical calculations of EPM convective amplification.
- Time scales and qualitative phenomenology similar to experimental observations: ALE on JT-60U and fast chirping in Alfvén Cascade experiments on JET.
- Applications to ITER indicate fairly benign behaviors except for the reversed shear operations. Hybrid scenario is optimal $\Rightarrow$ G. Vlad *et al.*, IT/P3-31 in Thursday Poster Session.

