Excitation of zonal flows and their impact on dynamics of edge pedestal collapse (TH/8-3)

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Edge Localized Modes (ELMs)

- **Edge localized modes (ELMs):**

  → Disruptive instability occurring in the edge region of a tokamak plasma due to quasi-periodic relaxation of an edge transport barrier (ETB)

  - Unmitigated large (Type-I) ELMs are serious concern in ITER operation → RMP, Pellet pace making etc.
  - Understanding physics of **the origin of ELM crash** and ensuing **energy loss mechanism** has been a central issue in fusion plasma physics society for decades.

ELM crash dynamics

- **Current picture:**
  - **Type-I ELM** triggered by destabilization of **ideal peeling-ballooning mode** **[Snyder et. al., PoP 2002]** and its nonlinear evolution (**filaments**, **[Wilson and Cowley, PRL, 2004]**)
- Some recent MHD simulations highlight the role of **nonlinear dynamical processes** in ELM crash
  - Stochastization of magnetic fields [**M3D**, **JOREK**, **BOUT++]** and ensuing energy loss **[T. Rhee, et. al., NF, 2015]**
  - Variation of coherence time **[Xi et. al., PRL, 2014]**

A missing piece in earlier NL simulations

- Lack of self-consistency in turbulent transport dynamics
- In particular, generation and role of zonal flows (ZF) in an ELM crash has not been fully explored.
- ZF is expected to have influence on ELM crash dynamics:
  - **Energy re-distribution** in **early stage** of an ELM crash
  - Nonlinear evolution in **later stage** **when ideal MHD driver becomes sufficiently weak**

→ **Main focus of this talk:**

How do ZFs affect the crash dynamics?

Model

- **Reduced 3-field MHD equations keeping U_{00} and P_{10}**

$$m_i n \frac{\partial U}{\partial t} = -m_i n \mathbf{V}_E \cdot \nabla U + B_0^2 \nabla_{||} \left(\frac{J_{||}}{B_0} \right) + 2\mathbf{b}_0 \times \kappa_0 \cdot \nabla P$$

$$U = \frac{1}{B_0}\left(\nabla_\perp^2 \Phi + \frac{1}{en} \nabla_\perp^2 P \right)$$

$$\frac{\partial P}{\partial t} = -\mathbf{V}_E \cdot \nabla P - \frac{10}{3} \frac{P_0}{1+5\beta/6} \frac{\mathbf{b}_0 \times \kappa_0 \cdot \nabla \Phi}{B_0} + f_K v_e^2 D_{RR} \frac{\partial^2 P_0}{\partial r^2}$$

$$\frac{\partial A_{||}}{\partial t} = -\nabla_{||}\Phi + \frac{\eta}{\mu_0}\nabla_\perp^2 A_{||} - \frac{\eta_H}{\mu_0}\nabla_\perp^4 A_{||}$$

Geodesic Curvature Coupling (GCC)

$$\frac{\partial U_{00}}{\partial t} = -\left[\tilde{\Phi}_{mn}, \tilde{U}_{mn}\right] + \left[\tilde{A}_{||mn}, \tilde{J}_{||mn}\right] + 2\left\langle \mathbf{b}_0 \times \kappa_0 \cdot \nabla P_{10} \right\rangle$$

$$\frac{\partial P_{10}}{\partial t} = -\left[\tilde{\Phi}_{m\pm1n}, \tilde{P}_{mn}\right] - \frac{10}{3} \frac{P_0}{1+5\beta/6} \frac{\mathbf{b}_0 \times \kappa_0 \cdot \nabla \Phi_{00}}{B_0}$$

- Simulations done using the **BOUT++ framework** **[B Dudson, M Umansky, X Q Xu, et. al., CPC 2011]**

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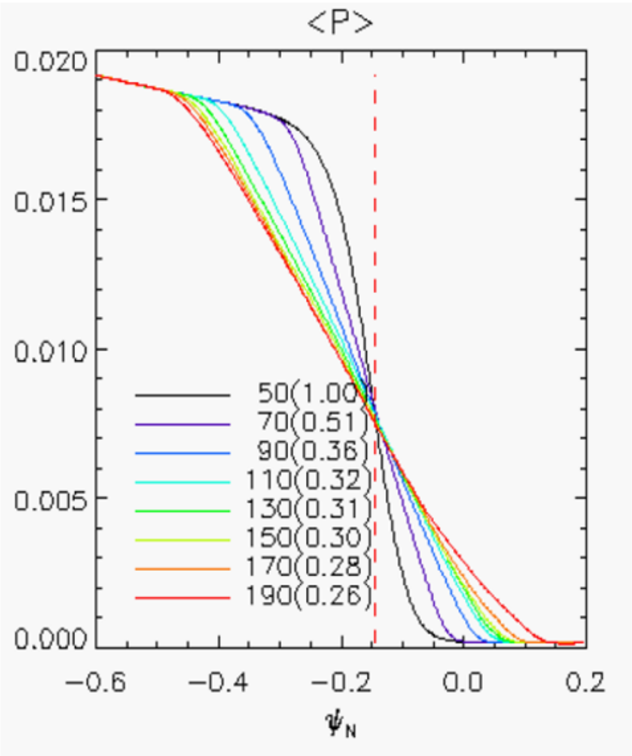
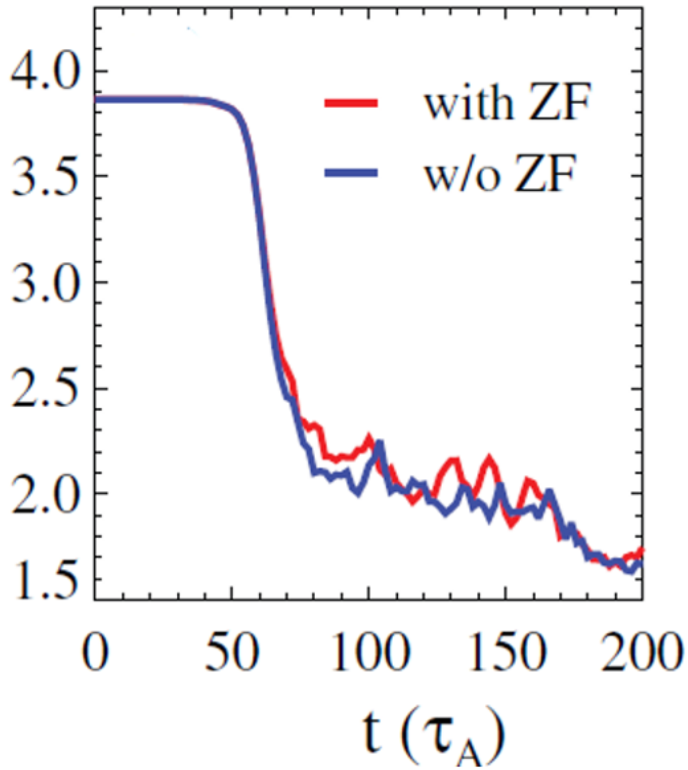
Pressure profile evolution

<P(r) >

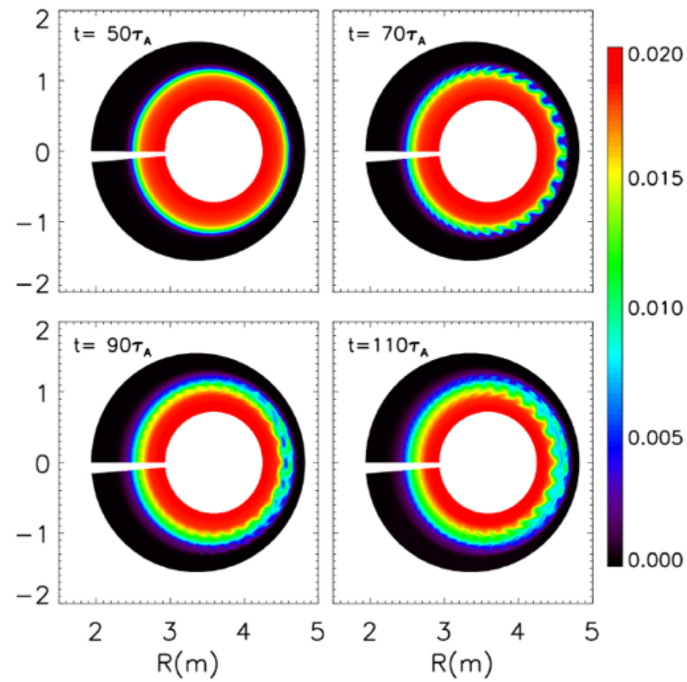


α_{max}

$\alpha = -2\mu_0 q^2 R_0 (dP_0/dr)/B^2$



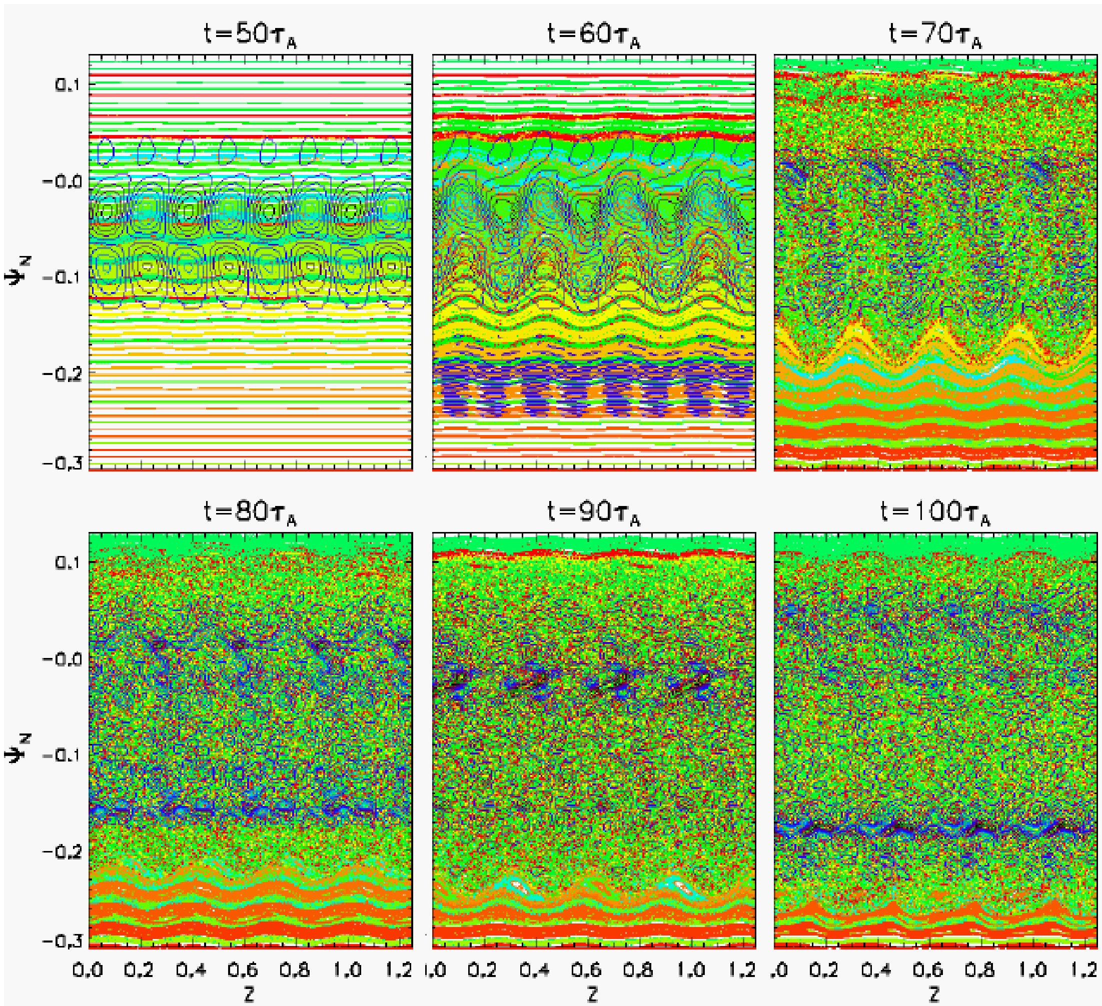
Pressure contour

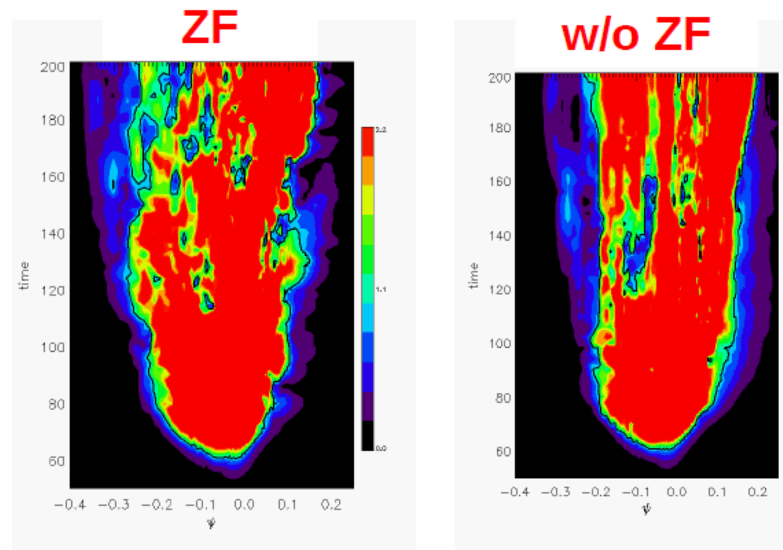


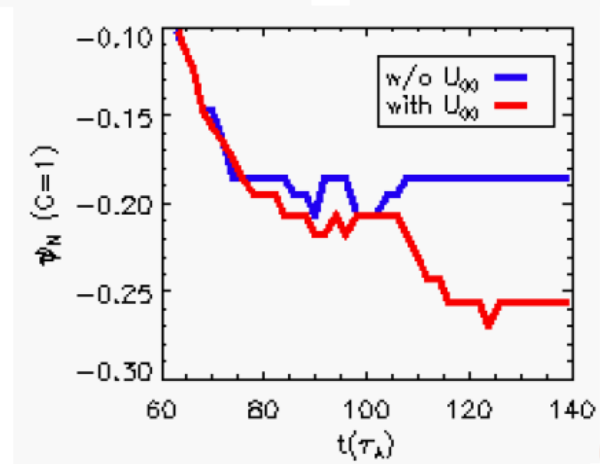
- Ideal MHD completely stabilized when $t > 65\ \tau_A$

Field line stochastization

Field line tracing shows a strong stochastization of magnetic field lines during a pedestal collapse → Deeper penetration when ZF is included

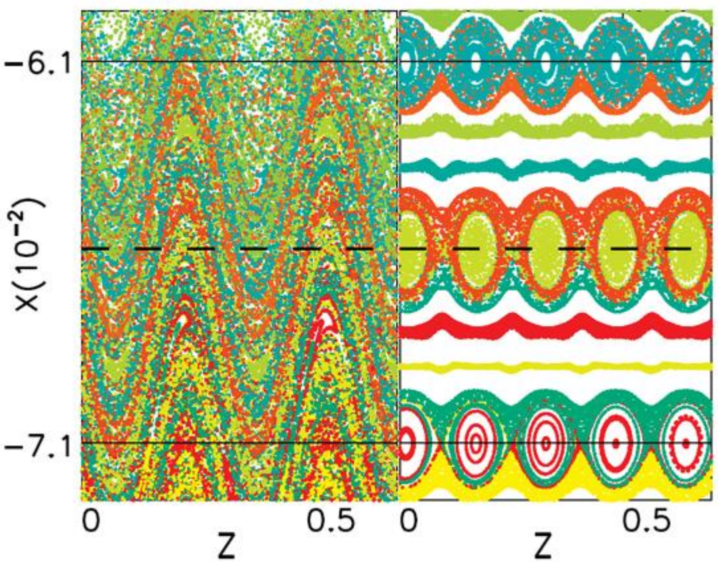


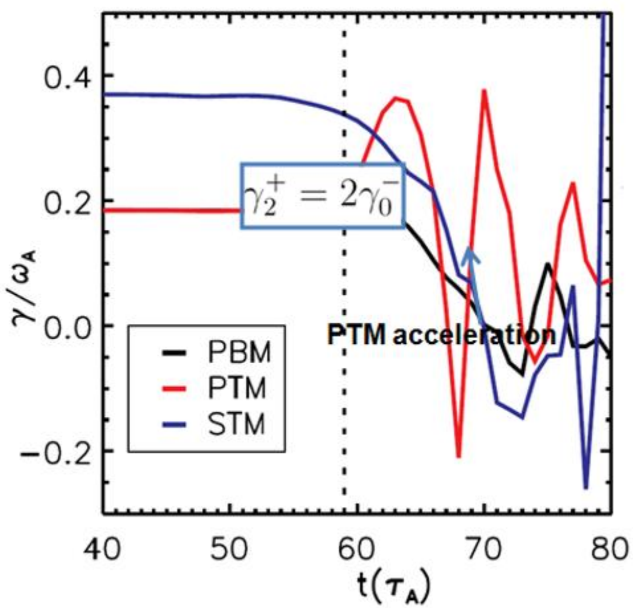


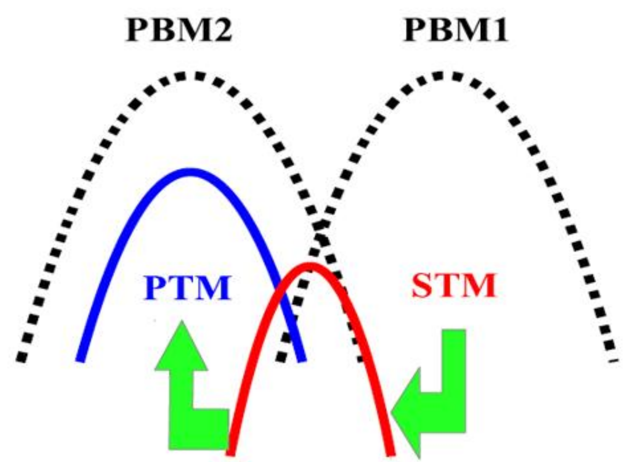


Dynamical process leading to stochastization

- Generation of a series of nonlinearly driven tearing modes (TMs) from initially unstable ballooning modes (BMs)
  - ✓ **Secondary Tearing Mode**: Agent of transferring K.E. of BM to PTM
  - ✓ **Primary Tearing Mode**: Stochastization through island overlap



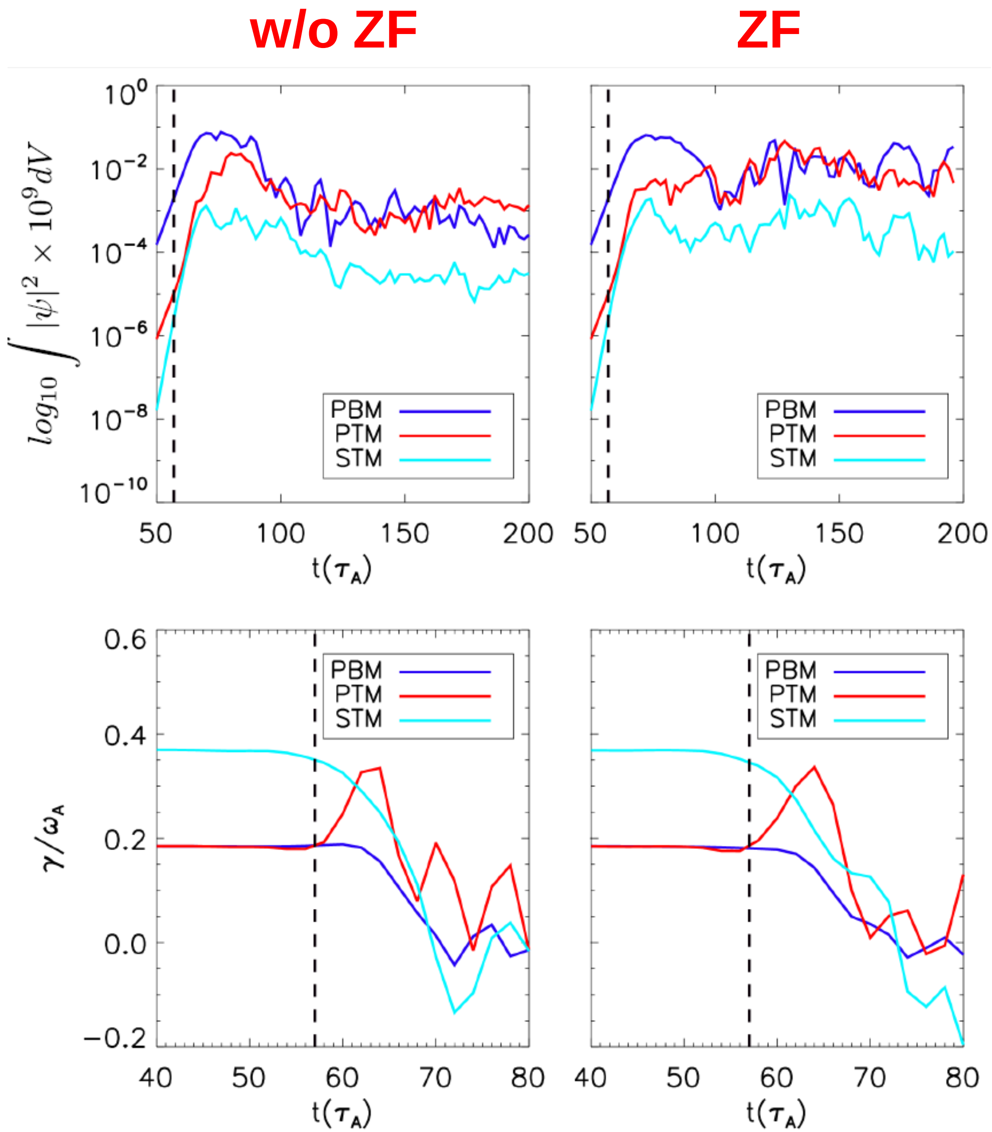




Dynamics of stochastization does not change by ZFs

- Nonlinear processes leading to field line stochastization are **identical**

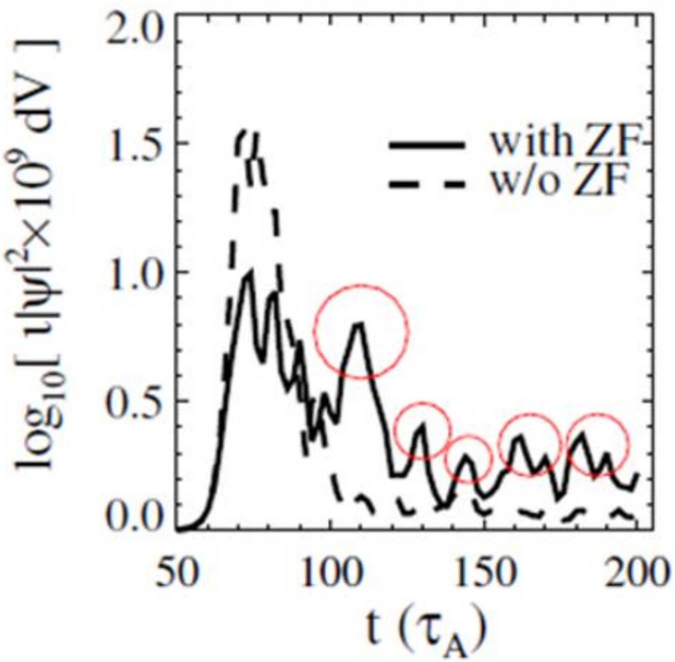
→ ZF does not alter NL interaction and the dynamics of field line stochastization

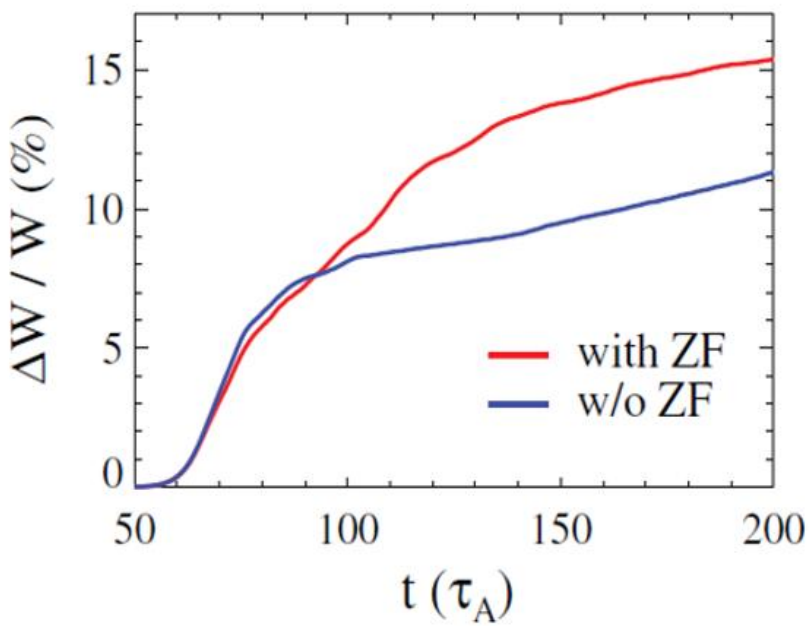


ZF governs dynamics in later stage of a crash!

- After an initial crash, several **smaller crashes** occur in later stage of a pedestal collapse (i.e. when t $\geq 100\tau_A$)

→ effectively **prolongs the crash time** and **enhances eventual energy loss**





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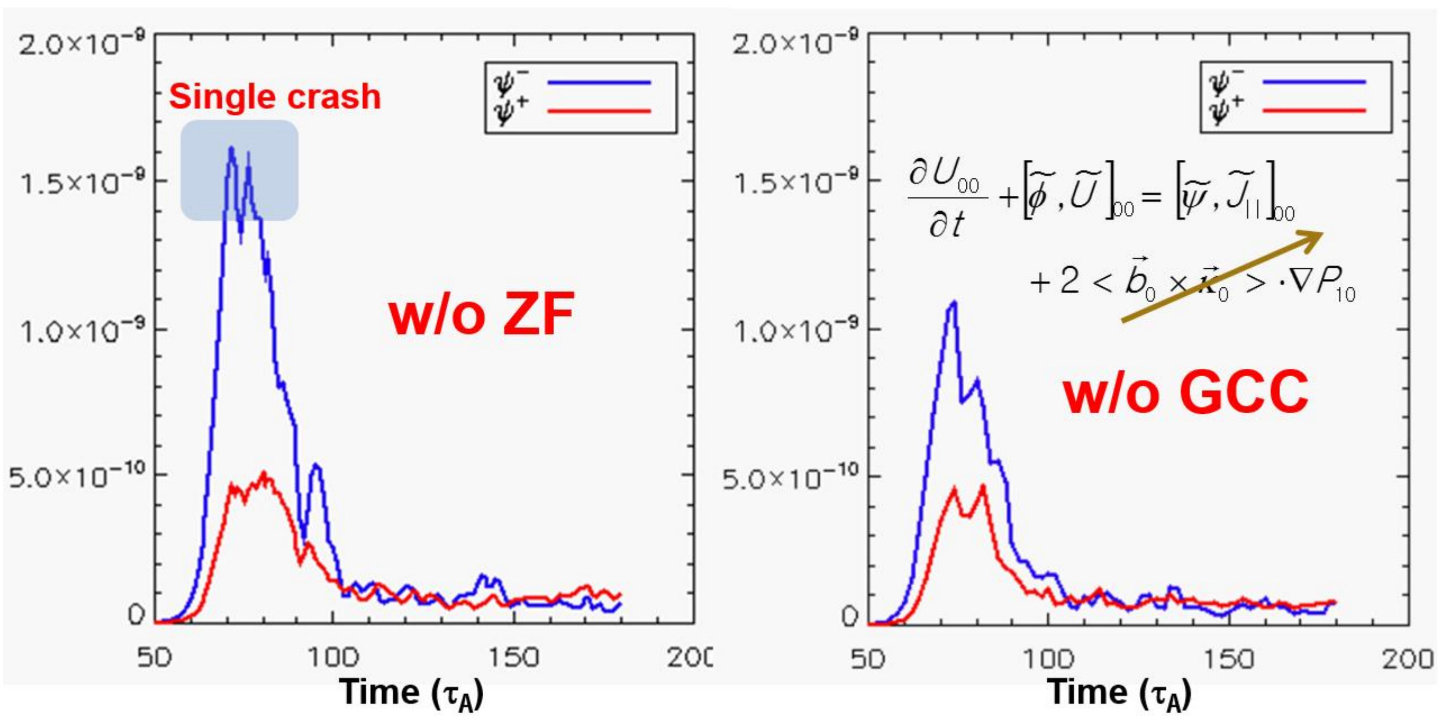
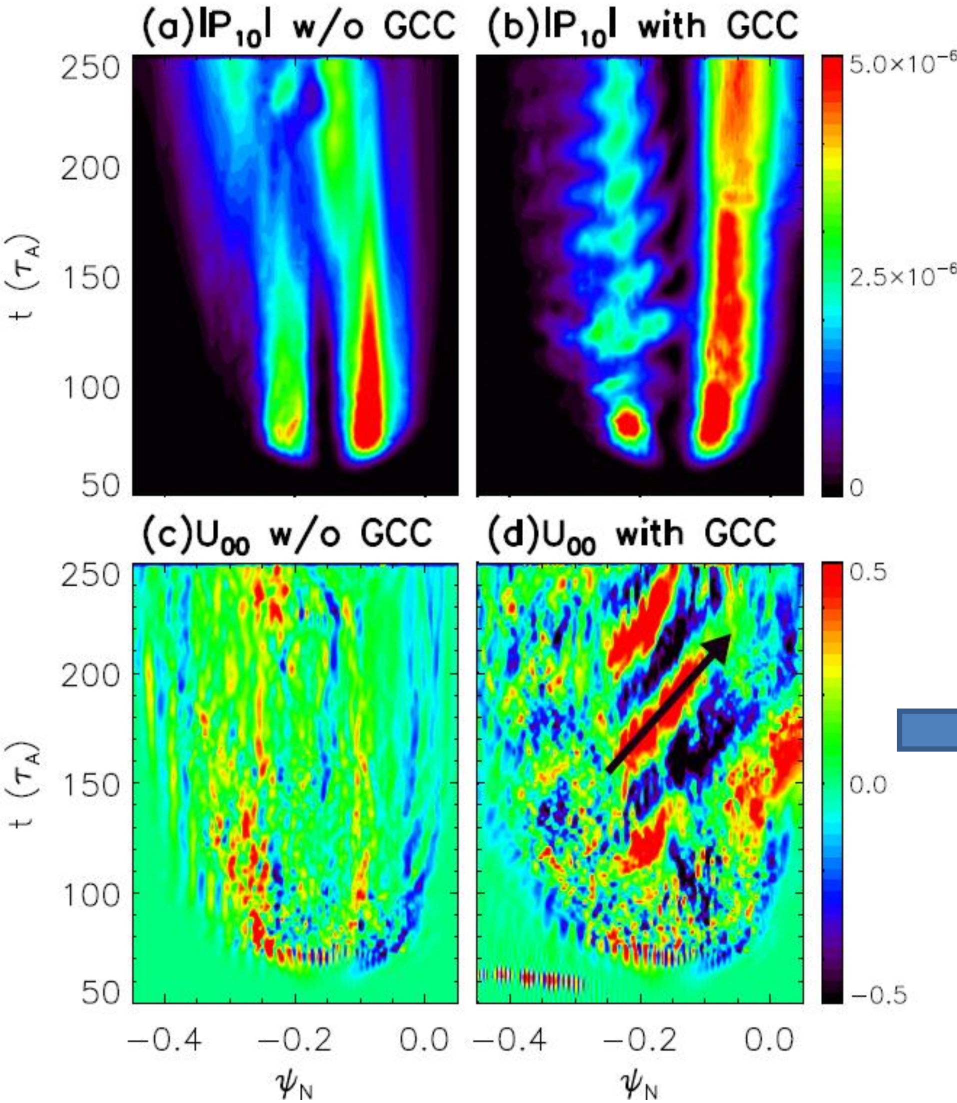
Geodesic curvature coupling likely plays a role

A similar evolution of an crash (with reduced initial amplitude) to the "w/o ZF" case happens when **the geodesic curvature coupling (GCC) term** in U_{00} is neglected

→ Strongly suggests the influence from GAM



GAM driven by GCC responsible!

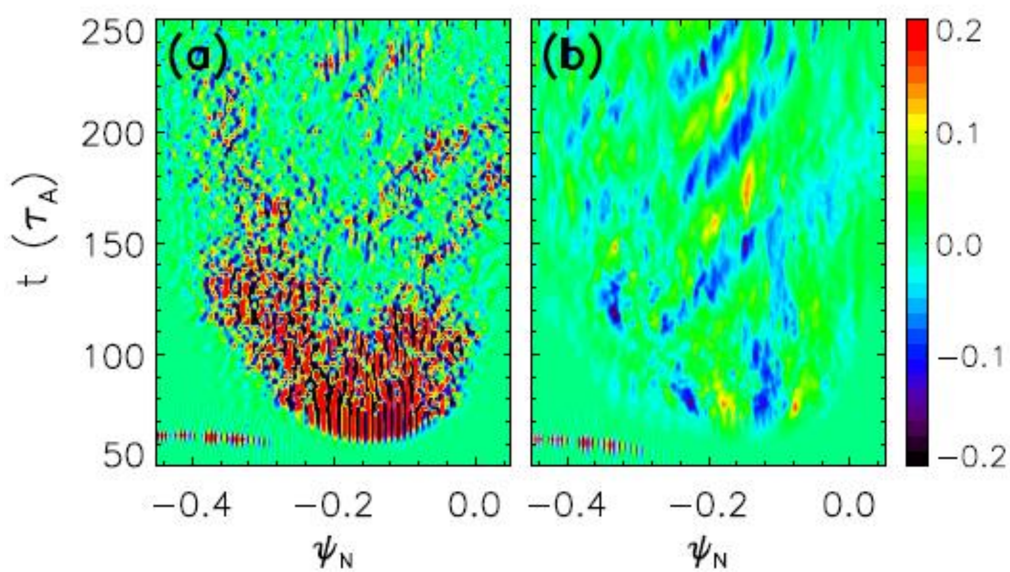


- $|P_{10}|^2$ is **persistent** even when t >120 τ_A.
- $< U_{00} >_{GCC}$ governs $<U_{00}>$ in later stage
- GAM oscillations found with period

$$\tau \simeq 50\tau_A \simeq 1.85 \times 10^{-5} sec.$$

$$\omega = 2\pi f \simeq \sqrt{20/3}\, c_s/R$$

Reynolds stress **GCC**



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Origin of secondary crashes

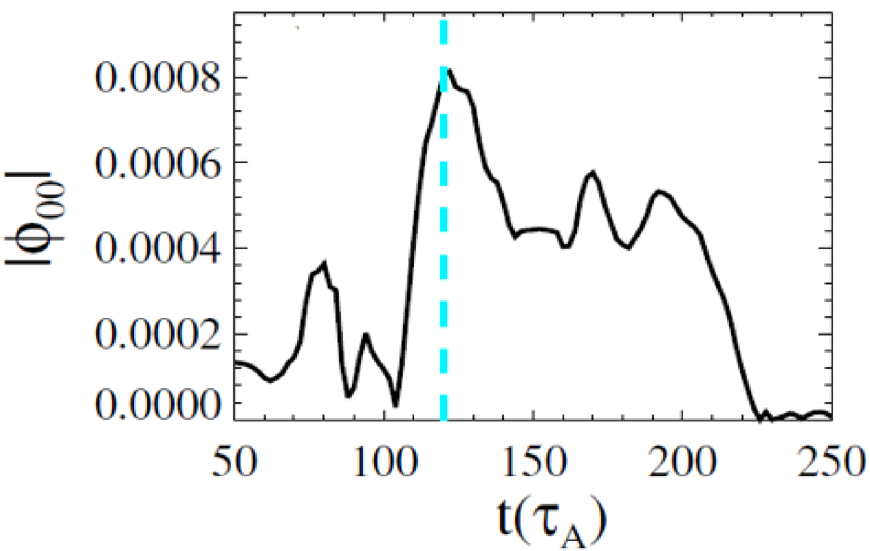
- Should be correlated to the GAM generation
- Two possibilities: (1) **ZF-driven instability** (2) Cross-phase change due to GAM
- Secondary crashes arise when Φ_{00} is driven large and ideal MHD completely stabilized.
- A linear analysis at t=120 suggests that an instability set in before the secondary collapse at ψ_N=-0.23 when $|\phi_{00}|$ is maximized

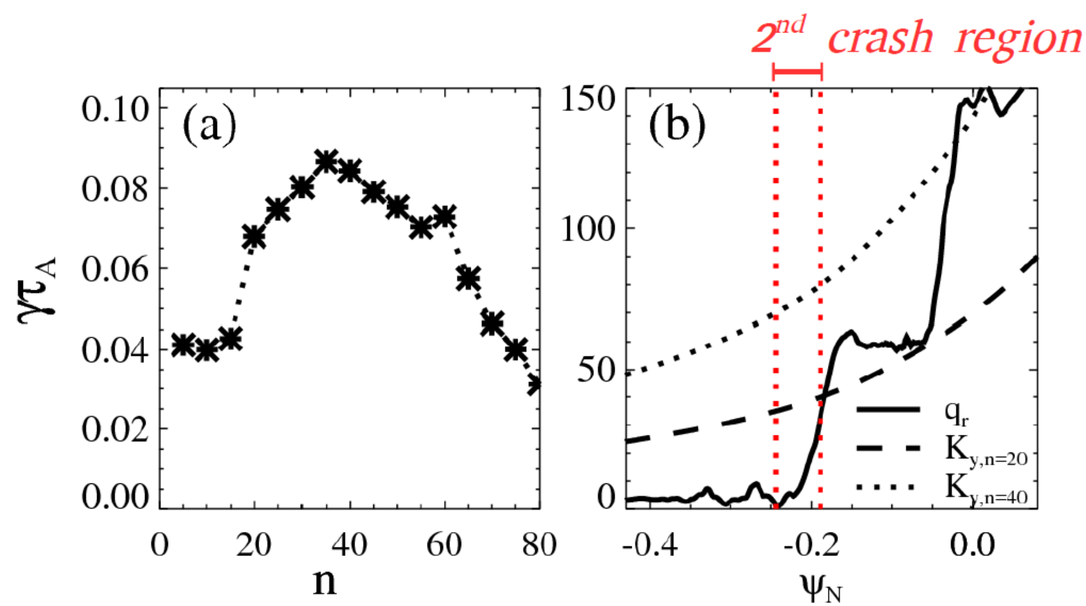
  → suggests the onset of ***an ZF-driven instability***

  → **analytic theory under development**

$$q_r = \frac{1}{\phi_{00}}\frac{d\phi_{00}}{dr}$$

K_y : poloidal mode number





Possible experimental connection

- An ELM crash may be decomposed into
  - a main crash for a short time ← origin: destabilization of ideal MHD
  - **a series of smaller crashes ← origin: ZF-driven mesoscale transport**

→ **Prolongation of ELM crash period** and **continuous increase of energy loss**

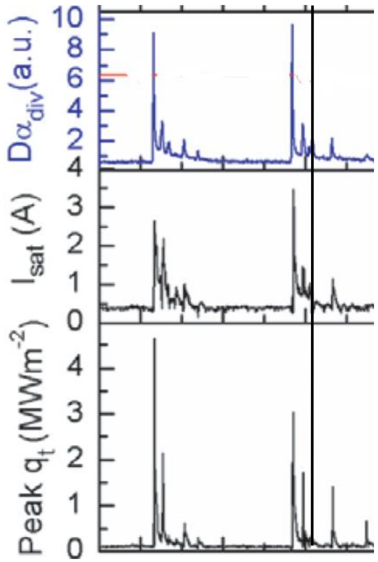
Signature of

Compound ELMs!!

[Zohm et. al., NF 1995],

[Wang et. al., NF 2013]

[J. Kim, Private Comm. 2015]



Shed light on the physics of Compound ELMs: Compound ELMs might originate from the NL interactions *between* GCC-driven GAM and fluctuations when the ideal MHD driver becomes stabilized.

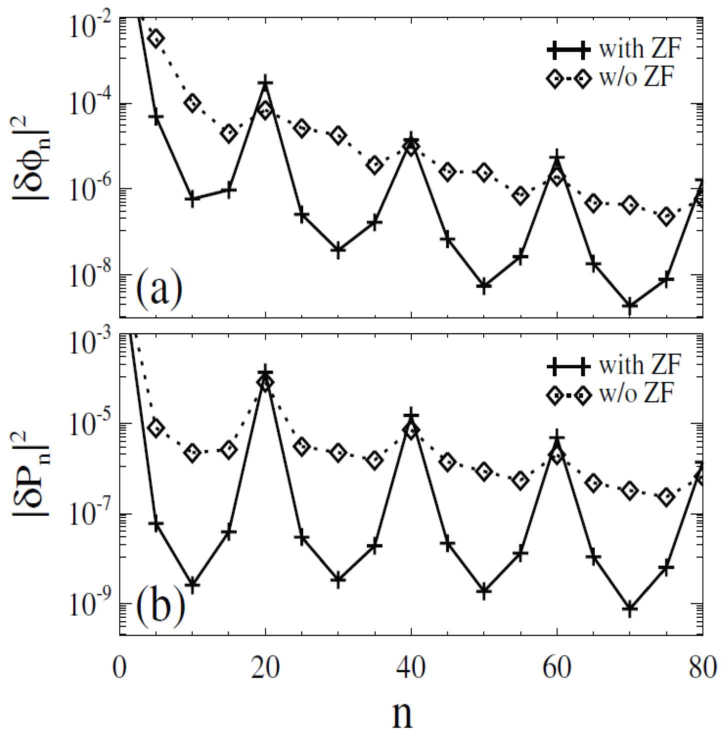
Fluctuation energy condensation

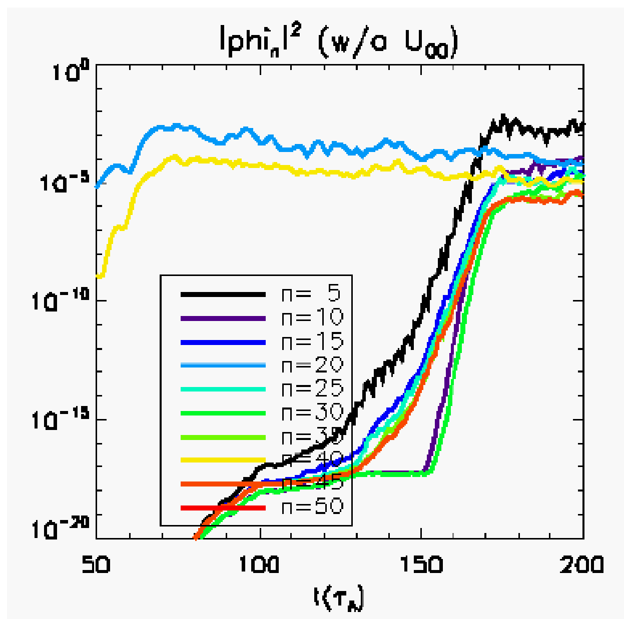
- **Delay of energy equipartition observed when ZF is included.**

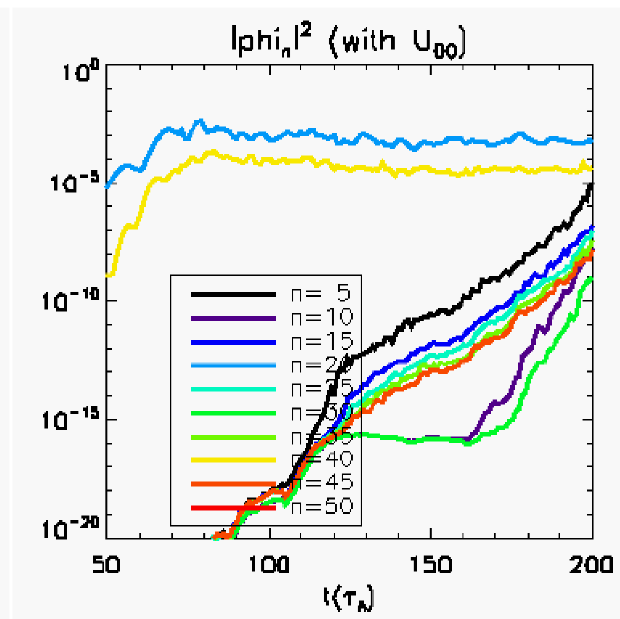
  → Strong condensation of fluctuation energy into ZFs

  → Suggests persistency of the dominant mode in the inter-ELM period

  → Self-consistent repetitive ELM simulations necessary







Conclusions

- Zonal flows may be driven strongly and affect pedestal collapse dynamics:
  - small secondary crashes followed by a big main crash
  - increase of net crash time and heat loss due to small crashes

  } **Compound ELMs?**

  - fluctuation energy condensation at harmonics of initially unstable modes

➡ **ELM dynamics must retain ZF evolution and transport physics self-consistently!!**

- Prediction:
  - Small crashes in prolonged ELMs may be accompanied with GAM
- Ongoing work:
  - Analytic theory for strong excitation of zonal flows by P_{10} & comparison to poloidal asymmetry driven ZF excitation **[Hassam, PoP 1994]**

    → Pellet induced ELMs?

Back-Ups

Simulation conditions

- Simulations done using the **BOUT++ framework** **[B Dudson, M Umansky, X Q Xu, et. al., CPC 2011]**
- No sources/sinks → Not flux-driven simulations
- Computational domain: -0.48≤ ψ_N ≤0.26
- Boundary conditions: Dirichlet (*U*), Neumann (*P*), zero-Laplacian ($A_{||}$)
- Monotonic q-profile: $1.19 \leqslant q \leqslant 5.0$ $0.66 \leqslant s = (r/q)(dq/dr) \leqslant 6.26$
- Initiate simulations from a strongly unstable initial pressure profile with a single unstable mode (n=20).

✓ Parameters:

Resistivity: $S = \mu_0 R V_A / \eta = 10^9$ $D_{RR} = \pi v_e R \sum_{m,n} (\delta B_{mn}/B_T)^2 \delta_{n,m/q}$

Hyper-resistivity **[Xu, et. al., PRL 2010]** $S_H = \mu_0 R^3 V_A / \eta_H = 10^{12}$