Long-term Alfvén instability nonlinear simulations and high-bandwidth linear eigenmode surveys

ID: 42

Donald A. Spong[1], Jacobo Varela[2], Luis Garcia[3]

[1]Oak Ridge National Laboratory, Oak Ridge, TN, USA

[2]National Institute for Fusion Science, Toki, Japan

[3]Universidad Carlos III de Madrid, Leganés, Spain

spongda@ornl.gov

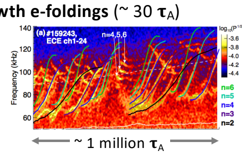
ABSTRACT

- Fast ion driven Alfvén instabilities are often observed to persist at sustained/steady amplitudes in experiments for 10^5 to 10^6 Alfvén times ($\tau_{Alfvén} = R_0/v_A$).
- Nonlinear saturation effects and mechanisms that lead to self-organized states are important since they influence the mode intermittency and associated fast ion transport levels.
- Gyro-Landau fluid models (TAEFL/FAR3D) have achieved very long simulation times for these instabilities (up to 50,000 Alfvén times).
- The GTC model is also used for long time gyrokinetic-PIC simulations

BACKGROUND

Alfvén instabilities are often observed to persist over 10^4 to 10^7 Alfvén times (R_0/v_A)

- **Observed time scales encompass many linear growth e-foldings (~ 30 τ_A)**
  - Nonlinear effects dominate
- **Intermittency also important**
  - As fast ion/wave system resolves imbalances
  - As changing plasma conditions change the mix of drive/damping



- **Studies of EP induced transport must account for conditions consistent with long-term sustainment**
  - Mode structure, equilibrium changes from zonal flows/currents
  - Dynamic adjustment in particle and energy flows
  - Fast ion distribution function imprinted by AE turbulence history

Reduced MHD + Moment equations with Gyro-Landau closures (nonlinearities indicated in magenta, diffusive terms in blue)

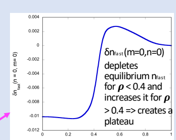
$$\frac{\partial\psi}{\partial t} = \frac{R}{B_\phi}\left(\mathbf{B}_0\bullet\nabla\phi + \tilde{\mathbf{B}}\bullet\nabla\phi\right) + \eta J_\zeta + \text{Thermal Ion FLR terms}$$

Generates zonal (n = 0) currents — Generates zonal (n = 0) flows

$$\frac{1}{\sqrt{g}}\frac{\partial U_\zeta}{\partial t} = \frac{\partial}{\partial t}\left[\nabla\times\left(\rho_m\sqrt{g}\mathbf{v}\right)\right]^\zeta = -\left[\nabla\times\left(\rho_m\sqrt{g}\mathbf{v}\bullet\nabla\mathbf{v}\right)\right]^\zeta + \left[\nabla\times\sqrt{g}\left(\tilde{\mathbf{J}}\times\mathbf{B}_{eq} + \mathbf{J}_{eq}\times\tilde{\mathbf{B}} + \tilde{\mathbf{J}}\times\tilde{\mathbf{B}}\right)\right]^\zeta$$
$$-\left[\nabla\sqrt{g}\times\nabla\left(p_{th} + T_{fast}\tilde{n}_{fast}\right)\right]^\zeta + \nabla_\perp^2 U_\zeta + \text{Ion/electron Landau damping terms}$$

$$\frac{\partial\tilde{p}_{th}}{\partial t} = -\mathbf{v}\bullet\nabla\tilde{p}_{th} - \mathbf{v}\bullet\nabla p_{th,eq} + \Gamma p_{th,eq}\nabla\bullet\mathbf{v} + \nabla_\perp^2\tilde{p}_{th}$$

$$\rho_m\frac{\partial v_{\parallel,th}}{\partial t} = -\rho_m\mathbf{v}\bullet\nabla v_{\parallel,th} - \hat{b}_{eq}\bullet\nabla\tilde{p}_{th} - \frac{\tilde{\mathbf{B}}}{B_{eq}}\bullet\nabla p_{th,eq} + \nabla_\perp^2 v_{\parallel,th}$$



Generates local flattening (n = 0) in fast ion density, by cancelling part of drive term

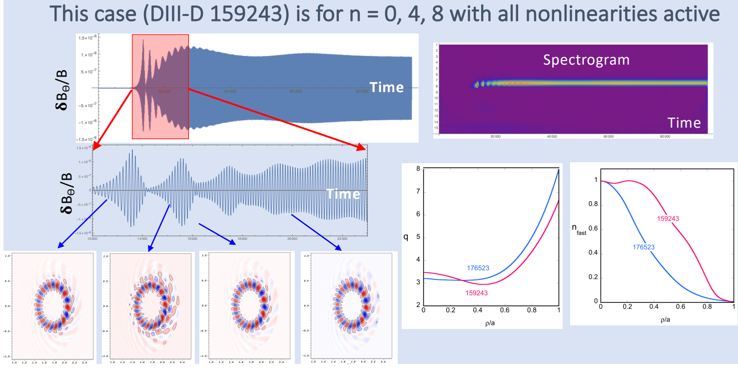
$$\frac{\partial n_{fast}}{\partial t} = -\mathbf{v}\bullet\nabla n_{fast} - \mathbf{v}_d\bullet\nabla n_{fast} - n_{f0}\nabla_\parallel v_{\parallel,fast} - n_{f0}\left(\mathbf{v}_d\bullet\nabla - \Omega_*\right)\left(\frac{e\phi}{T_{fast}}\right) + \nabla_\perp^2 n_{fast}$$

$$\frac{\partial v_{\parallel,fast}}{\partial t} = -\mathbf{v}\bullet\nabla v_{\parallel,fast} - \mathbf{v}_d\bullet\nabla v_{\parallel,fast} - \left(\frac{\pi}{2}\right)^{1/2}\bar{v}_{fast}\left|\nabla_\parallel\right| v_{\parallel,fast} - T_{fast}\nabla_\parallel n_{fast} - e n_{f0}\Omega_*\left(\frac{\psi}{R}\right) + \nabla_\perp^2 v_{\parallel,fast}$$

where $\mathbf{v} = \frac{\hat{b}_{eq}\times\nabla\phi}{B}$ $\nabla_\parallel = \left(\hat{b}_{eq}\bullet\nabla\right)$ $\hat{b}_{eq} = \frac{\mathbf{B}_{eq}}{B}$ $\bar{v}_{fast} = \sqrt{\frac{T_{fast}}{M_{fast}}}$ $\Omega_* = \frac{T_{fast}}{eBn_{f0}}\nabla n_{f0}\bullet\hat{b}_{eq}\times\nabla$

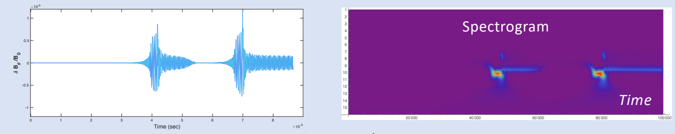
Simulation results

This case (DIII-D 159243) is for n = 0, 4, 8 with all nonlinearities active

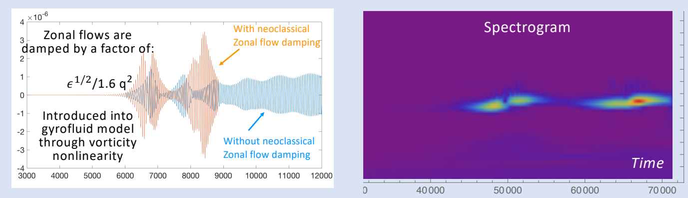


Simulation results

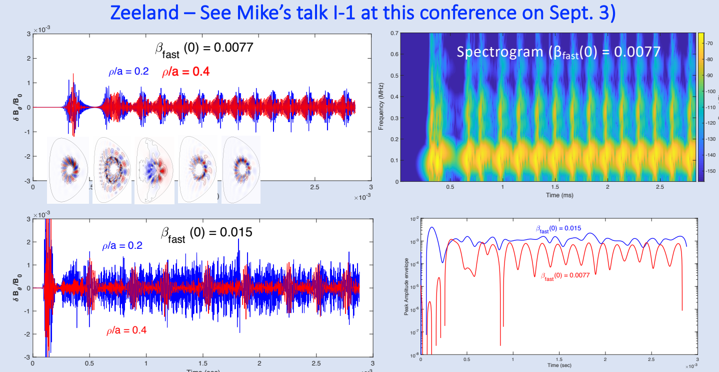
Bursting amplitudes if fast ion nonlinearities turned off => no profile flattening – only zonal flows/currents => Source instantly fills in losses.



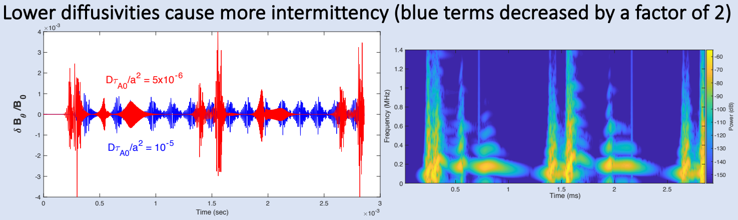
Neoclassical flow damping effects (Hinton/Rosenbluth) increases amplitude and intermittency



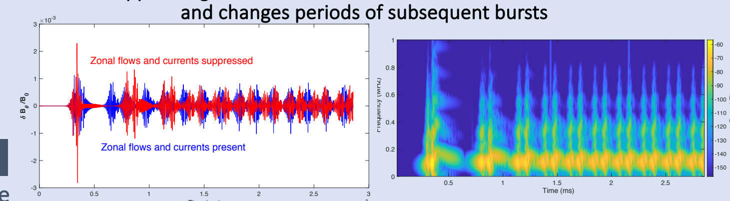
Longer time simulations(up to 3 msec) show repeating predator-prey phenomena - DIII-D # 176523 (Through recent collaboration with M. Van Zeeland – See Mike's talk I-1 at this conference on Sept. 3)



Lower diffusivities cause more intermittency (blue terms decreased by a factor of 2)



Suppressing zonal flows and currents increases initial bursts and changes periods of subsequent bursts



CONCLUSION

- Long-term multi-mode nonlinear simulations of Alfvén instabilities quite feasible with the TAEFL model
- Simulations show the importance of
  - Source/sink modeling => intermittency effects, diffusive transport over resonance regions
  - Regulation of mode growth by nonlinearly driven n = 0 components
  - Neoclassical flow damping effects important
- Long-term nonlinear effects distort linear mode structure, introduce frequency chirping, modify fast ion profiles, and drive zonal flows

ACKNOWLEDGEMENTS / REFERENCES

- *Work supported by U.S. Department of Energy, Office of Science Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC and the US DOE SciDAC GSEP Center. This research used the National Energy Research Scientific Computing Center which is supported by the Office of Science of the US Department of Energy under Contract Number DE-AC02-05CH11231.*