Stability of Edge Localized Modes with Flow Shear

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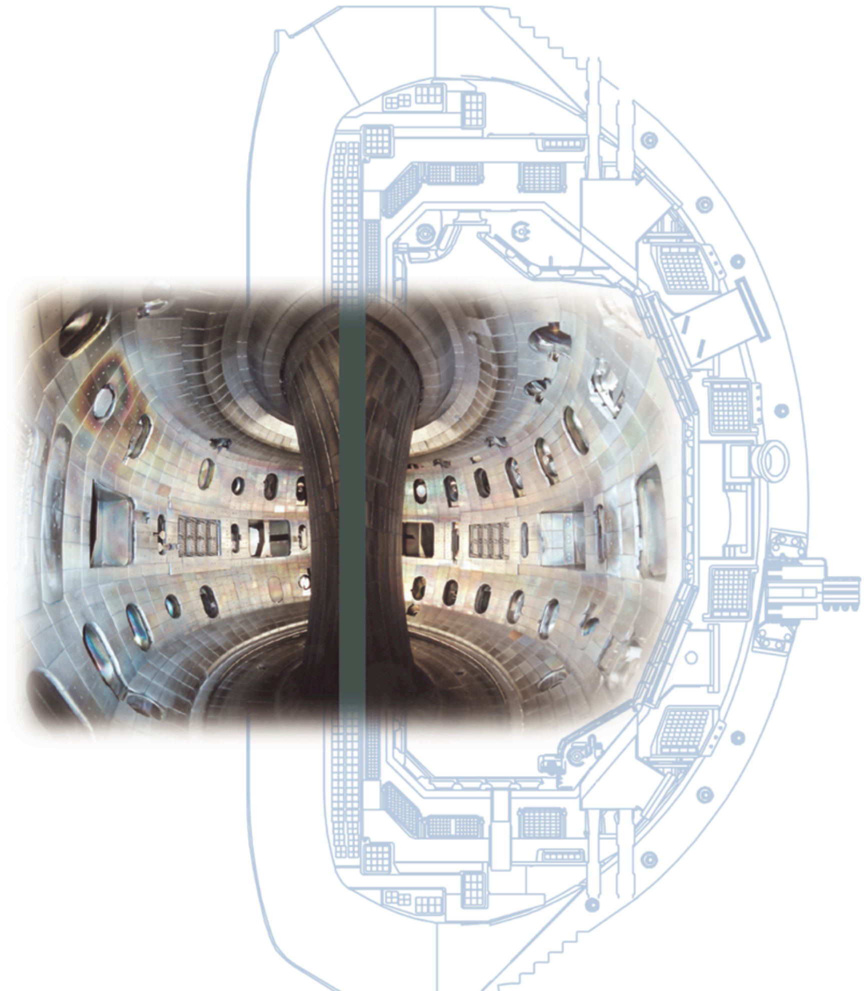

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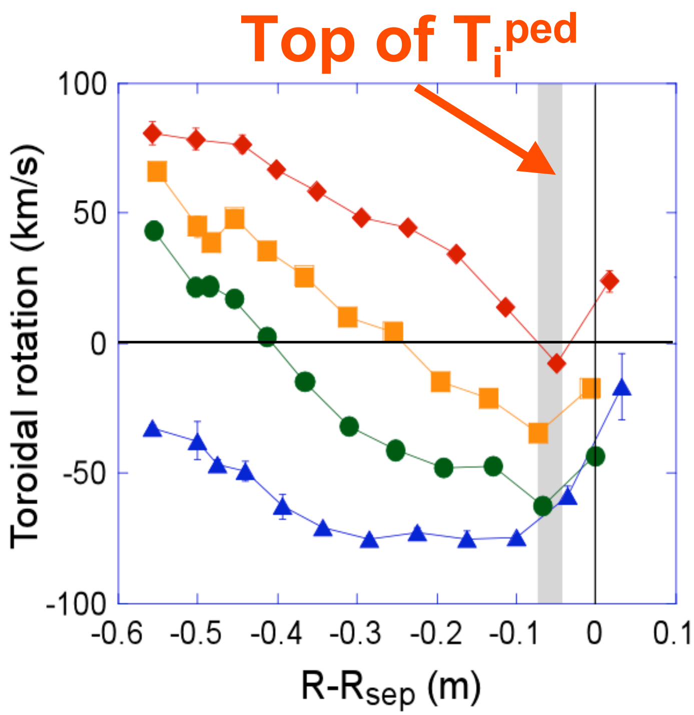
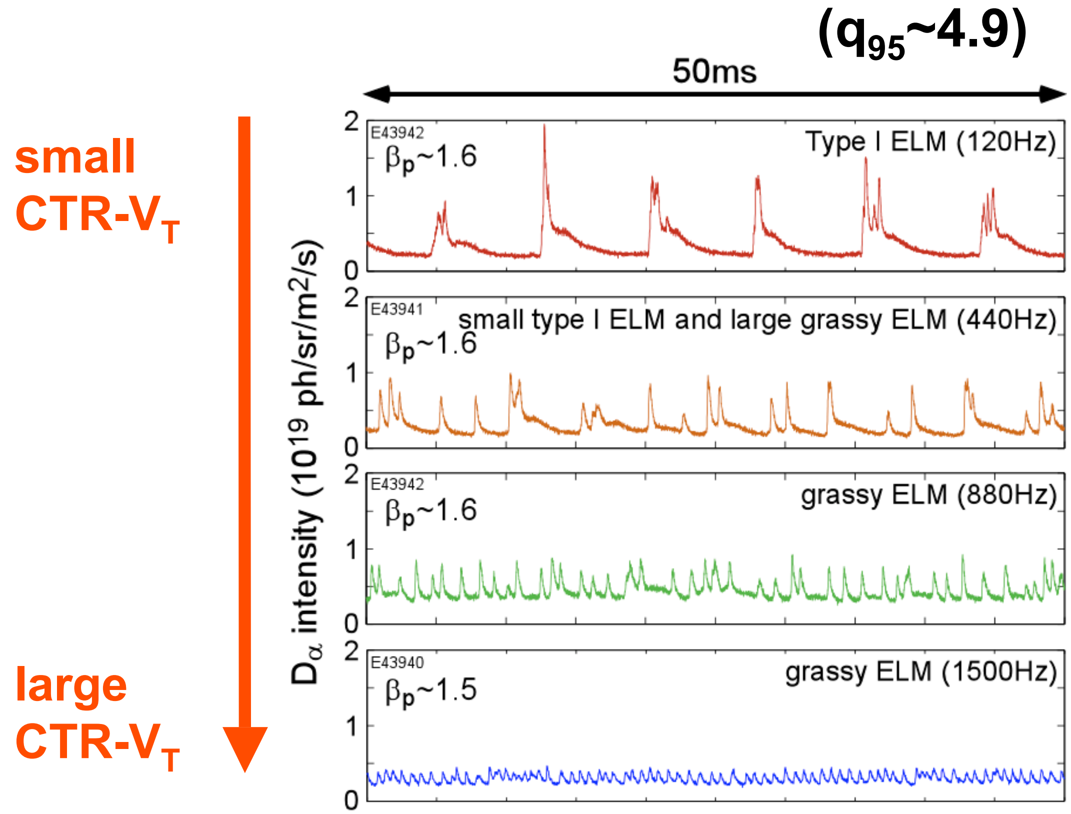
Motivation: JT60-U experiments suggest toroidal flow can strongly effect ELM behavior

- Larger counter rotation leads to smaller ELM and higher f_{ELM}.
- **DIII-D now has reversed a neutral beam injection (NBI) and can now conduct similar experiments.**
- What is the physics of this effect?





See: N. Oyama, et al., Nucl. Fusion **45**, 871 (2005)

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JT-60

Outline: Toroidal Flow Effects on ELMs

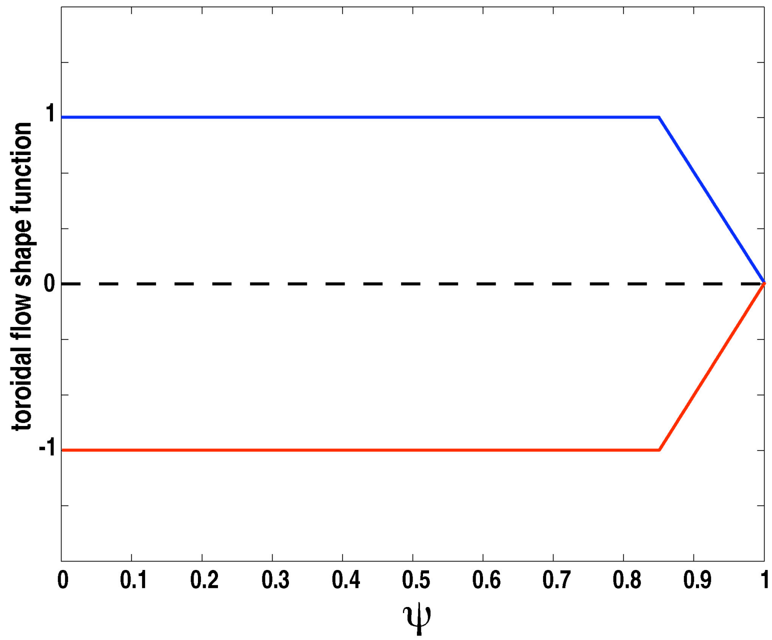
- **NIMROD and ELITE show effects of flow shear can either stabilize or destabilize linear growth rates and affects eigenfunctions.**
- **Simple g-mode model describes basic physics of flow shear effect in ideal MHD.**
- **Nonlinear results show eventual state of evolution of modes strongly affected by flow shear, with localization of the mode structure and shearing of vortices.**

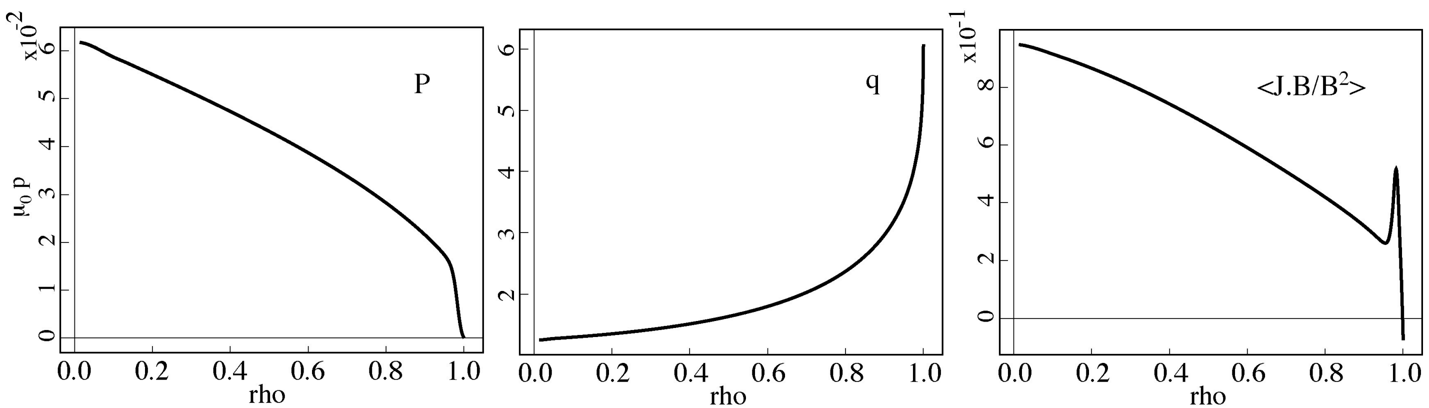
Simple Equilibria constructed to emulate experiment for study with NIMROD

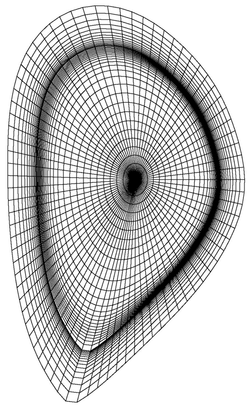
Flow profile modeled in NIMROD with constant gradient across pedestal region and rigid rotation in core.

Separatrix flow held 0.

Other profiles and shape are characteristic of DIII-D H-mode equilibria.







Resistive MHD Equations Used to Numerically Model Evolution in NIMROD change Effect of Flow

Poloidal plane represented by finite element grid, toroidal direction by spectral decomposition

Viscosity, Resistivity and Anisotropy can be removed to model the Ideal MHD Equations

Viscosity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \bar{V} = 0$$

$$\rho \frac{d\bar{V}}{dt} = \bar{J} \times \bar{B} - \nabla p - \nabla \cdot \Pi$$

$$\bar{E} = -\bar{V} \times \bar{B} + \eta \bar{J}$$

Resistivity

$$\frac{\partial T}{\partial t} + \bar{V} \cdot \nabla T + \Gamma T \nabla \cdot \bar{V} = -(\Gamma - 1)\nabla \cdot \bar{q} + (\Gamma - 1)Q$$

$$\bar{q} = -(\kappa_{||} - \kappa_{\perp})\nabla_{||} T - \kappa_{\perp} \nabla T$$

Thermal Anisotropy

Simple slab g-mode model can elucidate basic physics of flow effects.

Ideal model is general solution to MHD (full electromagnetic) stability against a gravitational force in the presence of flow.

1D shooting method used to solve for eigenvalue.

$$\bar{V} = v_{1x}\hat{x} + v_{1y}\hat{y} + (V_{oz}(x) + v_{1z})\hat{z}$$

And the equilibrium is (with constant gradients):

$$\frac{\partial}{\partial x}(p_o + \frac{B_o^2}{2\mu_o}) = -\rho g$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \bar{V} = 0$$

$$\rho \frac{d\bar{V}}{dt} = -\nabla p + \bar{J} \times \bar{B} + \rho g$$

$$\bar{E} = -\bar{V} \times \bar{B}$$

$$\frac{\partial p}{\partial t} + \bar{V} \cdot \nabla p + \Gamma p \nabla \cdot \bar{V} = 0$$

Assume complex exponential with eight equations, eight unknowns

$$\exp(\gamma t + i k_y y + i k_z z)$$

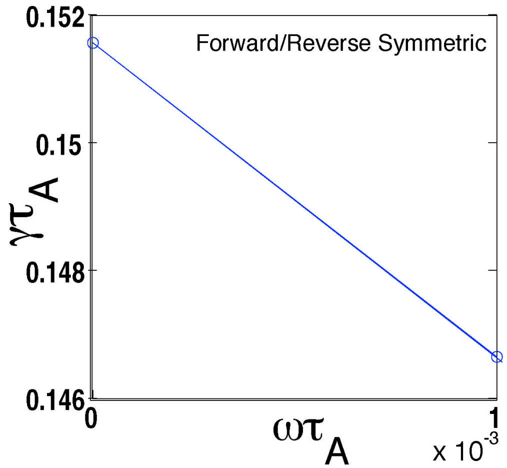
$$\rho_1, v_{1x}, v_{1y}, v_{1z}, B_{1x}, B_{1y}, B_{1z}, p_1$$

System reduces to set of two coupled ODEs

Profiles and parameters of simple model chosen to approximate those in DIII-D equilibria.

$$\frac{\partial v_{1x}}{\partial x} = A_{11} v_{1x} + A_{12} p^*$$

$$\frac{\partial p^*}{\partial x} = A_{21} v_{1x} + A_{22} p^*$$



$$A_{11} = \frac{iD\frac{\partial\omega}{\partial x} + \rho_o^2 g\gamma^3}{D\gamma}$$

$$A_{12} = \frac{-\gamma(\rho_o^2\gamma^4 + Dk^4)}{DS}$$

$$A_{21} = \frac{-S + g\frac{\partial\rho_o}{\partial x} + S\frac{g^2\rho_o^2}{D}}{\gamma}$$

$$A_{22} = \frac{-g\rho_o^2\gamma^2}{D}$$

$$D = \rho_o B_o^2\gamma^2 + \Gamma p_o S$$

$$S = \rho_o\gamma^2 + F^2$$

$$\omega = k_z V_{zo}$$

$$\gamma = \gamma_R + i(\gamma_I + \omega)$$

$$F = \bar{k}\cdot\bar{B}_o$$

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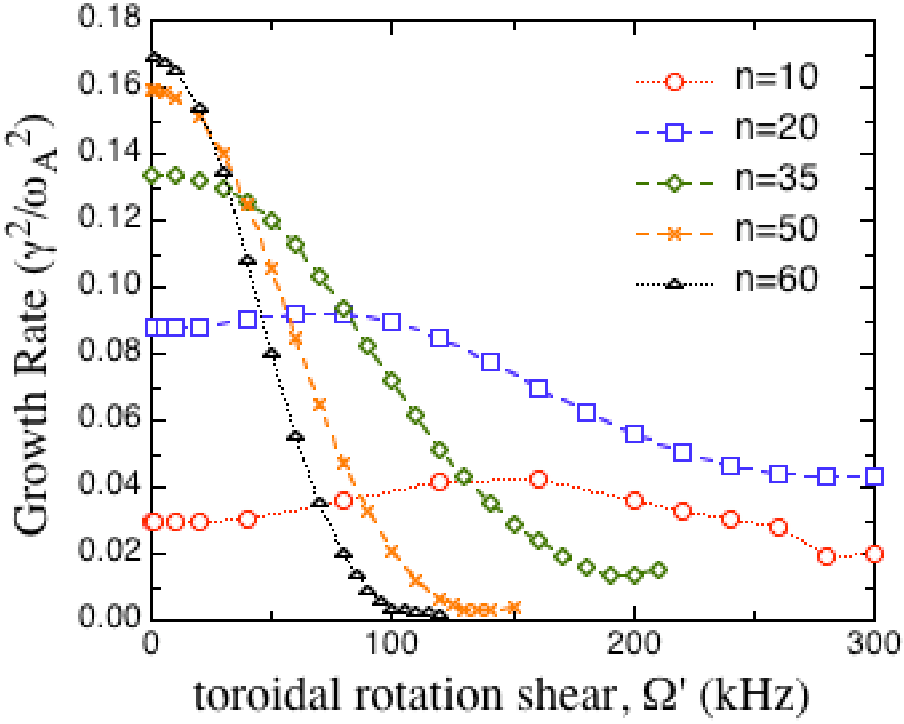
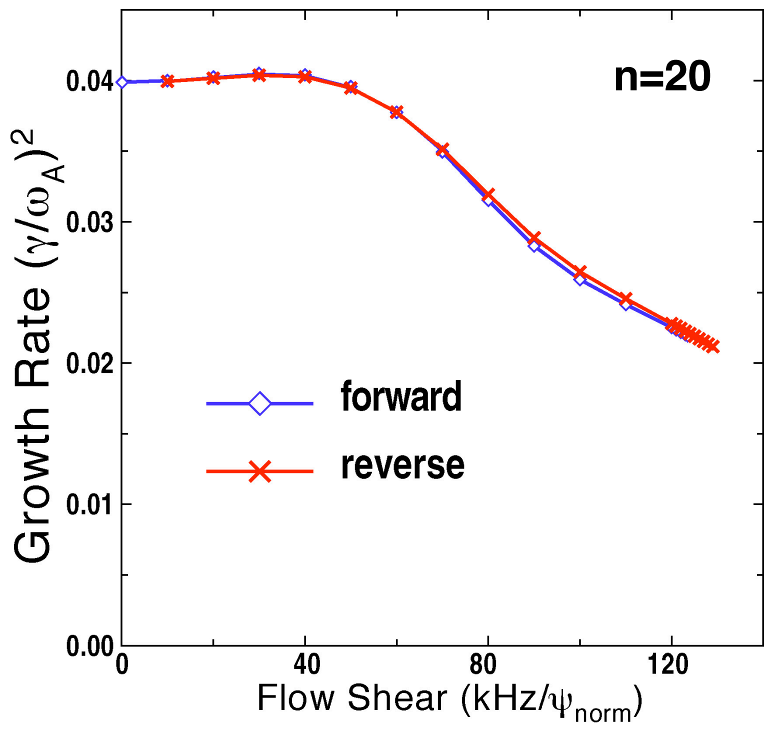
Flow shear can be linearly stabilizing or destabilizing to modes depending on details

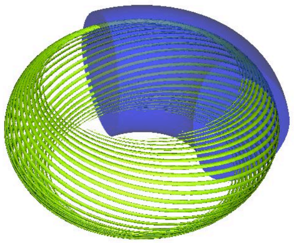
ELITE finds a similar stabilizing effect for the model equilibria with flow shear, but for other configurations can be destabilizing.

NOTE: Different computational modeling and dissipative effects may/will affect these results.



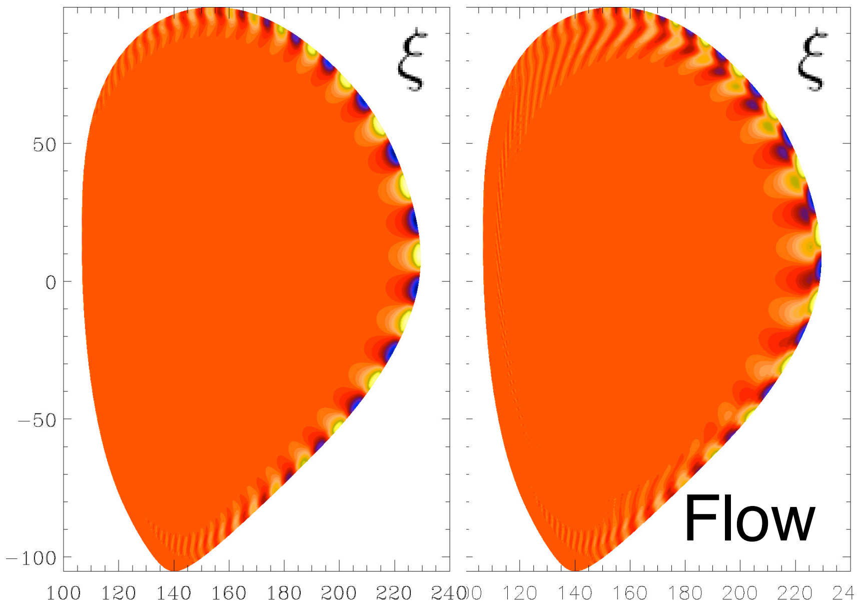


NIMROD and ELITE show strong affect on eigenfunctions from flow shear

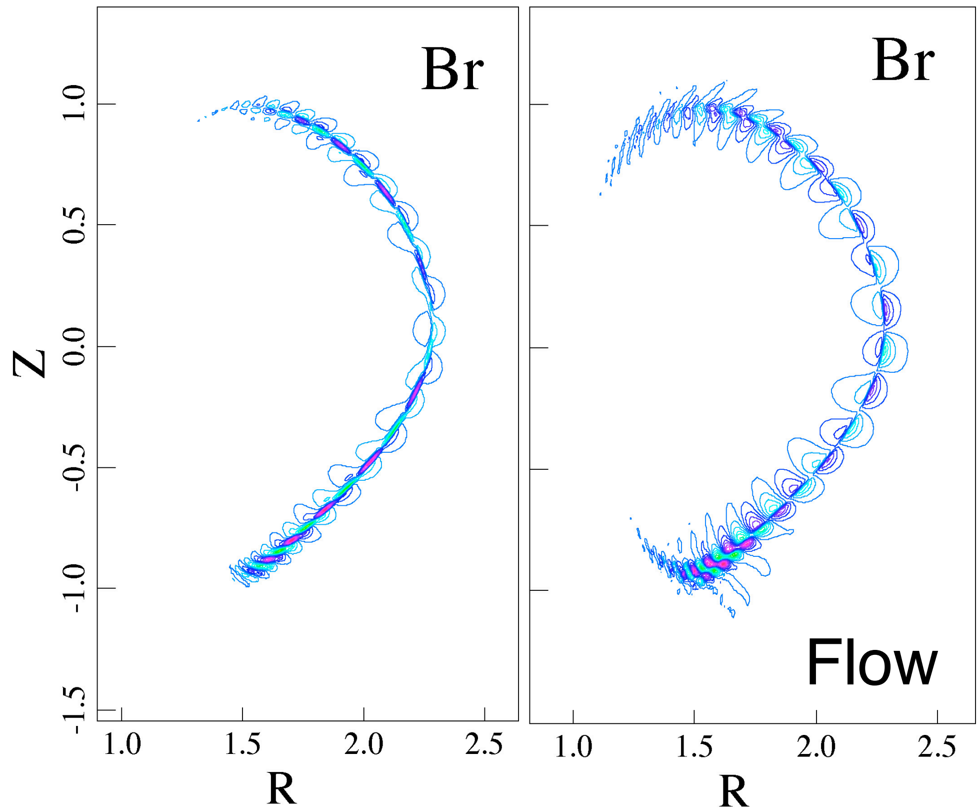


NIMROD and ELITE in qualitative agreement on eigenfunctions

ELITE



NIMROD



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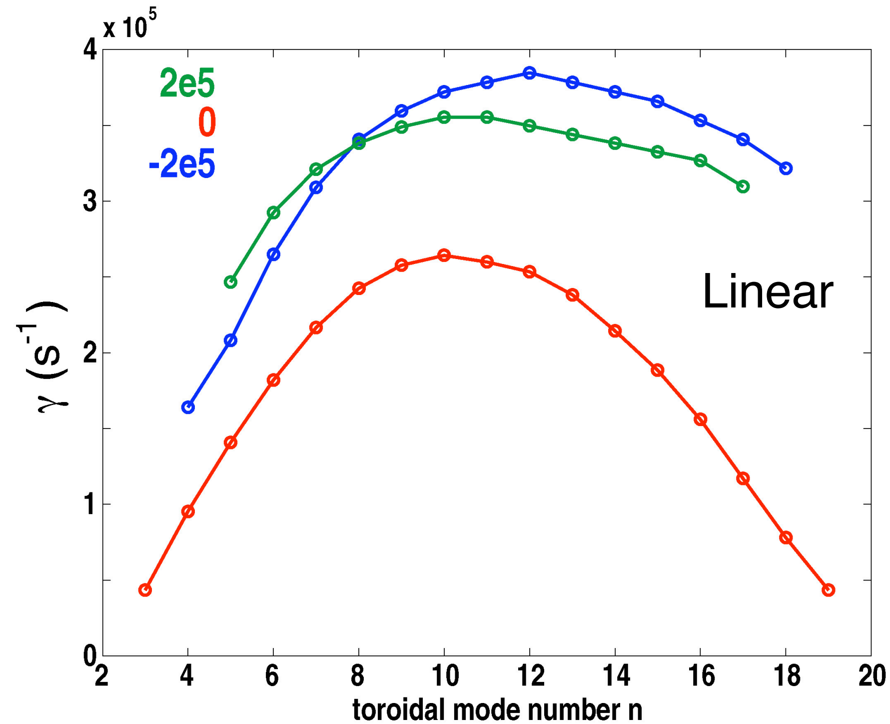
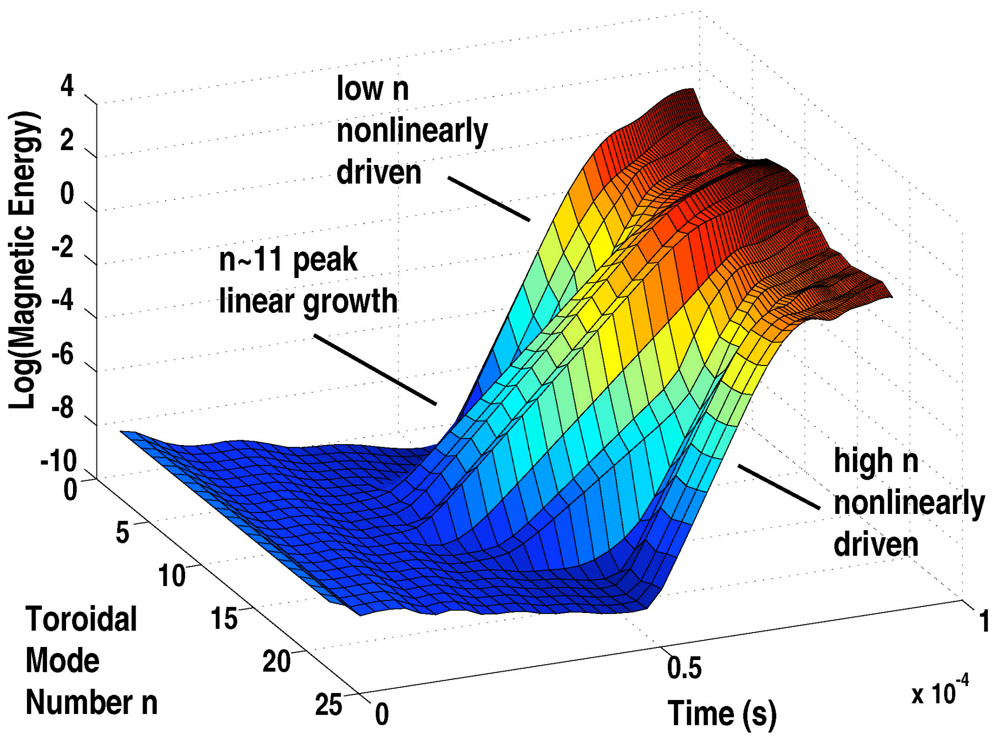
Nonlinear Study with NIMROD is beginning an exploration of how flow affects ELM evolution

- Linear spectrum (non ideal, anisotropic) shows peak growth at n~12.
- Nonlinear coupling drives low n and high n unstable.
- Flow destabilizes linear spectrum, but does not change qualitative nonlinear picture





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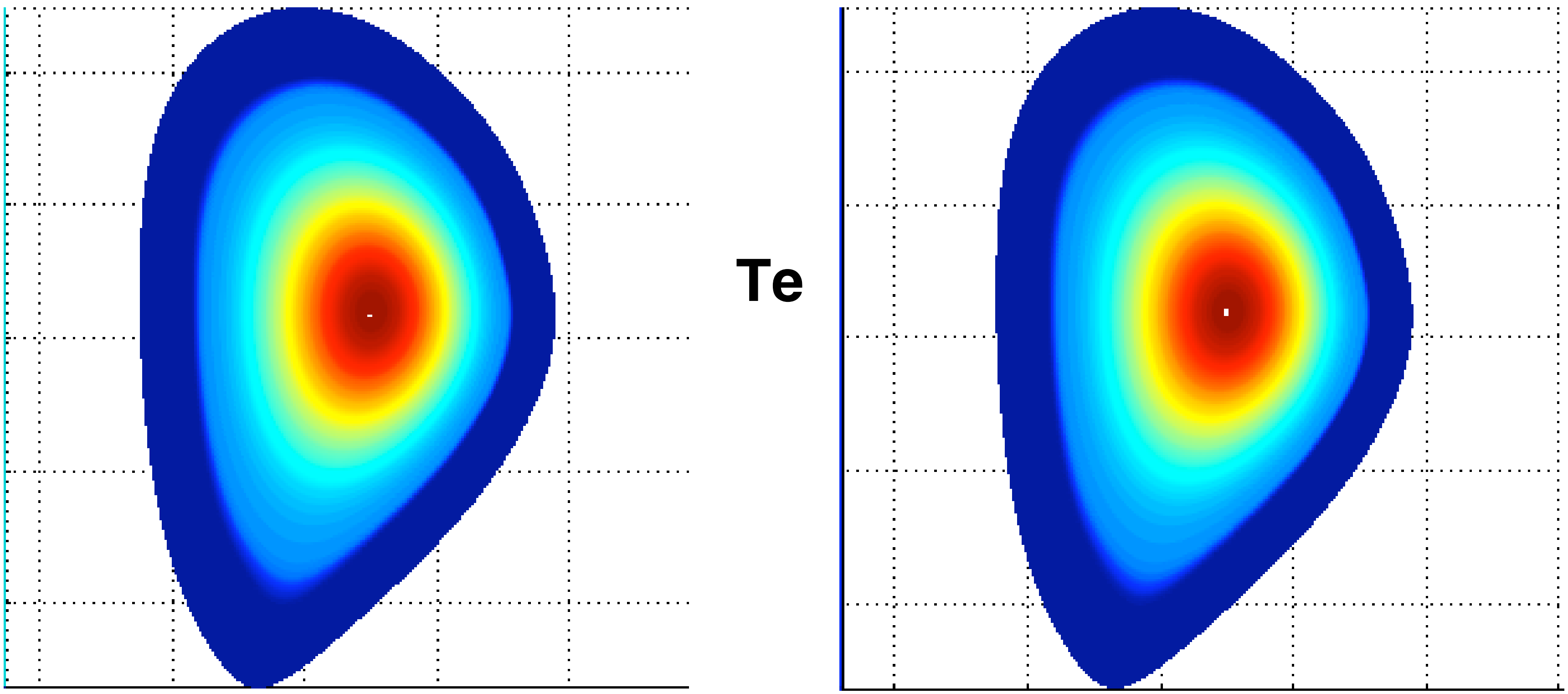
ELM localized nonlinearly by static imposed flow shear

Without flow, the high temperature filaments propagate to the wall

With flow, the perturbation is dragged by the fluid, significant localization in long term evolution



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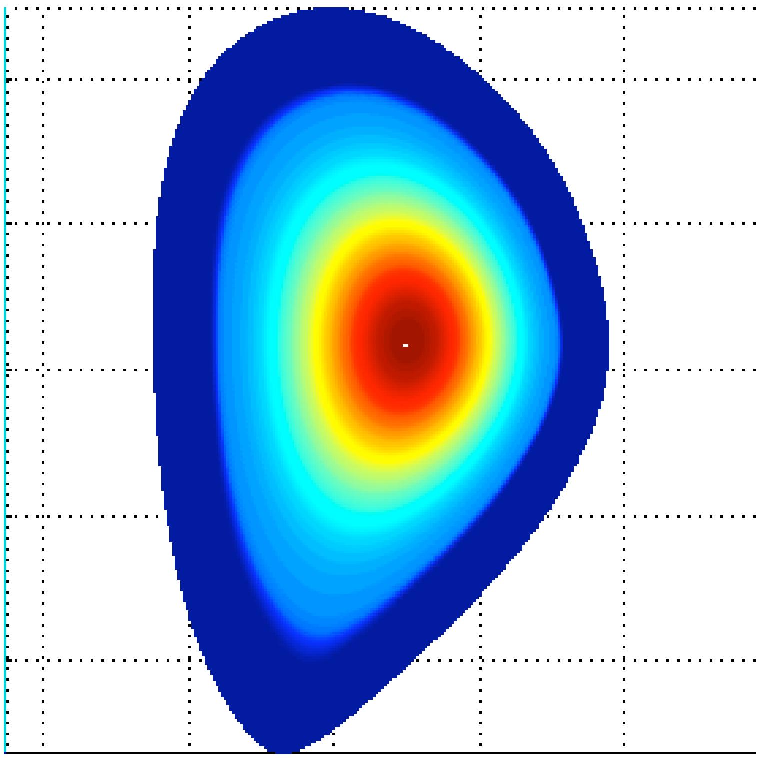

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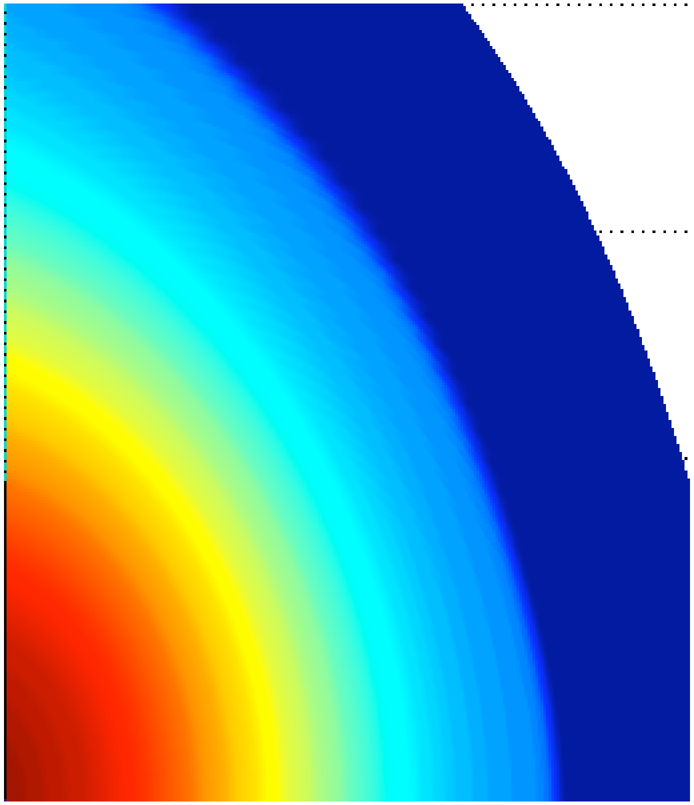
Vortices form and the filaments are sheared off, and do not propagate deep into the vacuum region



Summary of Results

- In general, flow shear can be linearly stabilizing or destabilizing depending on details of the equilibria and the model.
- NIMROD linear results show destabilization from flow, but little change to the shape of the spectrum.
    - nonlinear evolution not strongly affected by linear growth rate changes in this case
- Nonlinear evolution is strongly affected by flow shear. Significant localization of the mode structure occurs when vortices are formed as filaments propagate outward and are sheared off.