EXTENDED-MHD STUDIES OF FLOW-PROFILE EFFECTS ON EDGE HARMONIC OSCILLATIONS IN QH-MODE DISCHARGES

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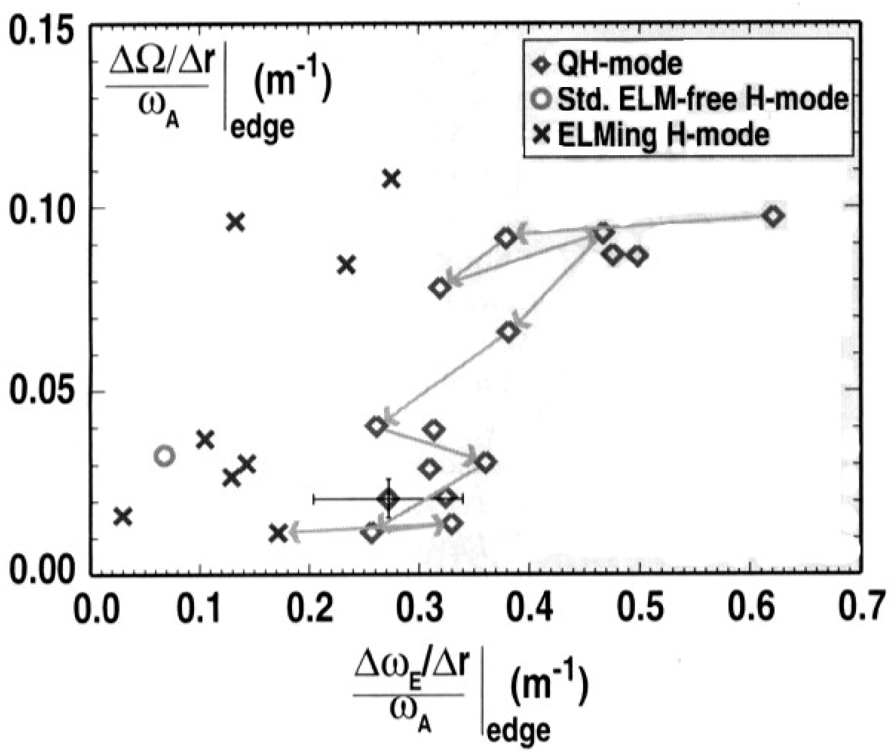
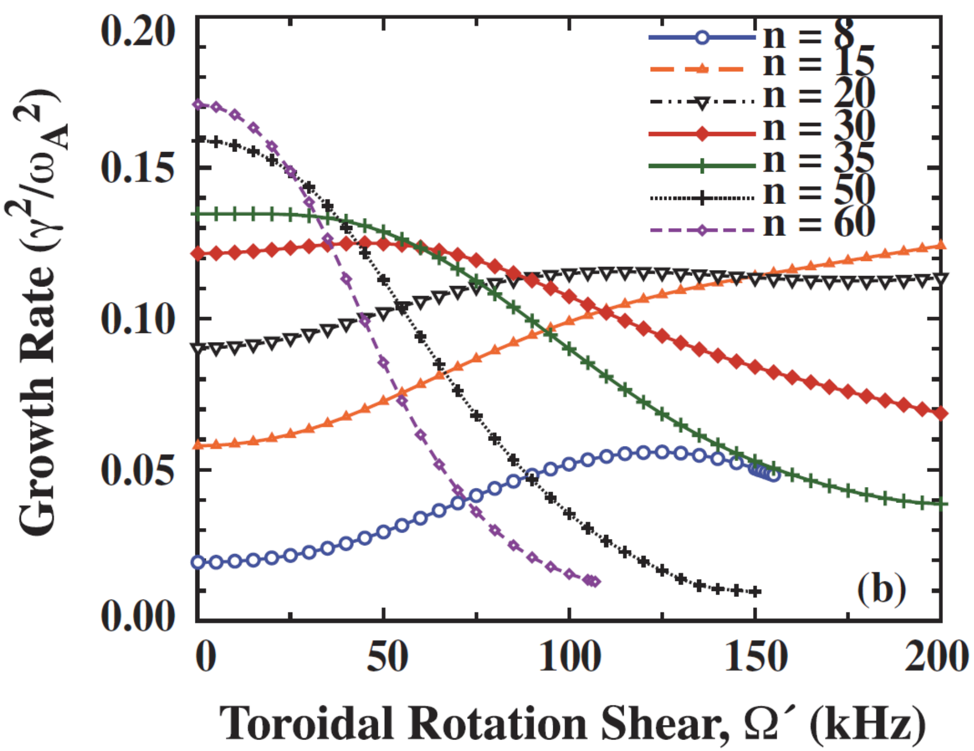
Tokamak operation with edge harmonic oscillations (EHO) provides access to a quiescent H-mode regime [Burrell 2012].

- EHO is characterized by a small toroidal mode number (n~1-5) perturbation localized to the magnetic separatrix.
- Particle transport is enhanced leading to steady-state pedestal profiles.
- Access to the EHO operation regime requires control of the flow profile.
- The aim of this work is to ascertain the role of the flow shear.
- In particular, experimental observations indicate that the ExB flow shear is a key component in the generation of EHO [Garofalo 2011].



The physical mechanisms of EHO are not fully understood.

- Linear MHD calculations suggest EHO may be a saturated kink-peeling mode partially driven by flow-profile shear [Snyder 2007].
- It is hypothesized that the saturated mode drives sufficient particle and thermal transport to maintain steady state pedestal profiles.
- Our intent is to investigate the nonlinear physics – although our initial results are linear.

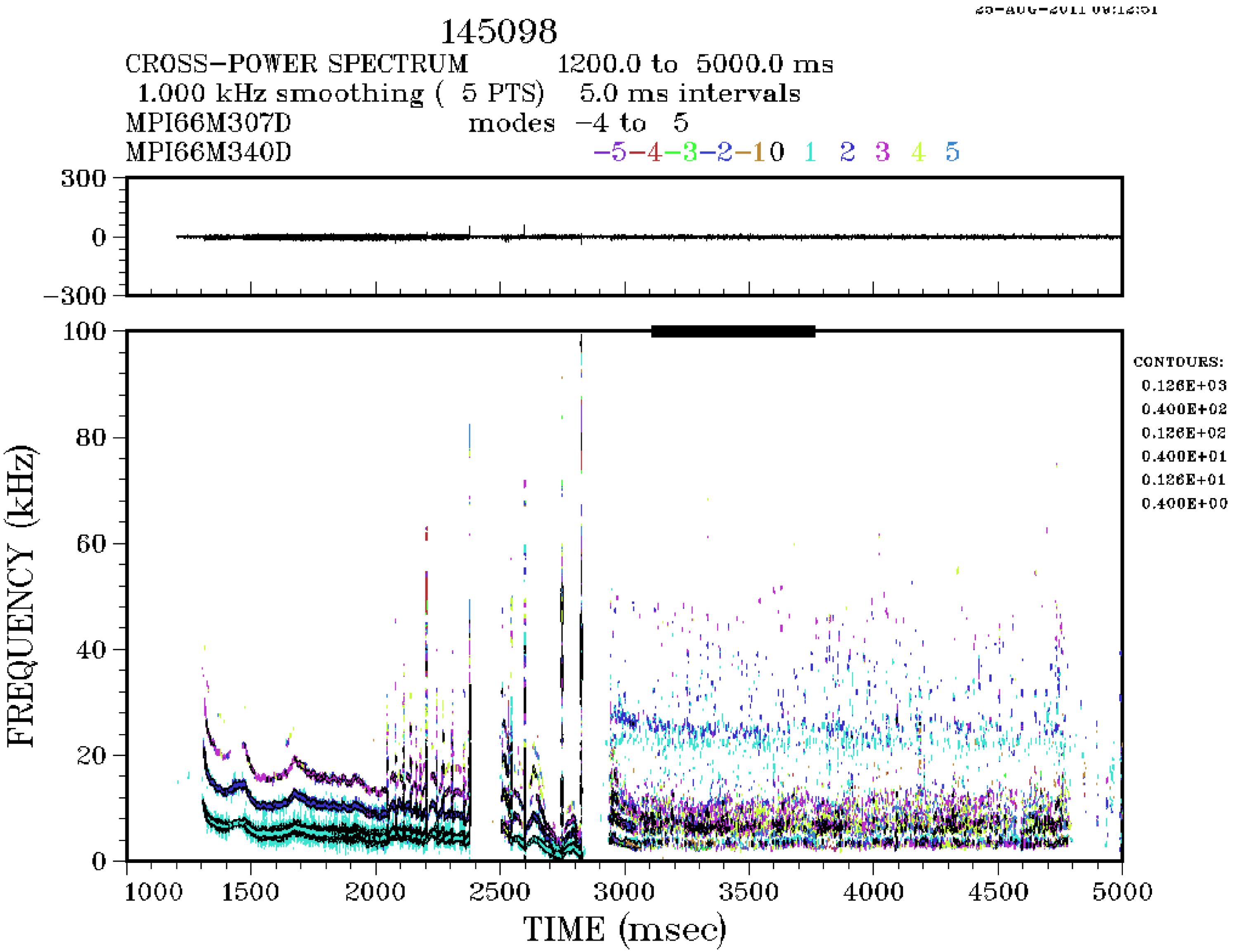


ELITE results from Snyder 2007

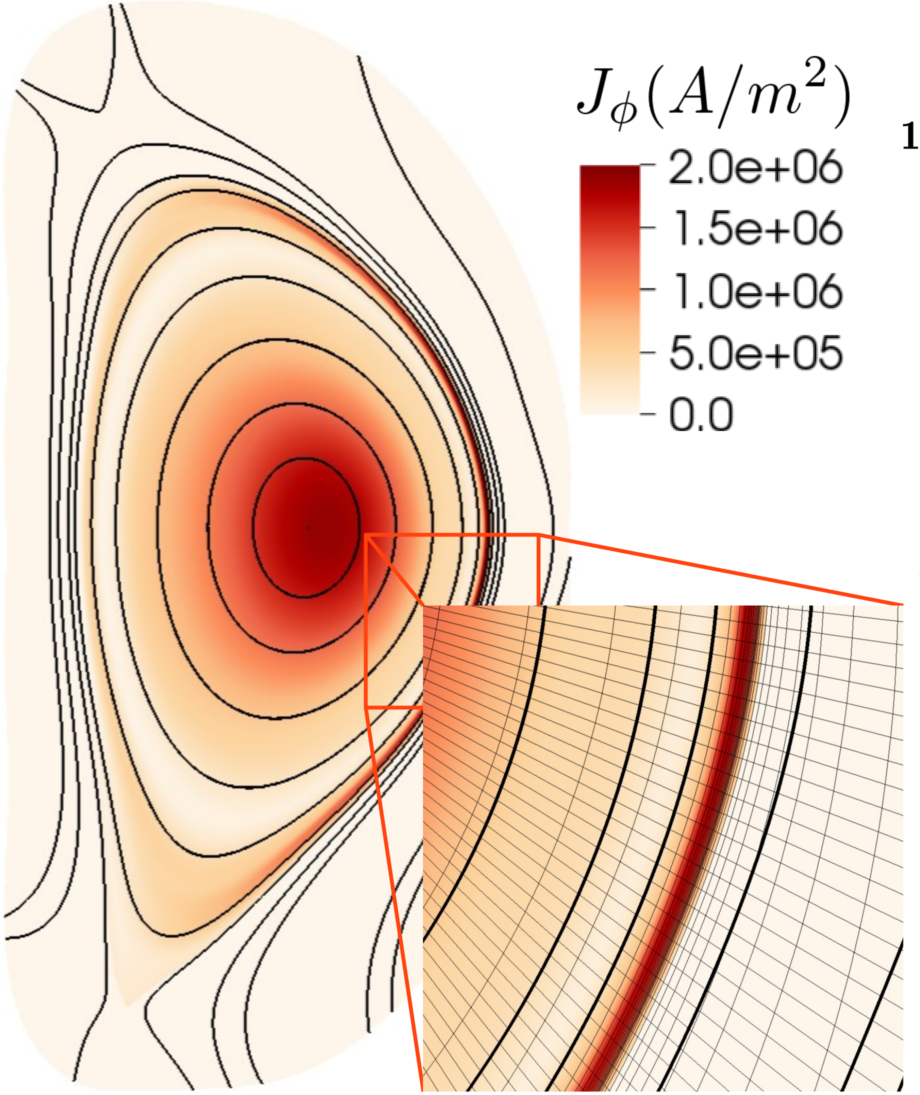
Why is NIMROD a suitable code for modeling EHO?

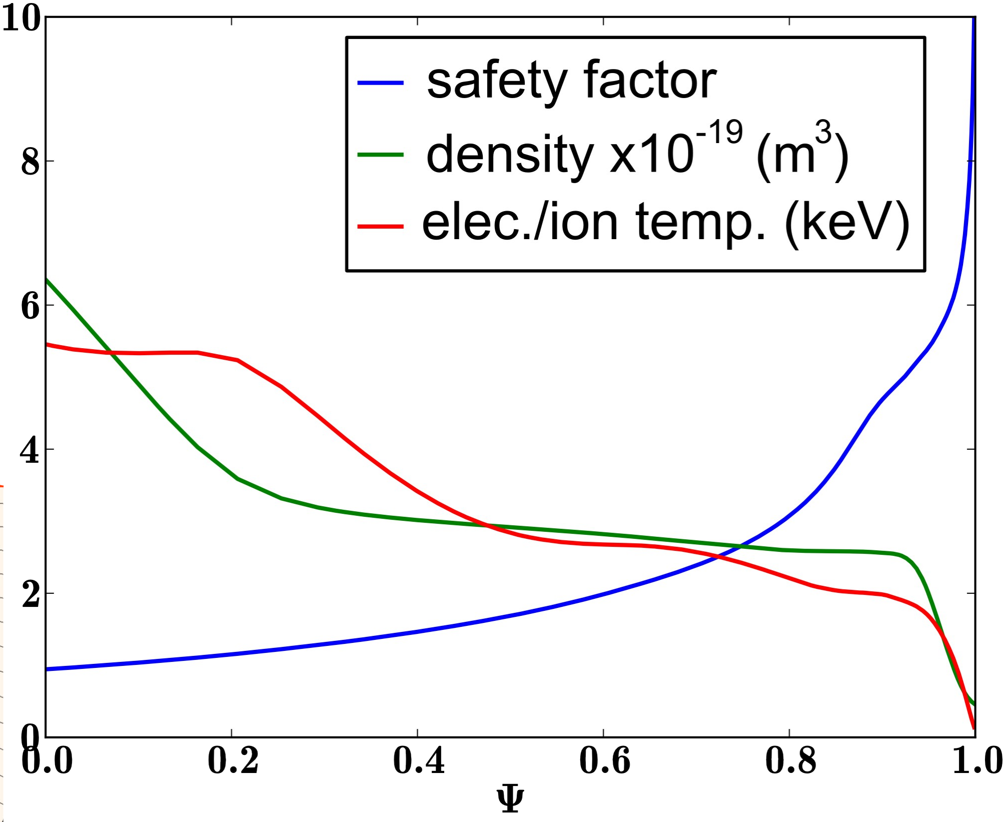
- Experimental observations show EHO is a low-n perturbation and thus global computations are necessary.
- In addition to the capability to model of flow-profile effects, NIMROD also retains important two-fluid and FLR terms.
  - Two-fluid effects are predicted to enhance the growth rate at intermediate wavenumbers and cut it off at large wavenumbers though diamagnetic effects [Hastie, Ramos, Porcelli 2003].
- Even if the high wavenumber modes are stabilized by two-fluid effects, they may be driven nonlinearly. Nonlinear modeling of EHO saturation requires resolution of a large toroidal mode spectrum.
- NIMROD is capable of modeling a realistic x-point geometry.

We analyze DIII-D shot 145098 at 4250 ms while the discharge is ELM free with broadband EHO.



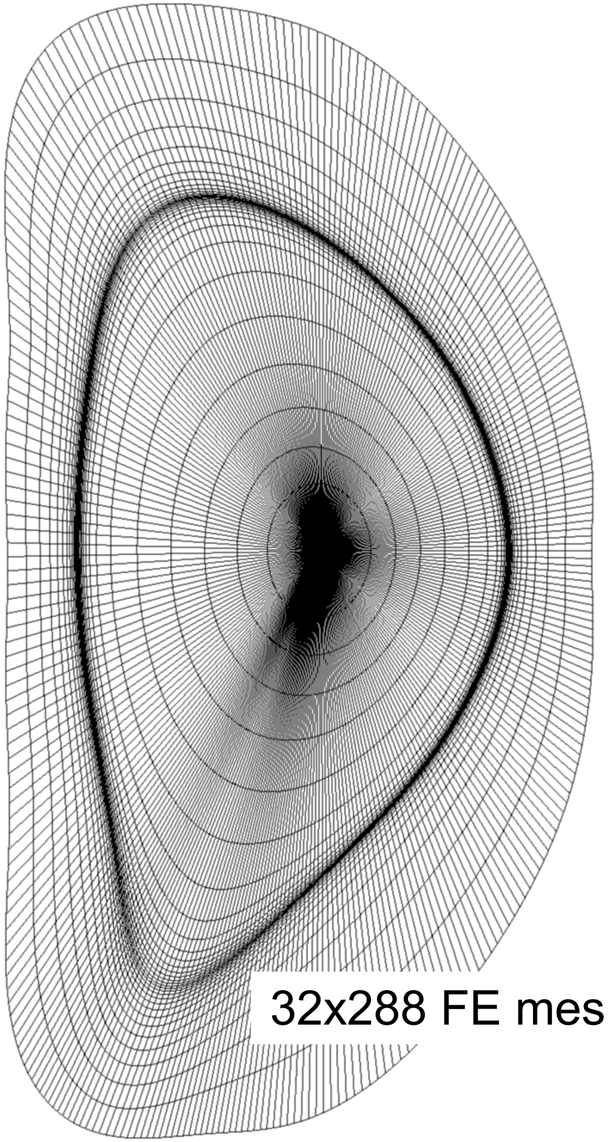
This DIII-D discharge is designed to resemble ITER shaping with beam and NTV torques applied to generate the rotation profile needed for EHO.





$$T_e(\psi_n = 1) = T_i(\psi_n = 1) = 100\ eV$$

Given the large edge safety factor (q_{95} ~ 5.5), our simulations require high poloidal resolution.



32x288 FE mesh

- Computations are performed with the NIMROD code (www.nimrodteam.org) on NERSC's Hopper Cray XE6.
- Computations use a packed, flux-aligned, 32x288 finite-element mesh with bi-sextic spectral elements.
  - 2.7 Million DOF for each Fourier component
- High toroidal mode number modes are still somewhat under-resolved.
  - Small particle hyper-diffusivity ($D_{hypd}=10^{-4}$ m^4/s) helps, and the effect on the mode growth rate is small.

Our model captures flow-shear, parallel-physics, finite-Larmor-radius, and two-fluid effects.

$$\frac{\partial n}{\partial t} + \mathbf{v}\cdot\nabla n = -n\nabla\cdot\mathbf{v} + D_n\nabla^2 n$$

$$m_i n\frac{\partial \mathbf{v}}{\partial t} + m_i n\mathbf{v}\cdot\nabla\mathbf{v} = \mathbf{J}\times\mathbf{B} - \nabla p - \nabla\cdot\mathbf{\Pi} - \nabla\cdot\nu m_i n\mathbf{W}$$

$$\frac{n}{\Gamma-1}\left(\frac{\partial T}{\partial t} + \mathbf{v}\cdot\nabla T\right) = -nT\nabla\cdot\mathbf{v} + \nabla\cdot\left(n\chi_\parallel\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\nabla T\right)$$

$$\mathbf{\Pi} = \frac{m_\alpha p_\alpha}{4eB}\left[\hat{\mathbf{b}}\times\mathbf{W}_\alpha\cdot\left(\mathbf{I}+3\hat{\mathbf{b}}\hat{\mathbf{b}}\right) - \left(\mathbf{I}+3\hat{\mathbf{b}}\hat{\mathbf{b}}\right)\cdot\mathbf{W}_\alpha\times\hat{\mathbf{b}}\right]$$

$$+\nu_\parallel m_i n\left(\hat{\mathbf{b}}\hat{\mathbf{b}} - \frac{1}{3}\mathbf{I}\right)\left(3\hat{\mathbf{b}}\cdot\nabla\mathbf{v}_\alpha\cdot\hat{\mathbf{b}} - \nabla\cdot\mathbf{v}_\alpha\right)$$

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \frac{\mathbf{J}\times\mathbf{B}}{ne} - \frac{\nabla p_e}{ne} + \eta\mathbf{J} - \frac{m_e}{e}\frac{\partial\mathbf{v}_e}{\partial t}$$

$$\frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{E} \qquad \mathbf{J} = \nabla\times\mathbf{B} \qquad p_\alpha = nT_\alpha$$

Our computations use experimentally small dissipation parameters.

- Resistivity varies with the profile proportionally to $T_e^{-3/2}$.
- Parallel diffusivities are chosen to be 1000x smaller than Braginskii values at the separatrix for computational practicality.
- Our model is first order in ion gyroradius, and thus is formally valid only up to intermediate-wavenumber edge-resonant modes.
  - The model may be qualitatively descriptive for large wavenumbers.

$$S_{core} = 1.9 \times 10^8$$
$$S_{edge} = 2.8 \times 10^7$$
$$P_m = \hat{\nu}_\perp = 5$$
$$\hat{\nu}_\| = 3.8 \times 10^6$$
$$\hat{\chi}_\perp = 1$$
$$\hat{\chi}_\| = 8.0 \times 10^8$$
$$\hat{D}_n = 1$$

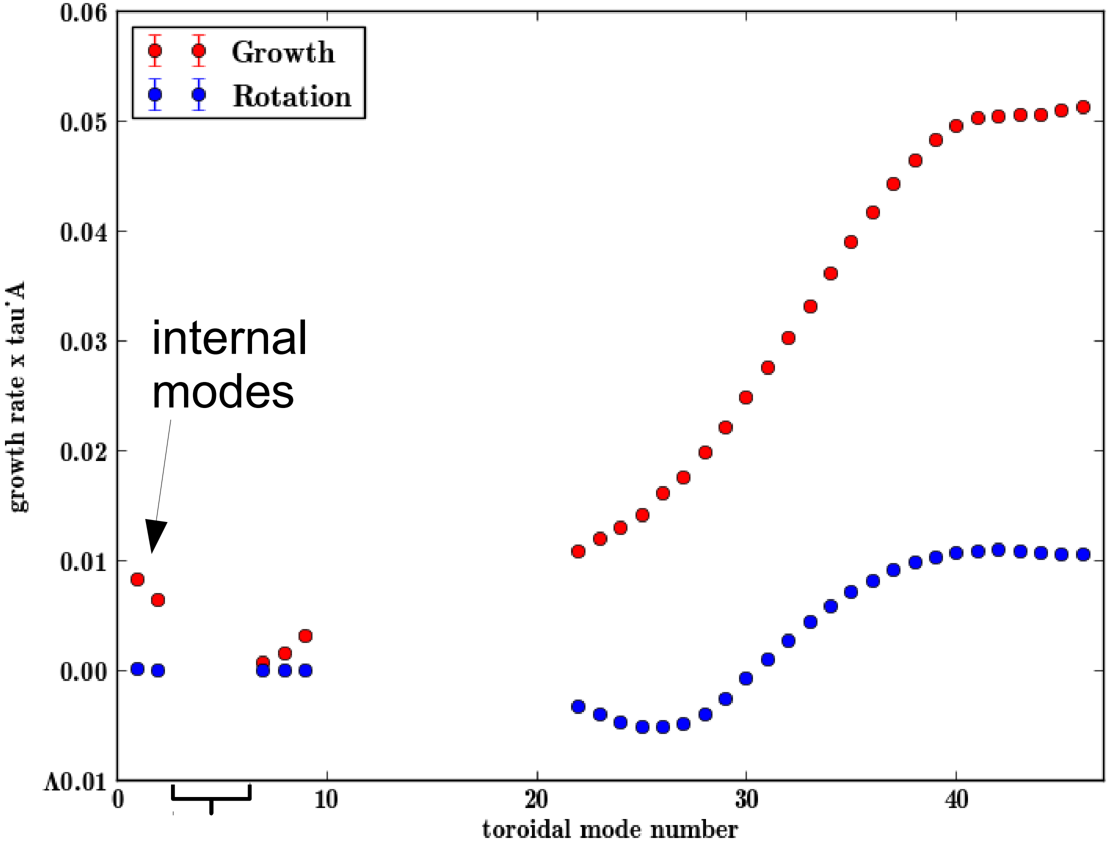
Hats indicate normalization by core resistivity.

$$\beta = 0.007$$
$$d_i = 0.1\ m$$
$$\rho_i = 0.004\ m$$

$$k_{n6}\rho_i = 0.23$$
$$k_{n15}\rho_i = 0.58$$
$$k_{n43}\rho_i = 1.6$$

$$\begin{aligned} k &\simeq n/R + m/r_s \\ &\simeq n/R + nq(r_s)/r_s \\ &\simeq 10n \end{aligned}$$

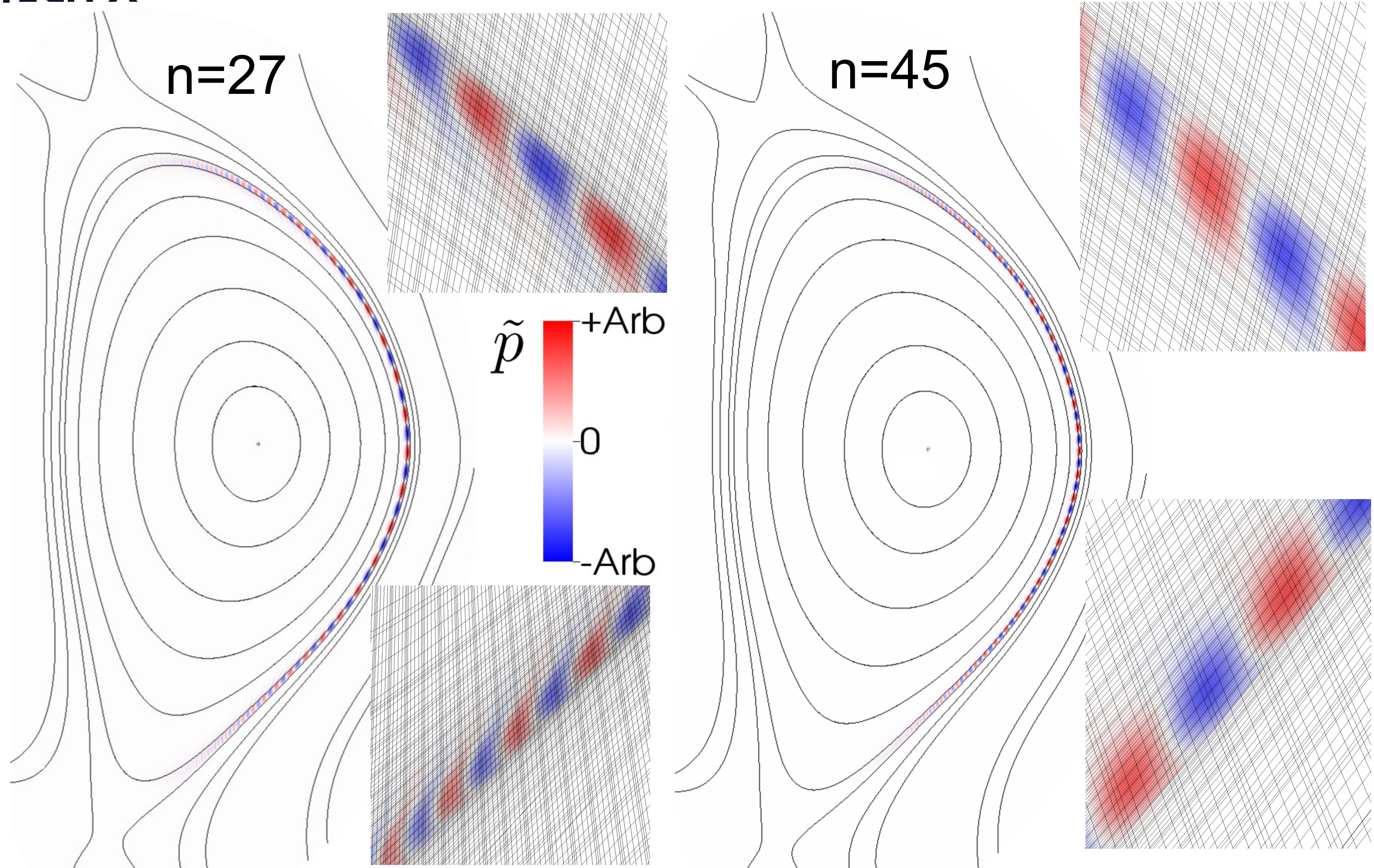
The linear toroidal-mode spectrum without background flow is stable in the edge for n<7.


MHD cases without flow (parallel physics included)

internal modes

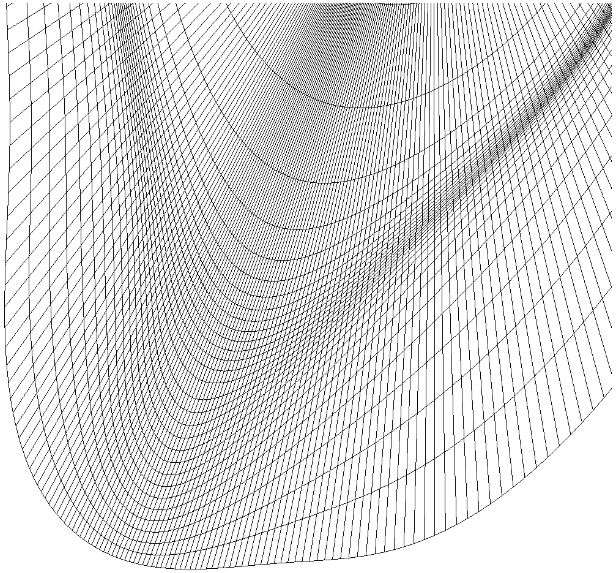
Stable or near marginal stability for n=3-6.

Modes are localized to the separatrix and are reasonably resolved.

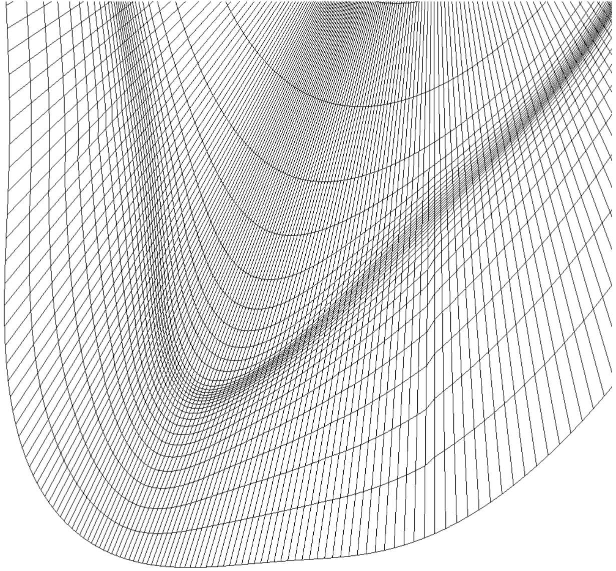


Computations need more resolution along the separatrix near the x-point.

- Our mesh is flux aligned within the separatrix, and the resolution is more limited in expanded-flux regions such as the x-point.
- By abandoning the mesh alignment to the flux in these expanded-flux regions, we are able to achieve better separatrix resolution.
  - These new meshes are developed and implemented, but they are untested. Thus they are a work in progress.

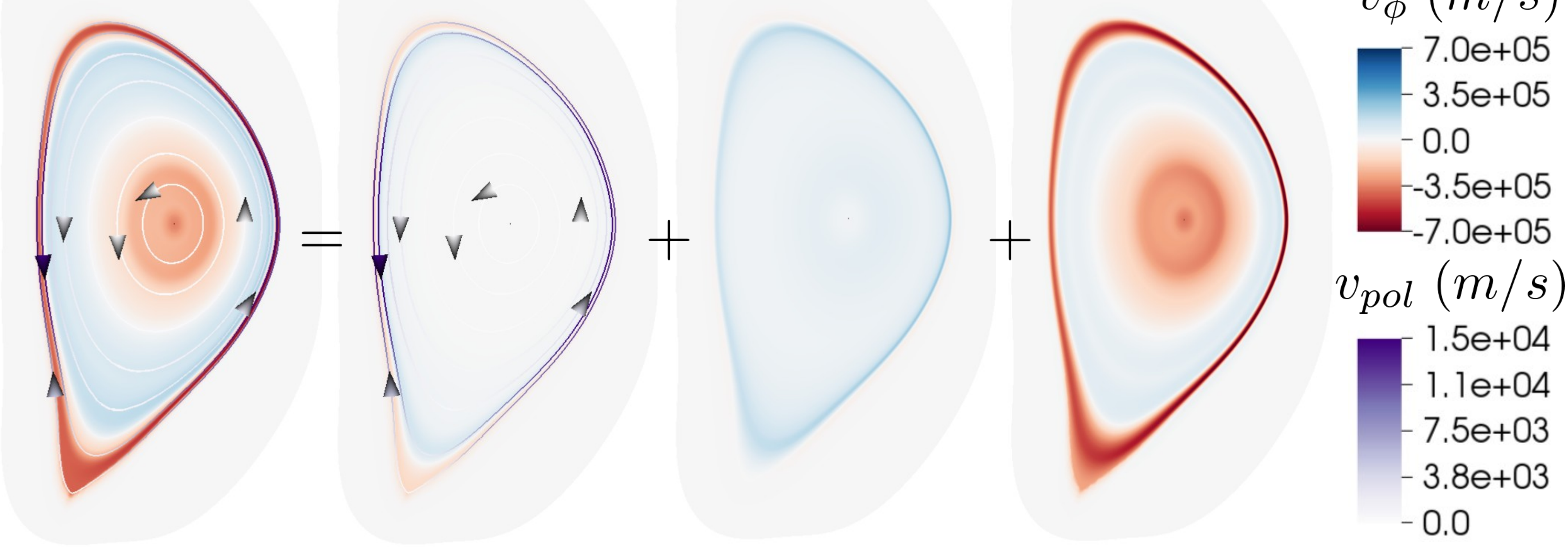


Current (upper) and proposed (lower) meshed



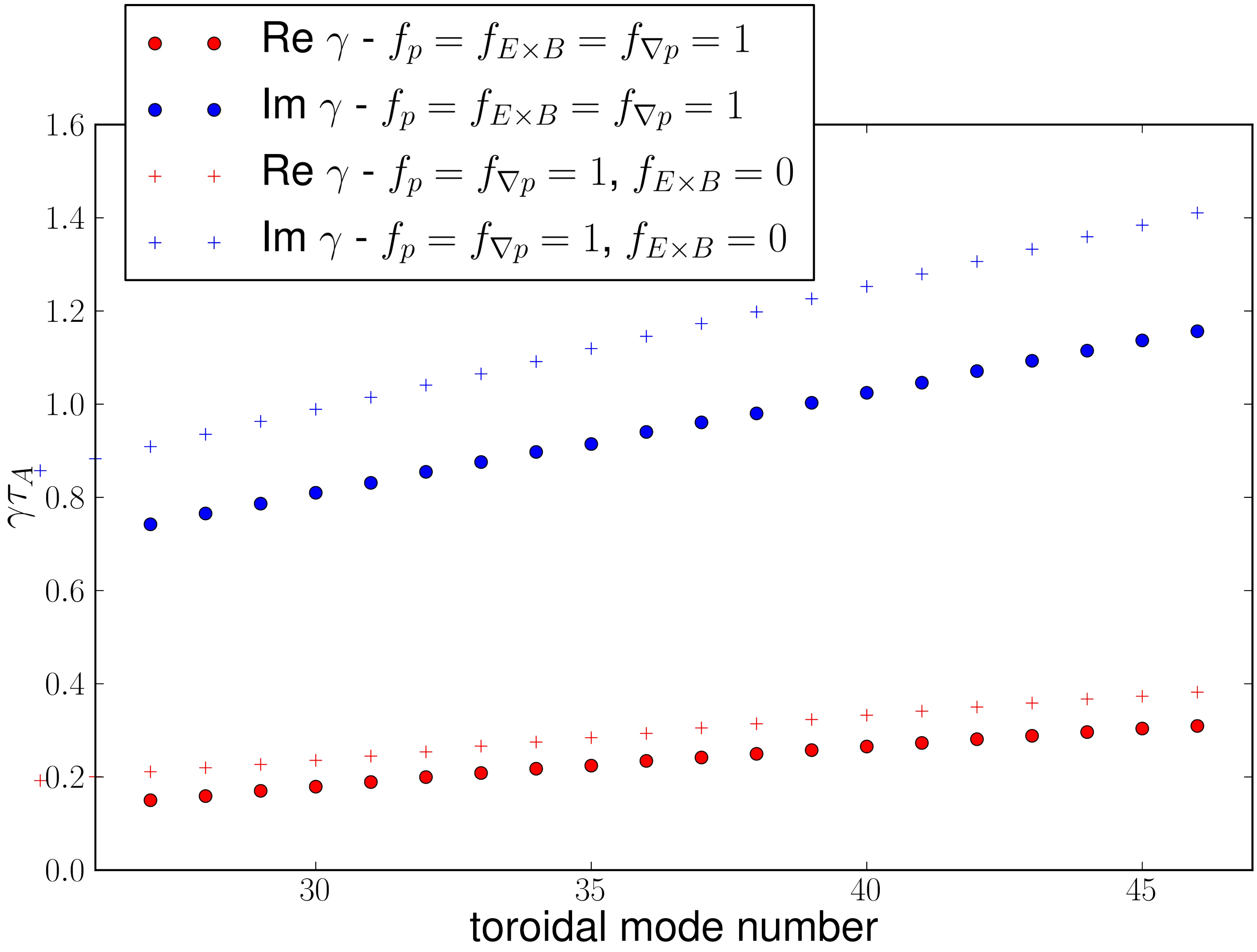
We now add equilibrium velocity, which has strong poloidal and toroidal shear at the edge.

$$\mathbf{v}_{EQ} = f_p K_p(\psi)\,\mathbf{B} + f_{E\times B}\Omega_{E\times B} R\hat{\phi} - f_{\nabla p}\Omega_{\nabla p} R\hat{\phi}$$



- We can vary the each contributions flow profiles, here we run cases with and without the ExB flow contribution.
- Profiles are shown for $f_p = f_{E\times B} = f_{\nabla p} = 1$.
- Flows are specified by the reconstruction up to the separatrix and extrapolated to zero beyond the separatrix.

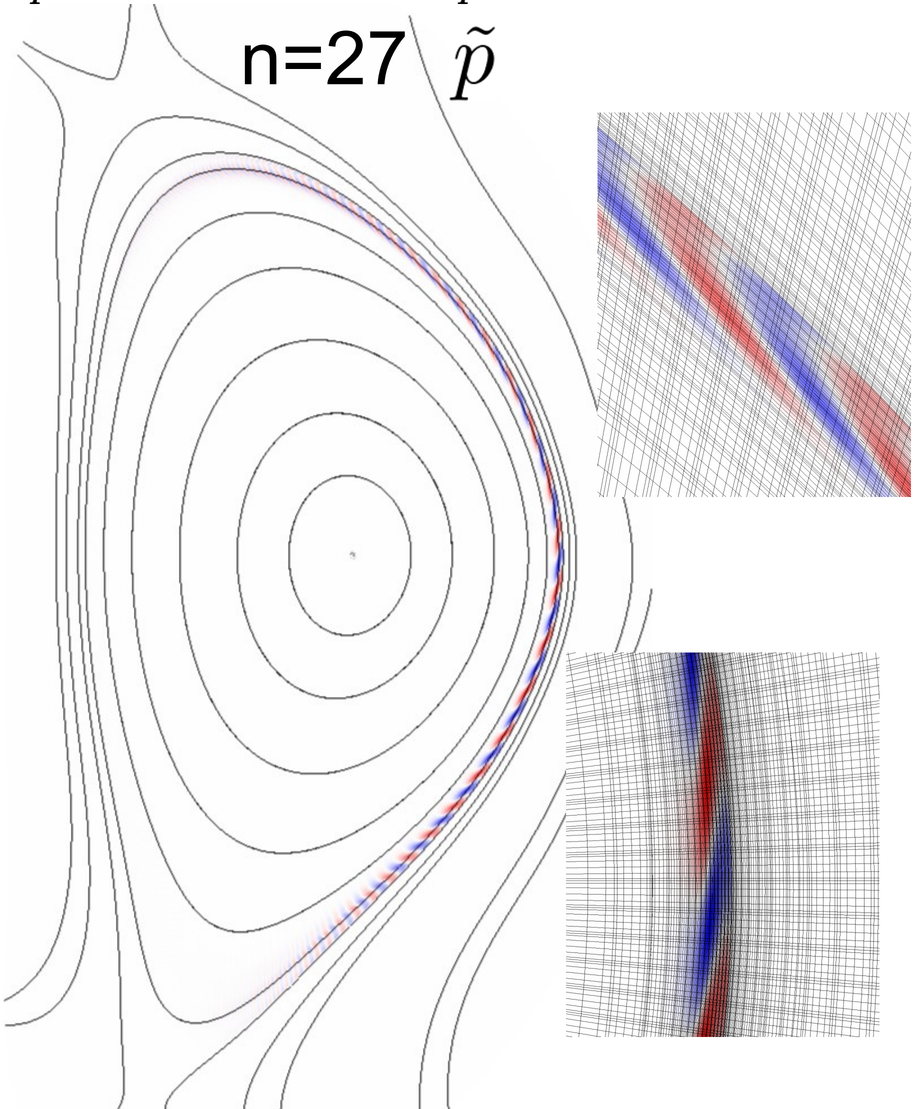
Cases are slightly stabilized by the ExB flow contribution.



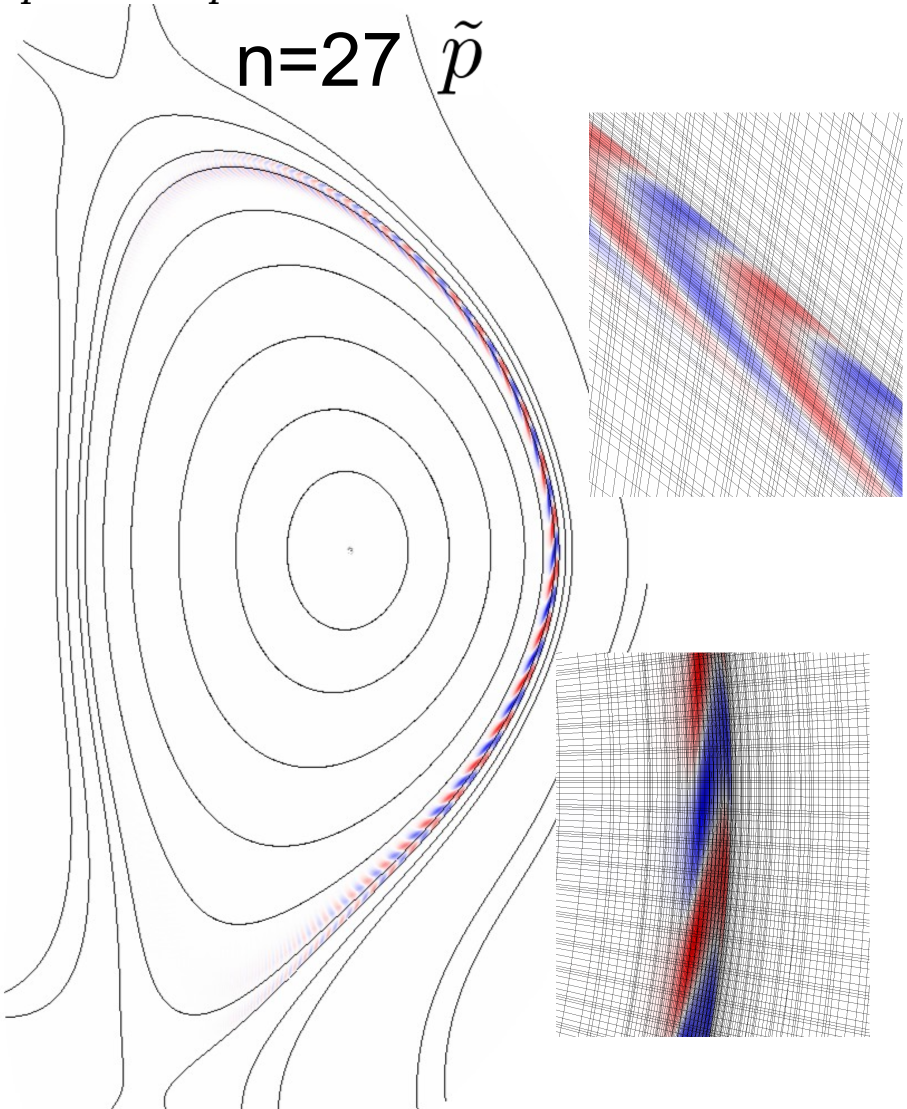
MHD (parallel physics included)

Although the growth rate differs, the mode structure remains with the same with and without ExB flow.

$f_p = f_{E\times B} = f_{\nabla p} = 1$



$f_p = f_{\nabla p} = 1\,,\ f_{E\times B} = 0$



ELITE computations show a peeling-like mode spectrum peaked at n=11, unlike our computations.

- Resolving this discrepancy is our top priority.
- There are several paths to investigate:
  - Confirm the equilibria used by NIMROD and ELITE match.
  - Currently we are using temperature dependent resisitivity, and large thermal conduction with a 100 eV plasma in the vacuum region. For comparison, we need to run NIMROD cases in the 'ideal' limit.
  - Perform a detailed convergence study and optimize mesh packing. In particular, try cases where the mesh is no longer aligned to the flux in flux expansion regions, and is packed tightly about the separatrix.

Summary

- We have studied the linear properties of an experimental reconstruction of a DIII-D discharge with EHO.
- Our initial results show the effect of the ExB flow to be stabilizing.
- The linear spectrum differs with ELITE, which shows a peeling-like spectrum, and this discrepancy needs to be resolved.
- Nonlinear simulations should be tractable with a peeling-like spectrum.