Shear flows in the pedestal and scrape-off layer and their effects on edge-localized modes

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Introduction

- Shear flows in the pedestal are an essential part of H-Mode.
- **Edge-localized modes (ELMs) cannot be studied properly without considering the effects of shear flows.**
- Can shear flows be generated self-consistently within a magnetohydrodynamic (MHD) model?
- **Yes, although MHD will not provide a complete answer.**
- A crucial (and trivial) observation is that the edge is a region of large gradients between a hot ("ideal") core, and a cold (non-ideal) scrape-off layer (SOL)**;** thus,
- **"Ideal MHD equilibrium" is not an accurate description of a (quasi-)steady-state at the edge; transport has to be included self-consistently.**
- **Finite resistivity,** augmented by **neoclassical effects**, is a necessary ingredient.

Outline

- NON-ideal MHD Equilibrium
  - Ideal MHD equilibrium,
  - Effects of transport (finite resistivity),
  - Self-consistent equilibrium flows generated by transport.
- Interaction of equilibrium flows with ELMs
  - Effects of flows on linear peeling/ballooning modes,
  - Nonlinear interaction of flows with peeling/ballooning modes.
- Summary

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"Classical" MHD equilibrium calculation with the Grad-Shafranov (G-S) equation

- $-\Delta^\star\psi = FF' + R^2p'$, where $p = p(\psi)$, and $F = F(\psi)$.
- If included, an *ad hoc* equilibrium flow has to be of the form

$$\mathbf{u} = \frac{\Phi(\psi)}{\rho}\mathbf{B} + R\Omega(\psi)\hat{\zeta},$$

  which leads to a more complicated G-S equation. (Hameiri (1983)).
- There are a number of problems with this procedure when studying edge plasmas.

Problems with "classical" equilibrium calculations

- We don't know how to evolve in time an *ad hoc* $\mathbf{u}(\mathbf{x}, \mathbf{t})$ in nonlinear calculations.
- The system is typically far from "transport-equilibrium" and evolves in undesirable directions.
- Question: How do we generate self-consistent flows in quasi steady-state conditions within MHD?
- We use an "initial/boundary value" approach.

Model Equations: without transport, damping **velocity u** leads to steady-state (an MHD equilibrium).

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0 \\
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} &= \mathbf{J} \times \mathbf{B} - \nabla p, \\
\frac{\partial p}{\partial t} + (\mathbf{u} \cdot \nabla) p &= -\gamma p \nabla \cdot \mathbf{u} + \kappa_{\perp} \nabla^2 p + \kappa_{\parallel} \nabla_{\parallel}^2 (p/\rho), \\
\frac{\partial \mathbf{A}}{\partial t} &= -\mathbf{E}, \\
\mathbf{E} &= -\mathbf{u} \times \mathbf{B} + \eta(\mathbf{J} - \mathbf{J}_{\mathbf{BS}}) \\
&= \nabla(V_l \zeta) - \nabla \phi.
\end{aligned}
$$

With transport, **u = 0** cannot lead to steady-state; examine Ohm's law:

- $\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta(\mathbf{J} - \mathbf{J_{BS}}) = \nabla(V_l \zeta) - \nabla\phi$, where V_l is the loop voltage, and $\mathbf{J_{BS}}$ is the bootstrap contribution to current.

- An axisymmetric system with $\mathbf{u} = 0$ requires $\eta(J - J_{BS})_\zeta = V_l/R$, which is possible only for a very special η-profile.

- Another option, of course, is to have 100% bootstrap fraction! (Not considered here.)

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With transport, **u≠0.** Some general characteristics of **u:**

- With $\nabla \cdot \rho\mathbf{u} = 0$, $\rho\mathbf{u} = (\rho u^{\psi}, \rho u^{\theta}, \rho u^{\zeta})$, and $\mathbf{B} = \nabla\psi \times \nabla\zeta + F\nabla\zeta$, $\rho\mathbf{u} = \nabla\chi \times \nabla\zeta + G\nabla\zeta$, we have:
- $-u^{\psi} = \eta(J - J_{BS})_{\zeta} - V_l$.
- Using $< \rho u^{\psi} >= 0$, we can show $V_l =< \rho\eta(J - J_{BS})_{\zeta} > / < \rho >\sim R_0\eta_0 J_0$.
- Because of Pfirsch-Schlüter currents, the flux is radially outward at the outboard midplane.

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With transport, **u≠0.** Some general characteristics of **u:**

grad-B dependence of power threshold in L-H transition

- Components of the Ohm's Law:

$$-u^{\psi} = \eta(J - J_{BS})_{\zeta} - V_l,$$

$$-\frac{\mathcal{J}F}{R^2}u^{\psi} = -\frac{\partial\phi}{\partial\theta} + \eta(\mathbf{J} - \mathbf{J}_{BS})_{\theta},$$

$$\frac{\mathcal{J}F}{R^2}u^{\theta} + u^{\zeta} = -\frac{\partial\phi}{\partial\psi} + \eta(\mathbf{J} - \mathbf{J}_{BS})_{\psi},$$

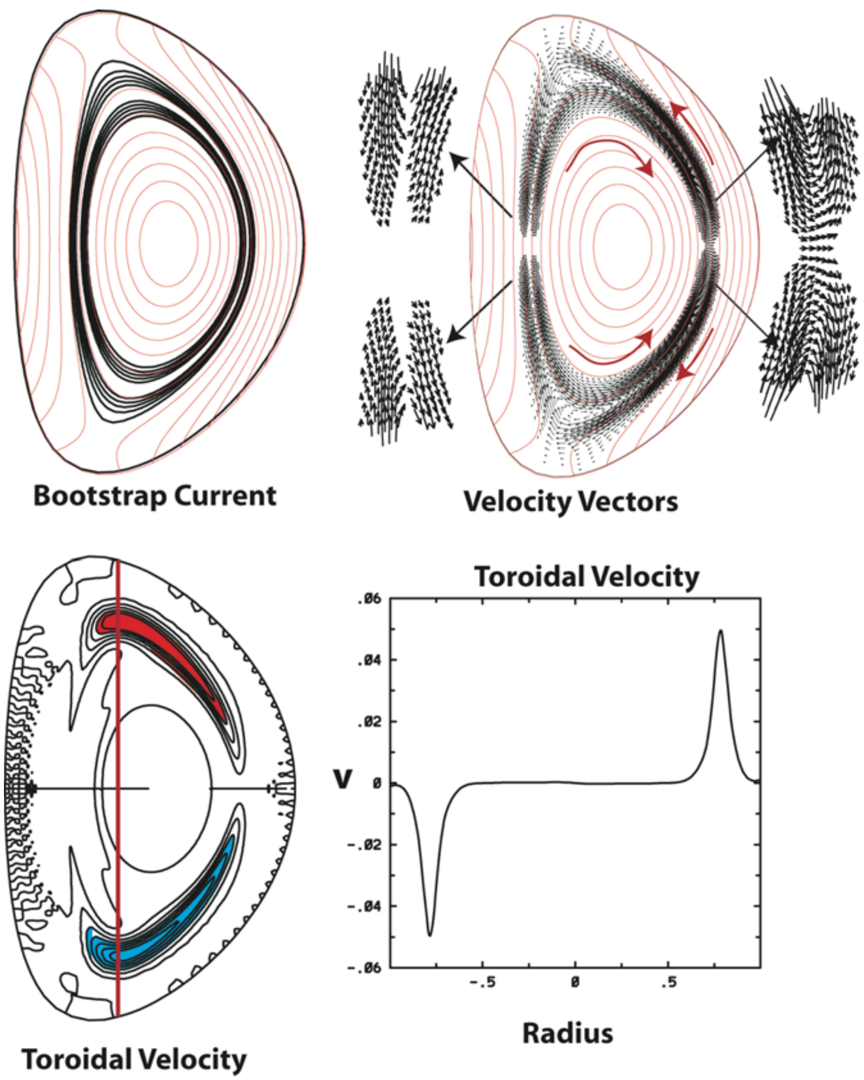
where $\mathcal{J} = 1/(\nabla\psi \cdot \nabla\theta \times \nabla\zeta)$.

- These equations are invariant under the transformation:

$$F \to -F,\ u^{\zeta} \to -u^{\zeta},\ \phi \to -\phi,$$

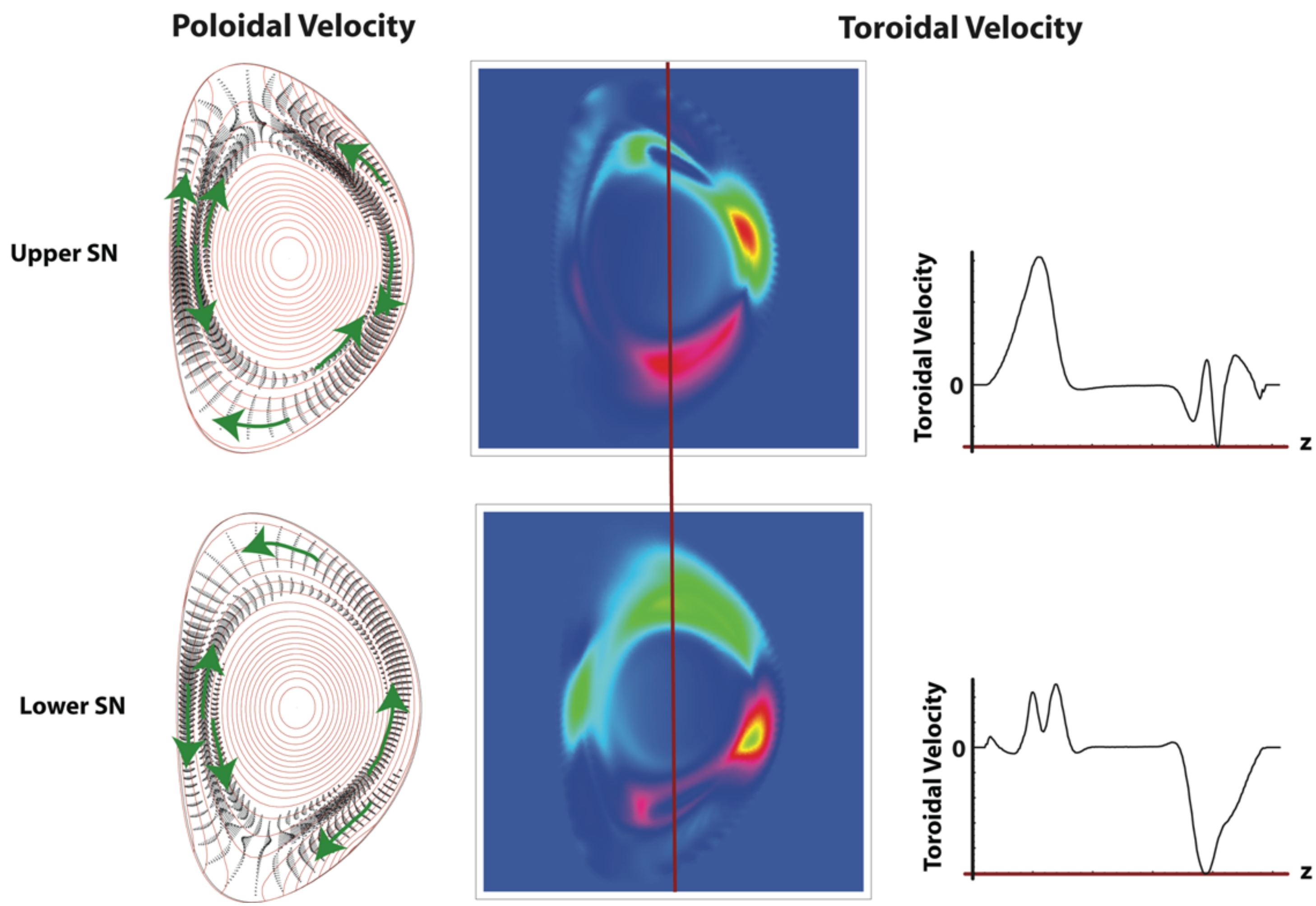
Reversing toroidal field reverses toroidal flow and potential ϕ.

Dipole equilibrium flow pattern in a double-null (DN) configuration



- A non-uniform "classical resistivity" profile with $S_0=10^6$, and $S_{SOL}=10^2$.
- A simple bootstrap current model, localized to the pedestal region, with $J_{BS}/J_0=0.3$ is used.
- Toroidal beta = 5×10^{-3}.
- The resulting flow has an Alfven Mach number $M\sim10^{-2}$, corresponding to velocities of order 10^4m/s.
- Induced toroidal flow is also dipolar and has no net toroidal angular momentum.

Equilibrium flows in single-null (SN) configurations

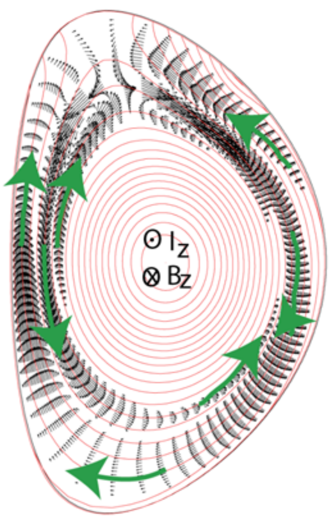


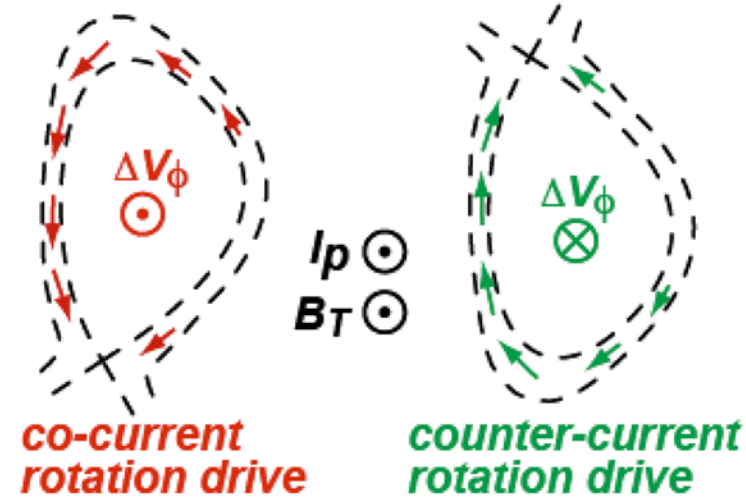
Interaction of the toroidal flow with the X-point transfers momentum to the vessel through the open field lines, leaving a net toroidal angular momentum contribution to the plasma.

Comparison with experimentally observed SOL flows

Poloidal Velocity

Upper SN

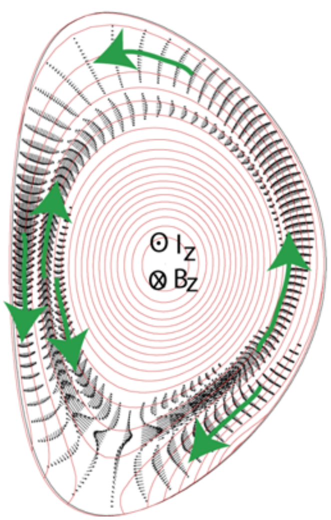




LaBombard, et al., Nucl. Fusion (2004), Phys. Plasmas (2005).

LaBombard, et al., Nucl. Fusion (2004)

Lower SN



- **Poloidal flow directions, and locations appear to be in agreement with experimental observations.**
- **When corrected for the different sign of the toroidal flux used in numerical calculations, the contribution to core rotation is also in agreement.**

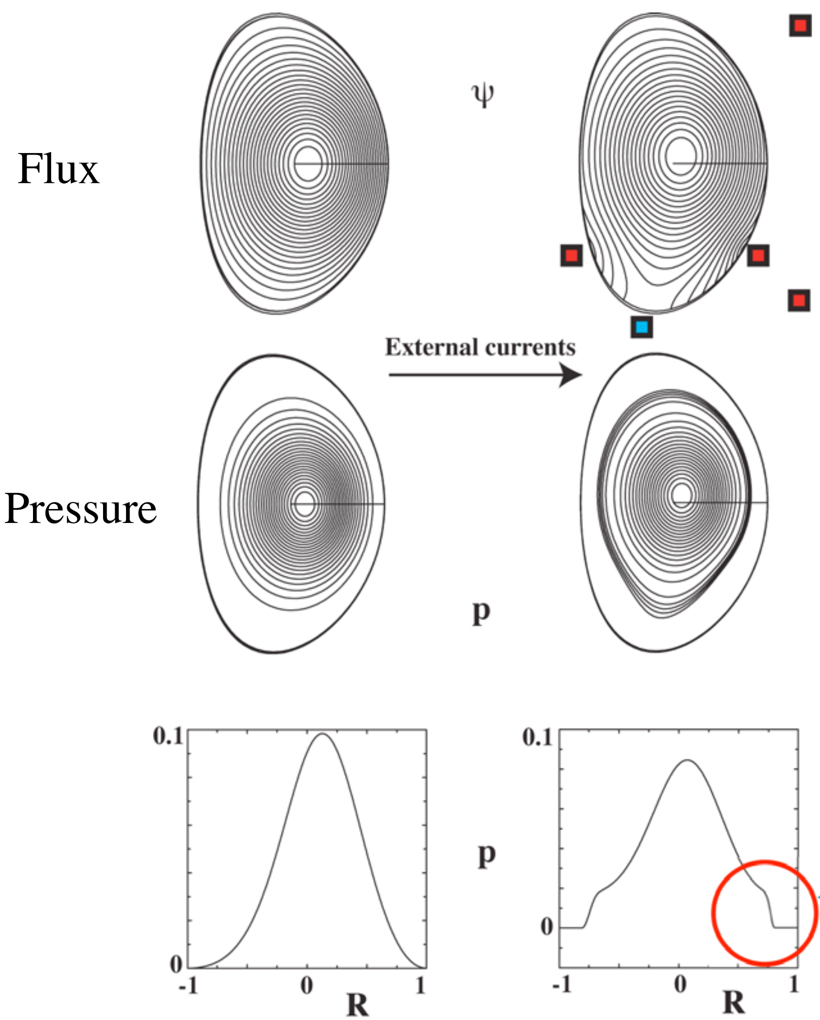
Part II. Effects of shear flows on linear/nonlinear ELMs.

- How do we generate the equilibria used in these calculations?
- Linear peeling/ballooning calculations and the effects of flow shear.
- Nonlinear calculations with flow.

We use external currents to shape the plasma

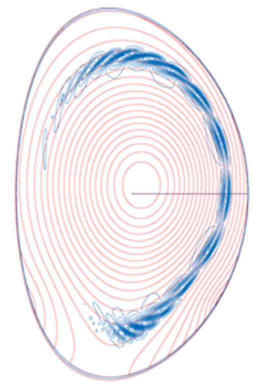
while keeping toroidal β and flux constant

Equilibrium

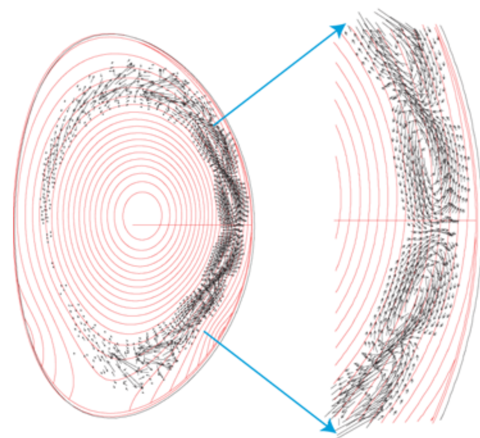


Pedestal
Height ~20%

Linear n=3 ballooning/peeling mode



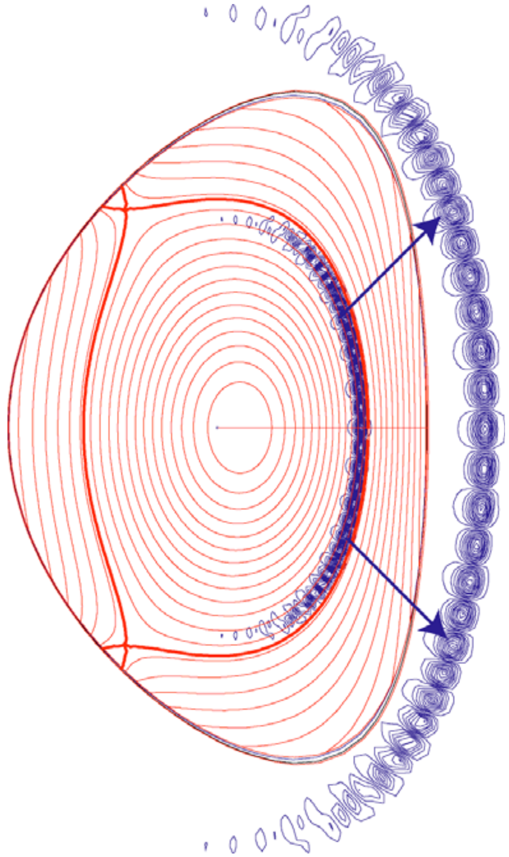
n=3 perturbed
pressure contours

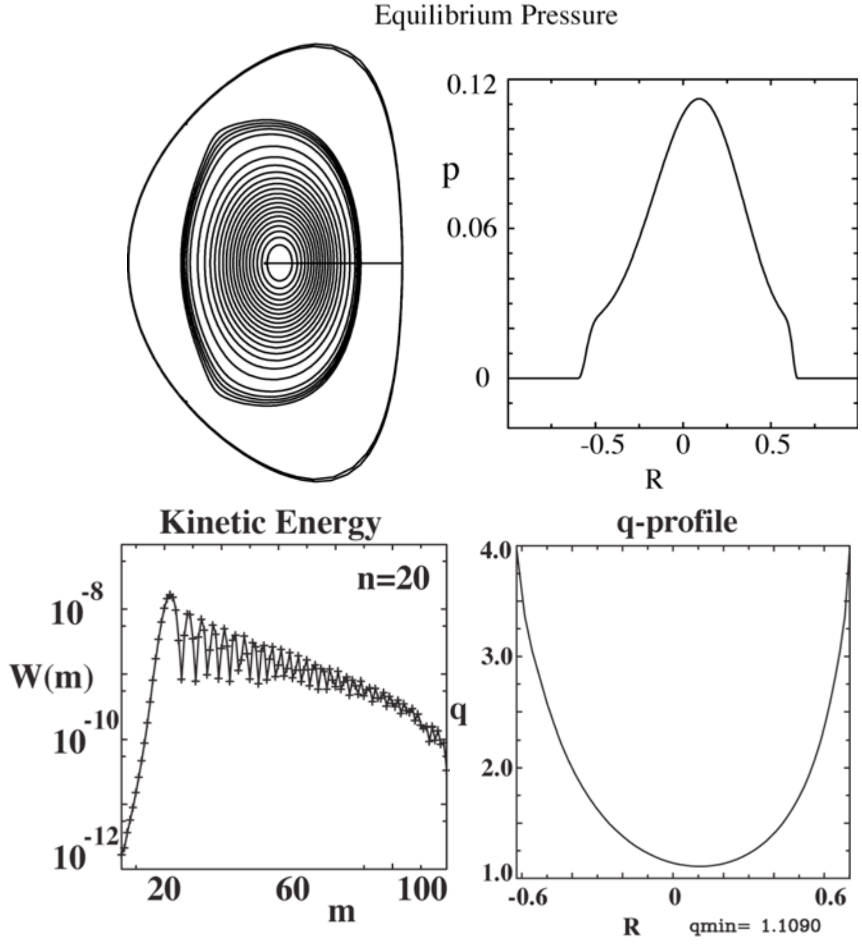


n=3 perturbed
velocity vectors

A “rectangular” equilibrium and linear n=20 mode

Equilibrium flux and perturbed pressure

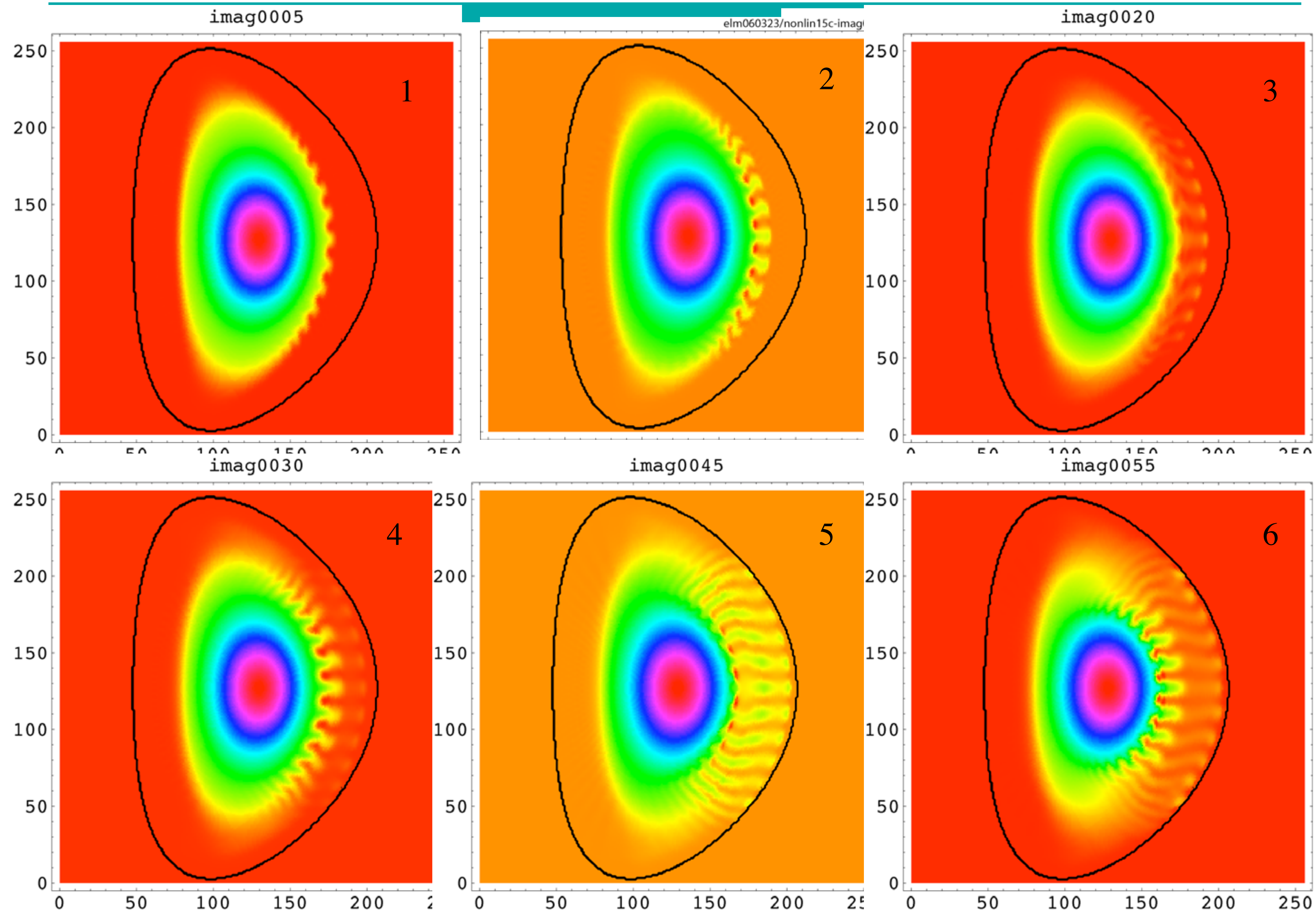




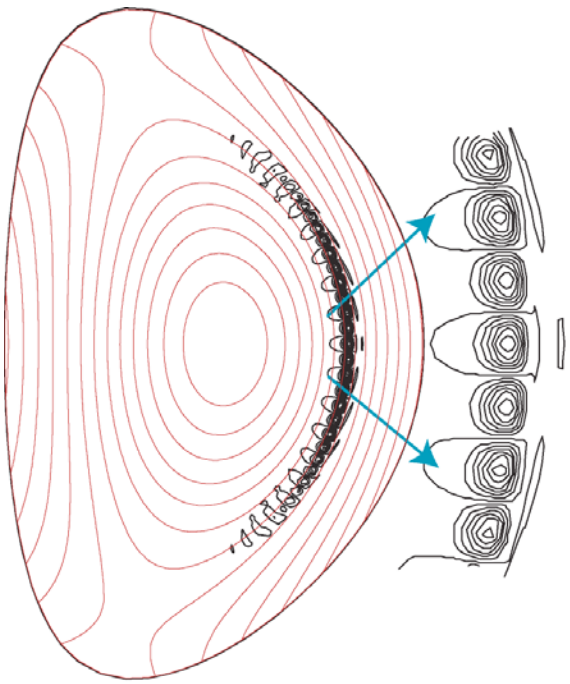
Number of convective-cell pairs ~ nq_s, where q_s=3 here.

Continual peeling away of the edge plasma

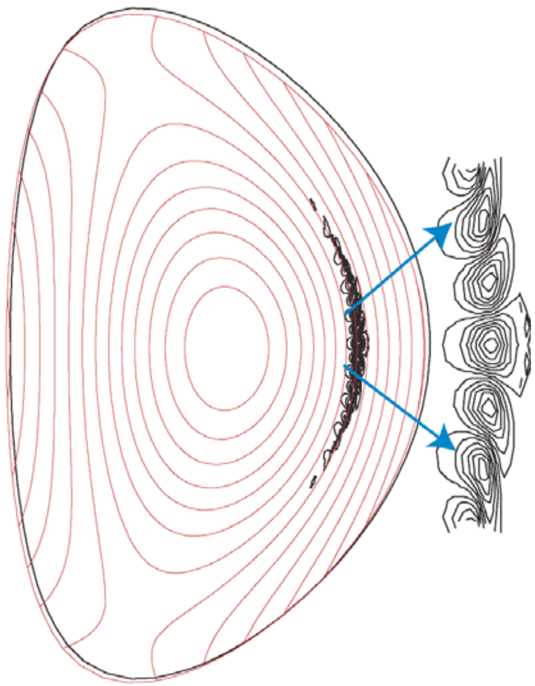
Large ELM's can affect the core plasma



Shear-flow effects on linear eigenfunctions



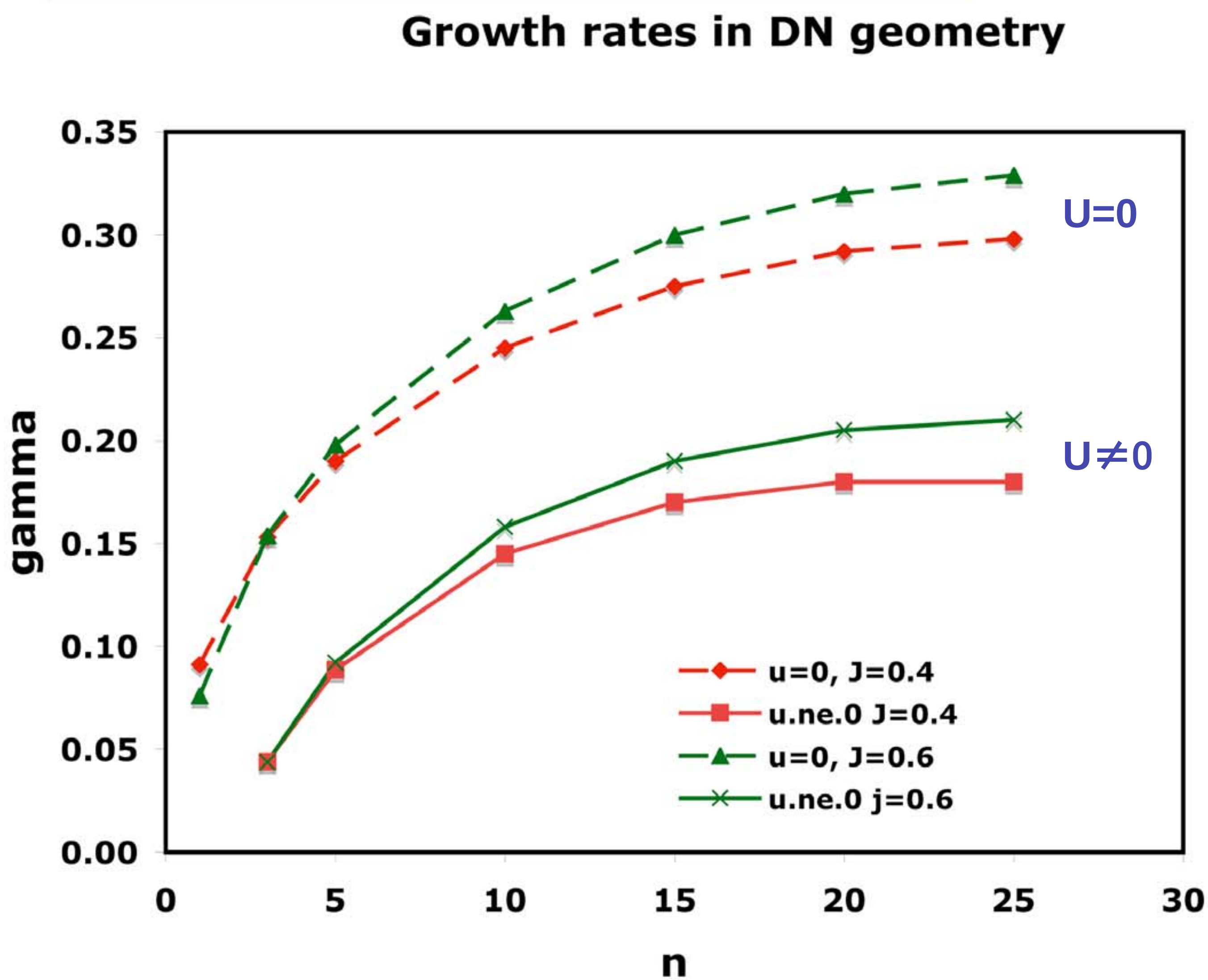
n=25, pressure
No shear-flow



n=25, pressure
With shear-flow

In addition to the usual shearing of the cells, the eigenfunction is localized to the midplane, where the flow is stagnant.

Shear-flow effects on linear growthrates



- Unlike toroidal shear flows, poloidal shear flows affect both low and high-n modes strongly.
- Here, n=1 becomes stable because it does not fit in the "window" at the midplane.

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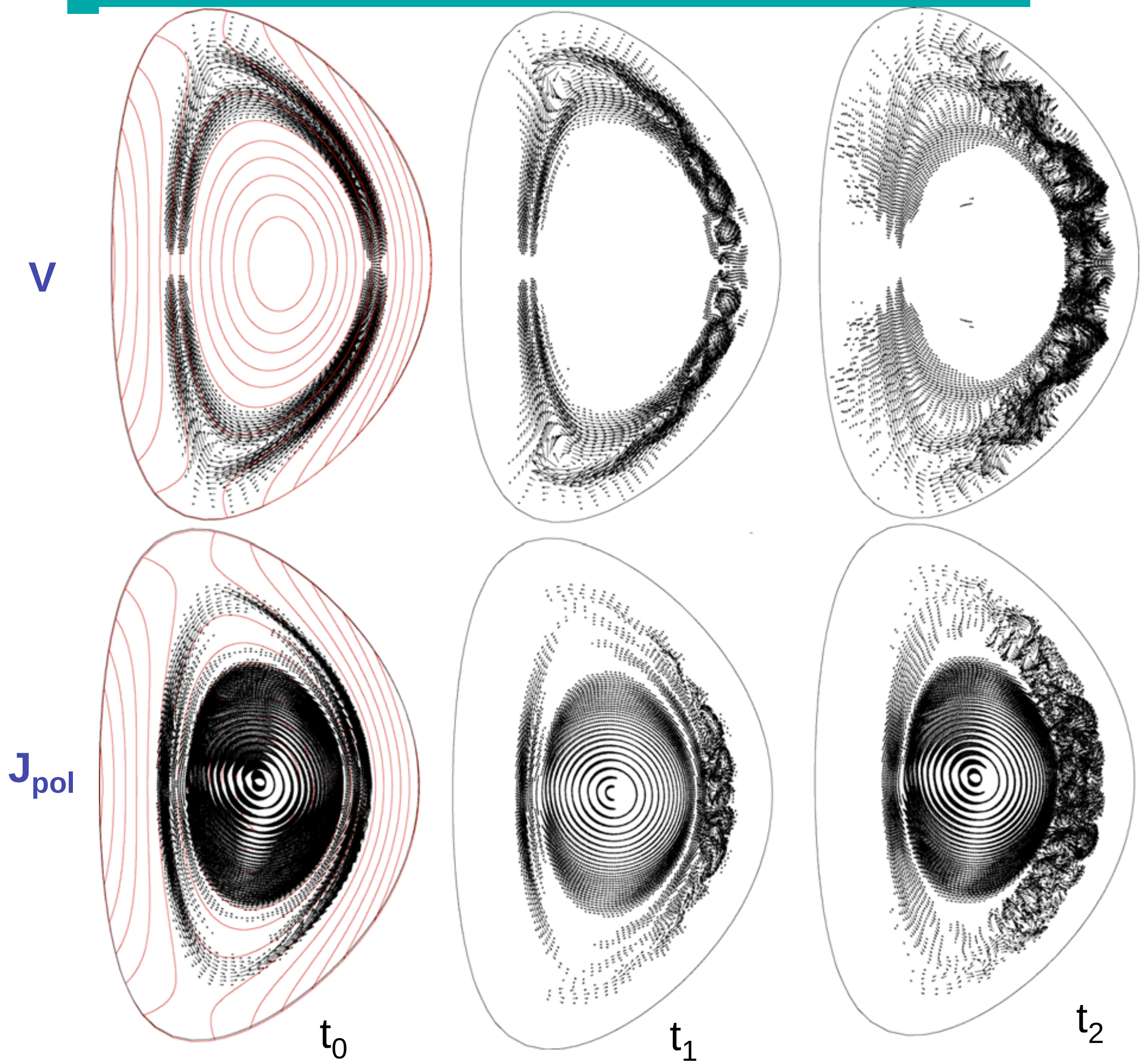
Shear-flow effects on nonlinear evolution



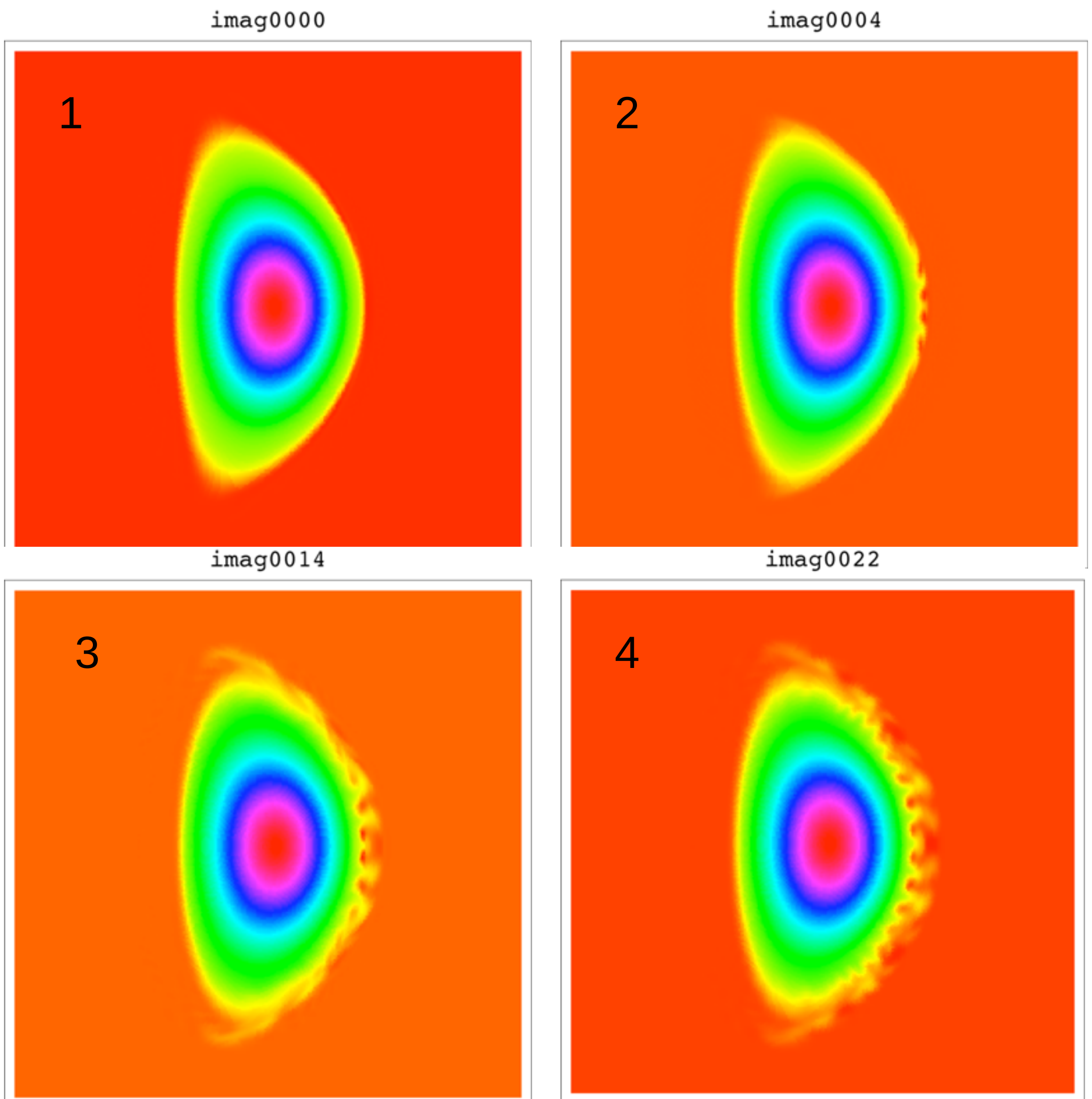
•Shear flow is nonlinearly modified and acquires the characteristics of the unstable mode.

•Thus it loses its effectiveness as "shear flow."

•Similarly, poloidal currents are modified and new currents are generated in the SOL in response to the nonlinear mode.

•We have not found a method that would maintain the shear flow.

Shear-flow effects on nonlinear evolution- effects on pressure



- Initial development of “fingers” is localized around the mid-plane.
- However, nonlinearly the whole outboard side gets affected, as in earlier runs.
- Propagation to the core continues, partially because the shear-flow diminishes.
- Flow rapidly carries the material that enters the SOL towards the X-points.

Summary

- We showed how shear flows at the edge may develop in the presence of transport within non-ideal MHD.
- Their location and direction are consistent with observations in C-Mod.
- Using simple symmetry arguments, we showed that reversing the toroidal field necessarily results in the reversal of the toroidal velocity and the potential. Both changes are in such a direction as to oppose the L-H transition.
- This feature may explain the difficulty, universally observed, in achieving H-mode when the grad-B drift points away from the X-point.
- Shear flows at the edge further localize the ballooning modes around the mid-plane; thus, they have a strong stabilizing influence on all n's.
- Self-consistent interaction of the flow with unstable modes needs further work. How do we maintain or recover the flow?