ELMs and ELM-free instabilities

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ELMs, ELM-stable plasmas

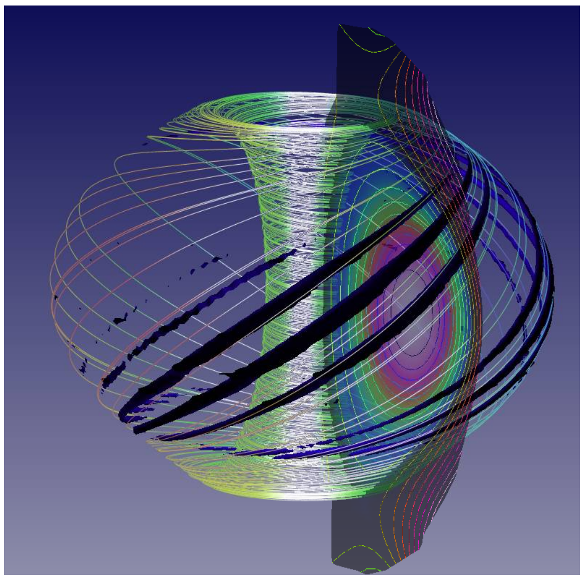
- Previous simulations of large Type I ELMs in DIII-D showed importance of magnetic tangle for free-boundary plasmas (Sugiyama et al, PoP 2010)
- Question 1: How well does MHD physics capture ELM and ELM-free stability?
  - One DIII-D equilibrium was from RMP-stabilized time, MHD simulation still showed ELM at near-real resistivity
  - Differences exist in edge instabilities in non-ELMing cases (eg., EHO)? Look at DIII-D, C-ModX
  - NSTX liquid lithium divertor stabilization of ELMs? X
- Question 2: DIII-D ELM case had low-mode-number interior modes, more slowly growing, but large
  - What affects edge instability coupling to interior?
- => The combination of toroidal rotation and two-fluid effects!

Equilibrium magnetic geometry influences ELM structure.

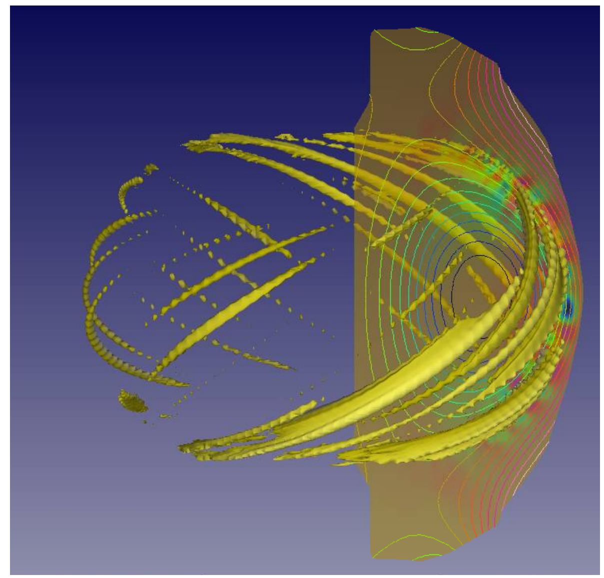
Spherical torus asymmetry may help explain n=3 field *de*stabilization of ELM in NSTX, compared to DIII-D stabilization (ignores rotation!)

NSTX

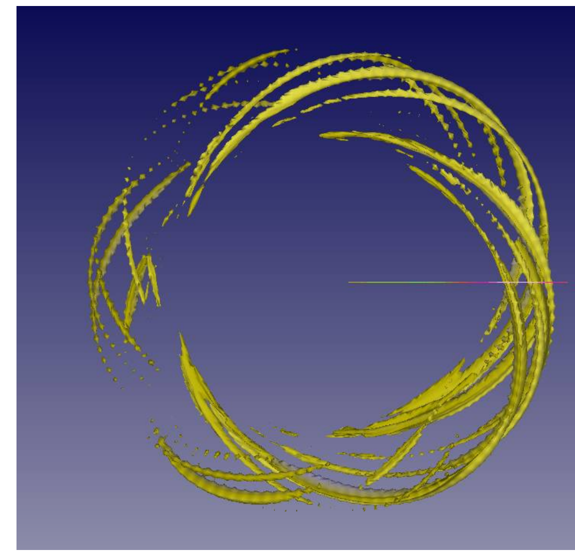
NSTX 129015 Spherical torus
n-pert contour on B-field



Ψ-pert

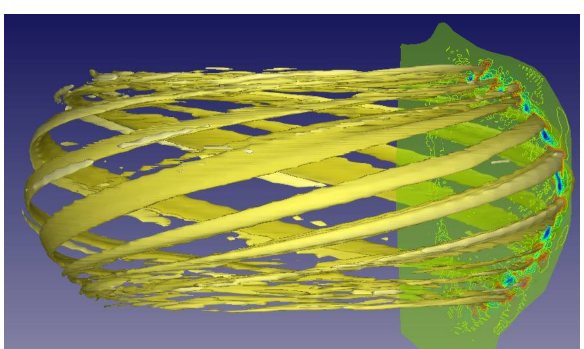


Top view Ψ-pert :
toroidal n=3,1

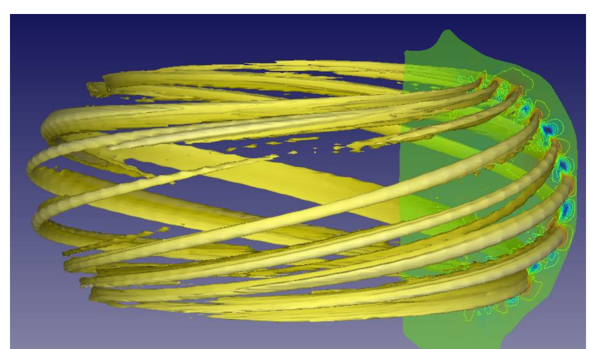


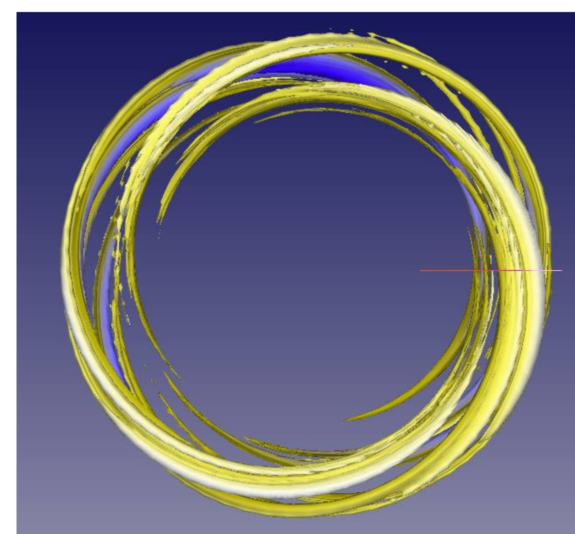
DIII-D

DIII-D 126006 tokamak
n-pert



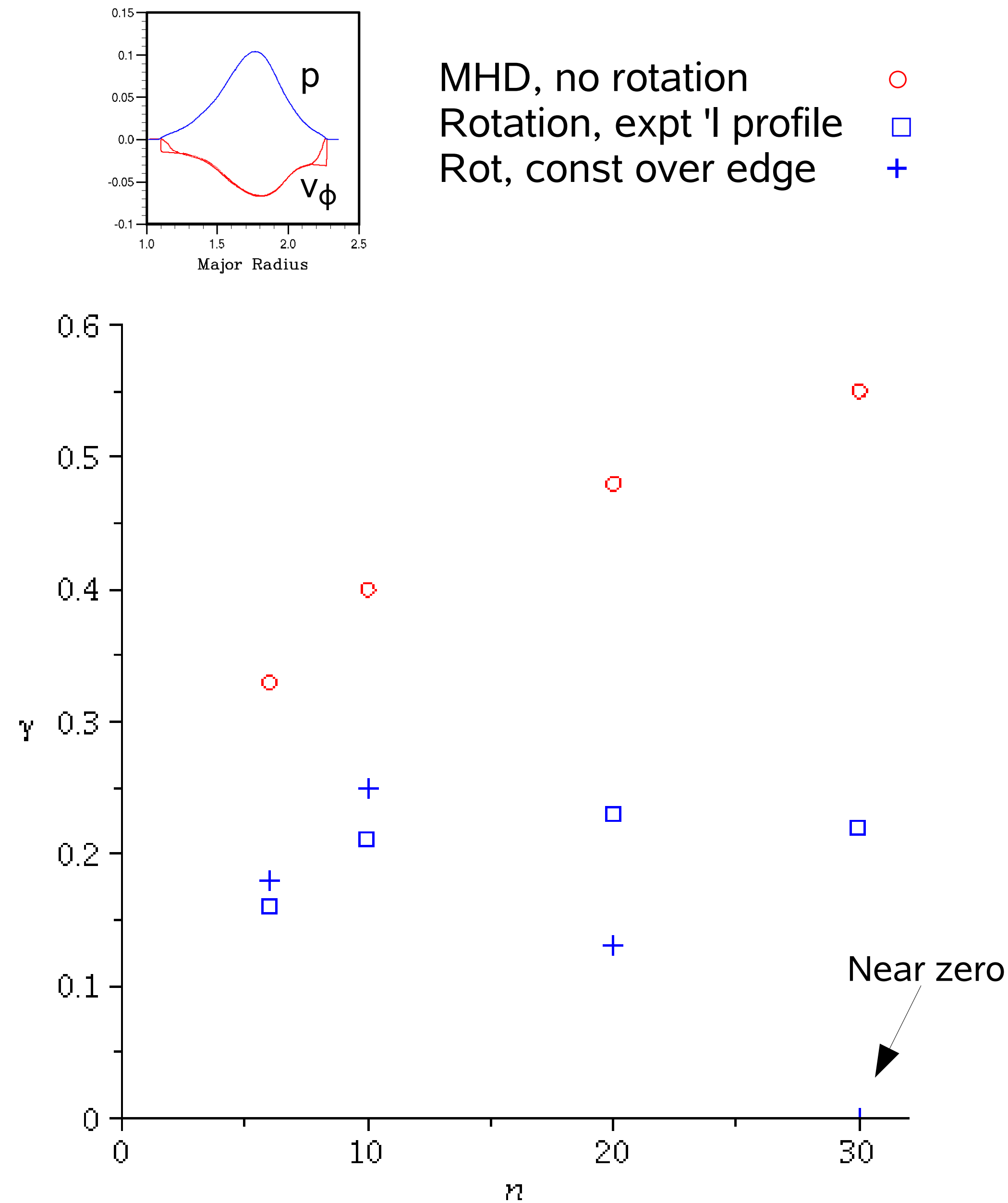
Ψ-pert





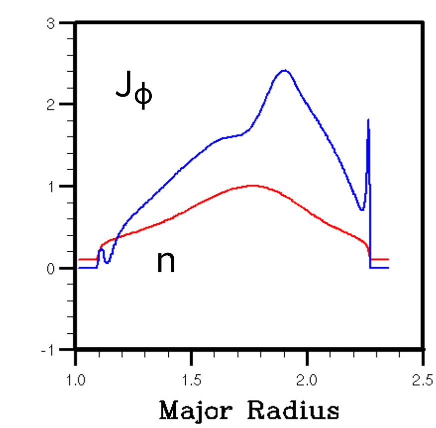
Linear Growth Rates: Toroidal rotation

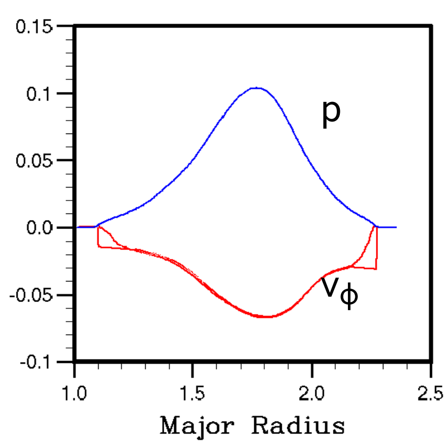
- Linear growth rates for free boundary DIII-D 126006 case, matching nonlinear run
  - 5X actual resistivity
- Toroidal rotation is stabilizing
- Edge rotation is more stabilizing than rotational shear at higher n
  - Expt'l rotation profile sheared over edge region (small but finite at plasma ,separatrix)
  - Compared to constant edge rotation (const Ω over ψ_N=0.7-1, where separatrix=1; sharp drop to zero outside plasma)
- Mode extends beyond separatrix to wall



Linear eigenmodes

- MHD
- MHD + rotation
- MHD + rotation, constant-edge

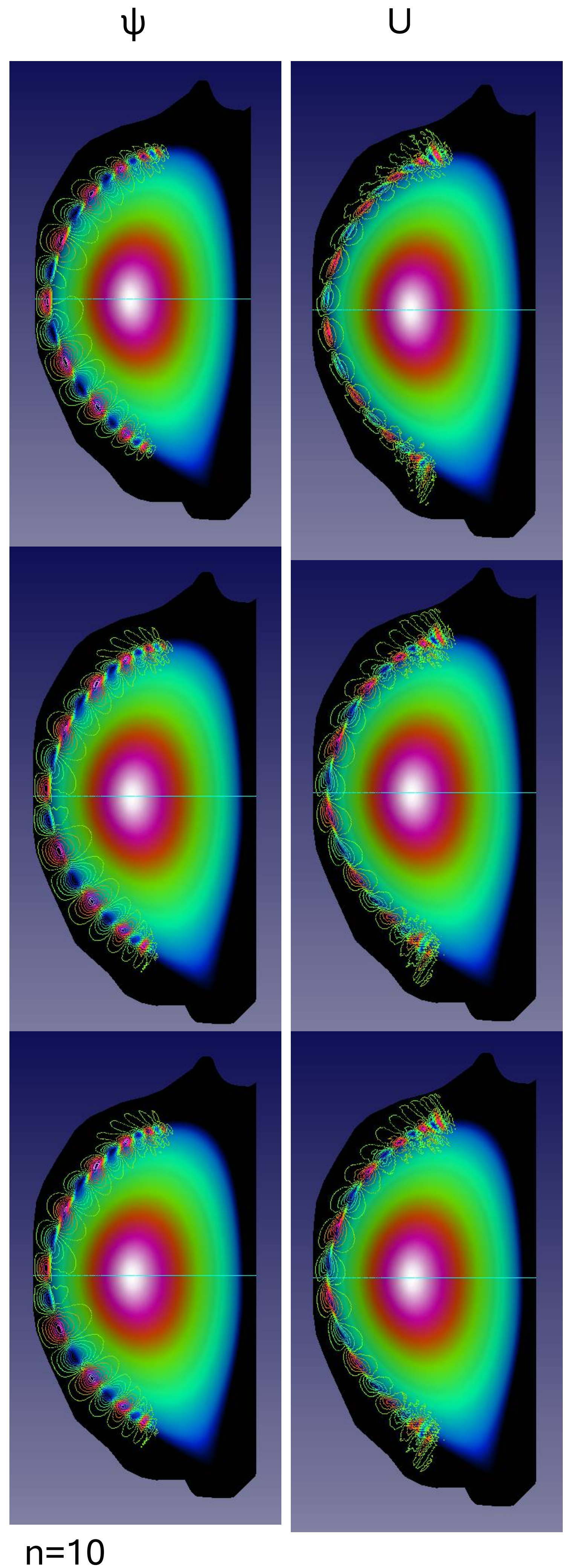


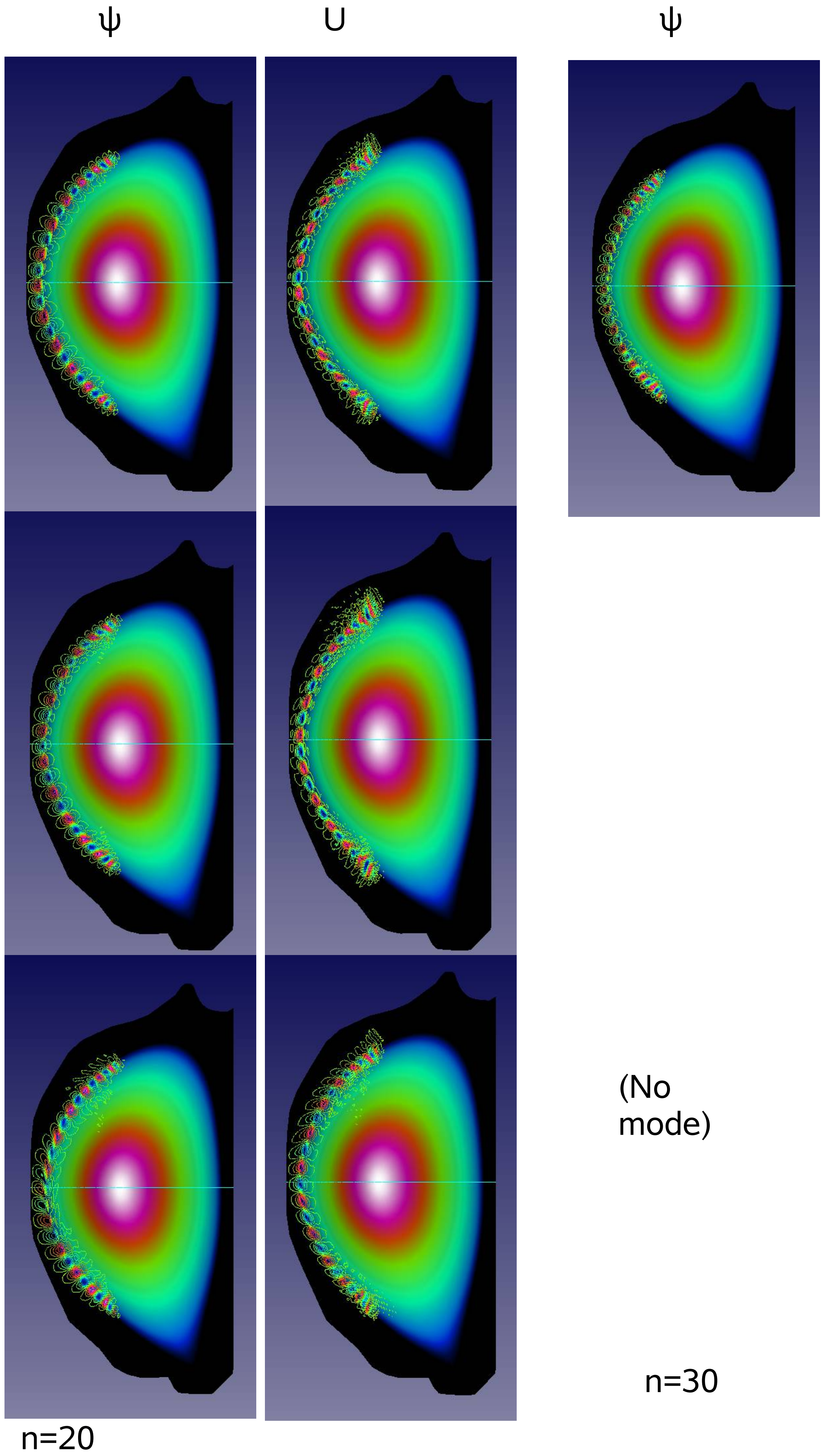


MHD

MHD +rot

MHD +rot, const edge




ψ
U
ψ
(No mode)
n=30
n=20

Nonlinear ELM differs from linear mode

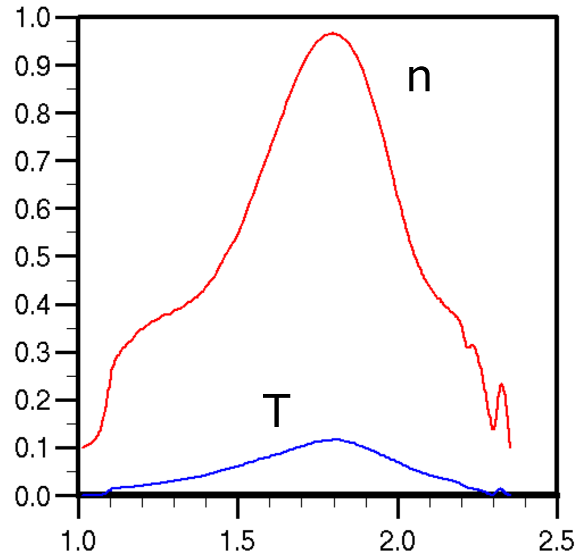
- Magnetic tangle reduces growth rates
  - Only “unstable” part of tangle can respond to a transverse perturbation; “stable” part remains unchanged
- Previously, showed that changing the “unstable” tangle loops by moving the boundary wall changed the nonlinear growth rate (Sugiyama, PoP 2010)
- Nonlinearly, strong toroidal harmonic consolidation, including $n\pm1$ beating, reduces early ELM to moderate wave numbers, despite increase of linear growth rates with n.
  - Consolidation may be increased by the tangle, since tangle loop spacing near X-point is strongly constrained by equilibrium field line spacing, independent of driving perturbation (testable expt'ly?)
- Direct comparison shows that nonlinear ELM growth rates are smaller than linear eigenmodes (non-rotating case)
  - DIII-D 126006 nonlinear ELM had max $\gamma=0.13$, dominant n=10,13 at ELM outburst
  - Difference even with 'free-boundary' linear eigenmodes

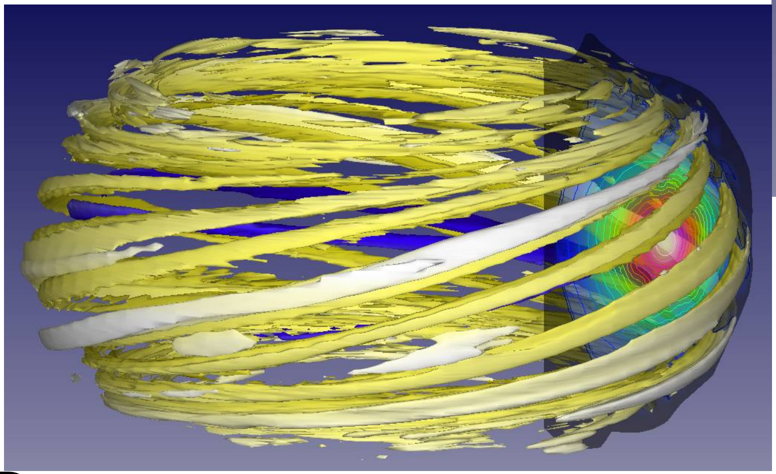
RMP stabilization – any other factors?

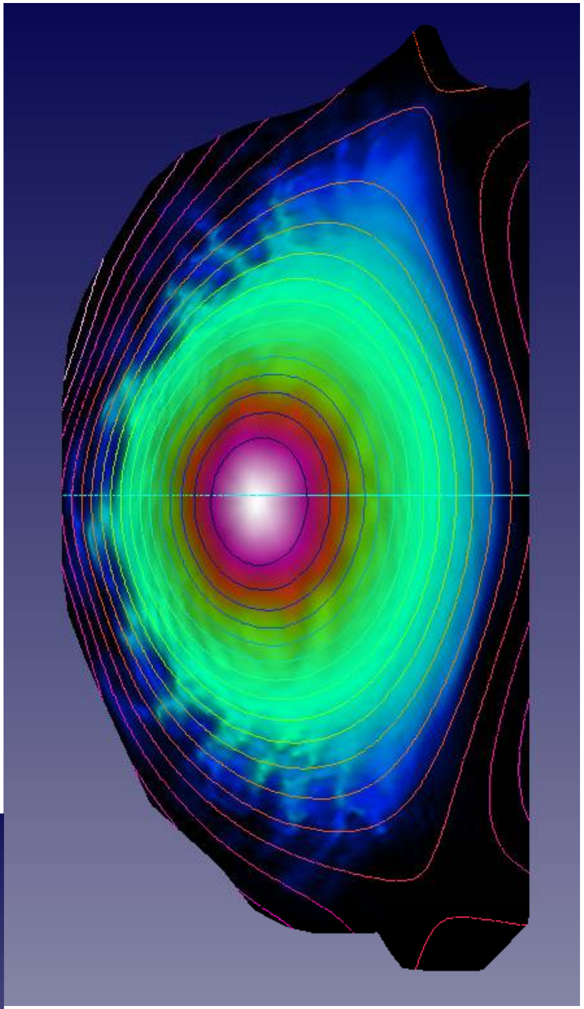
- The DIII-D 126006 case was from a time when RMP had stabilized the Type I ELMs.
  - But, simulation without RMP field showed an MHD ELM (at 5x actual resistivity, other dissipation larger, no rotation). Weaker than some other DIII-D Type I ELMs, but still large.
  - Also found slower growing, large low-n interior mode; mode also seen in experiment when toroidal rotation reduced
- Toroidal rotation alone does not explain experimentally observed stability or stabilization of interior mode; in fact, it increases ELM and speeds up interior mode growth somewhat.
  - Two-fluid alone has weak effects (on MHD unstable modes).
- Two-fluid effects combined with toroidal rotation appears more strongly stabilizing, both for ELM and associated internal mode.
  - Also for other, non-ELMing MHD edge instabilities
  - Numerical instability with two-fluid; long time stabilization unclear.

DIII-D EHO has characteristic shape

- MHD edge instability exists
- Smaller growth rate than ELM
- Like ELM, rapid growth to macroscopic size
- Single density 'ribbon' (wide poloidally, narrow radially) peels off to outside, largest near midplane
  All cases: MHD, 2F, rotating
- Toroidal rotation somewhat stabilizing in MHD





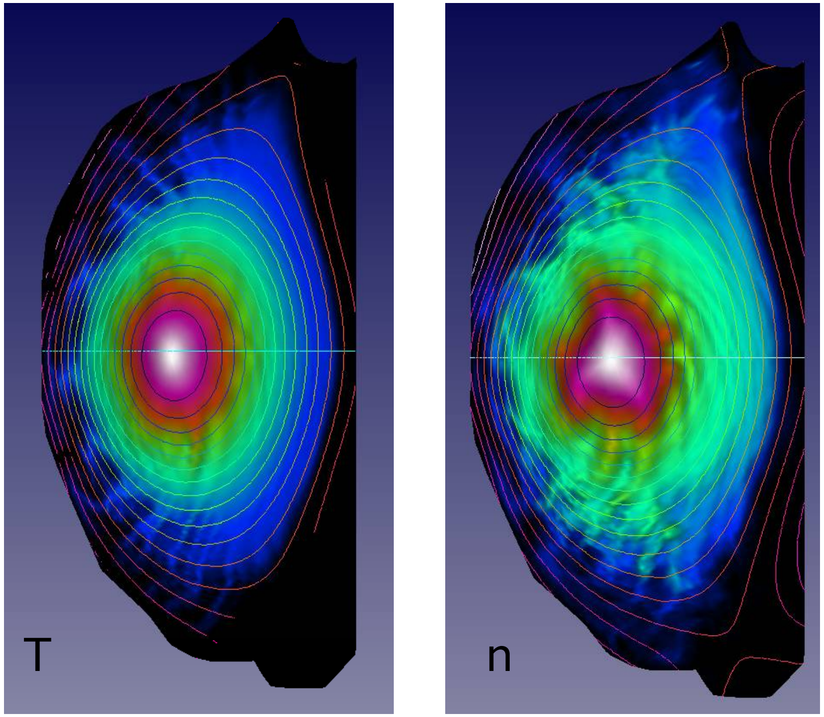


n

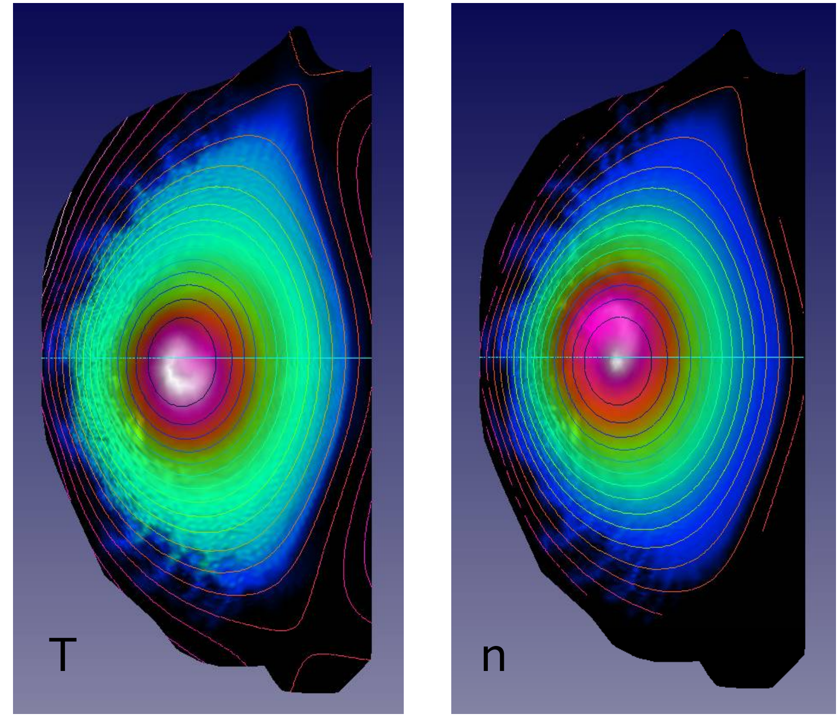
n-pert

128542
Toroidal rotation

Two-fluid plus rotation reduces edge instability and coupling to interior low-n mode



MHD, no rotation

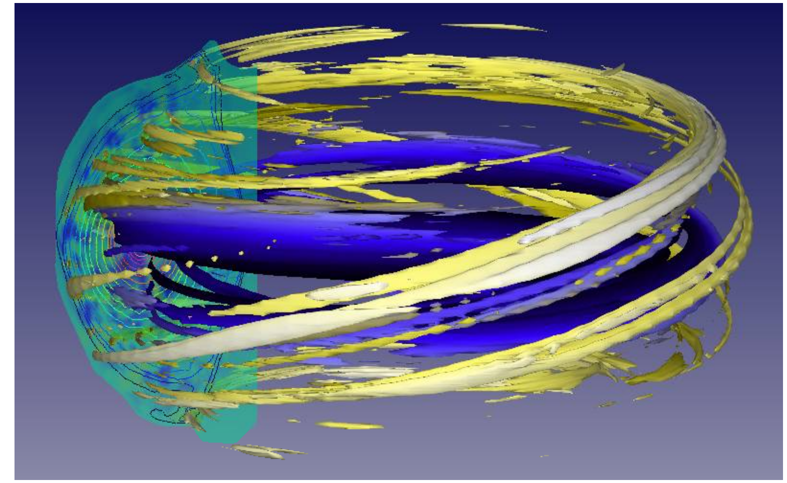


Two-fluid+rotation

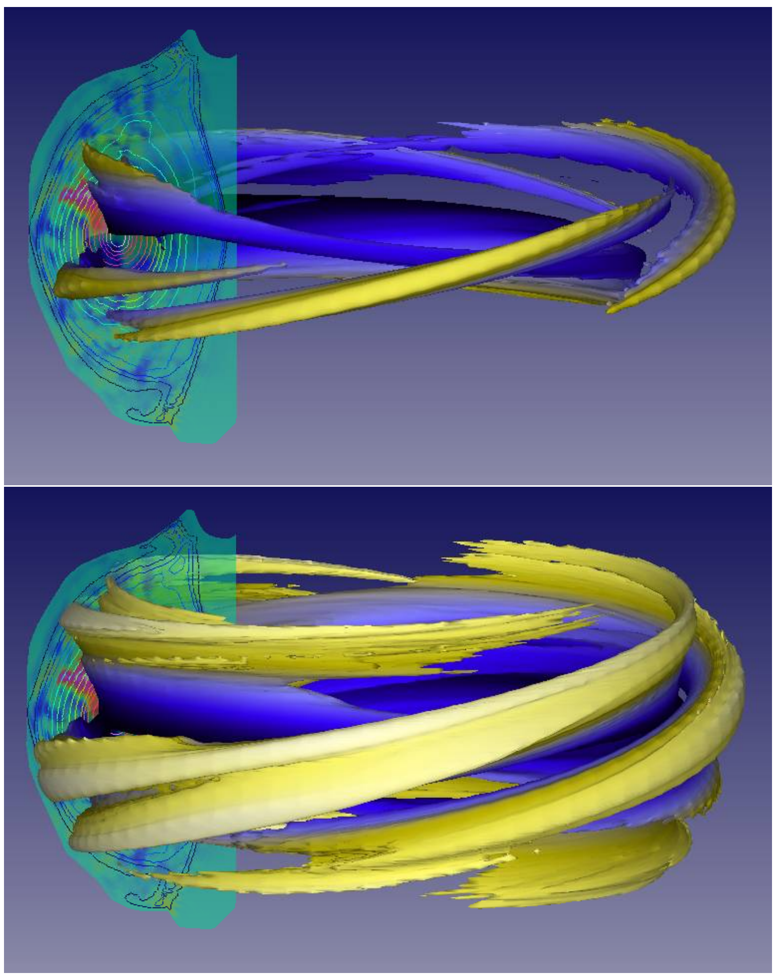
- All cases at same time t=77
  - MHD already has interior low-n mode with equal |n-pert| to edge.
- Rotation, two-fluid are somewhat stabilizing compared to MHD.
- Two-fluid plus rotation with the expt'l profile is much more stabilizing. Weaker, broader midplane edge instability, single pulse, still hits wall. No interior mode.

Strong interior mode at later time. Similar to ELM interior mode; not conventional island. Seen in ELM expt, but *not* EHO.

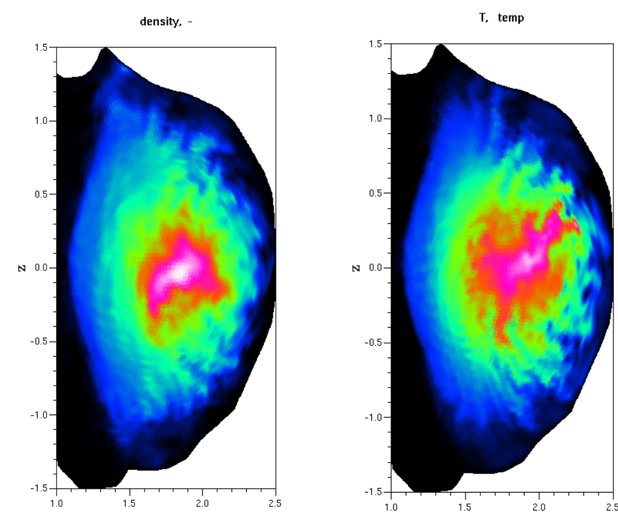
Perturbed density contours : $\check{n}/n_o$=0.07



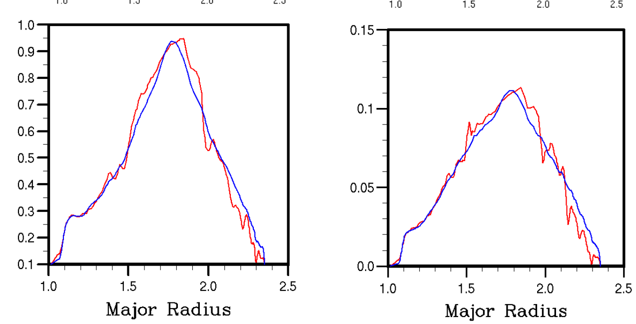
Perturbed poloidal flux contours, colored by total pol flux: 0.0015 top, 0.0004 bottom



MHD η=3x10^{-8}, factor 24x high



n (left)
T (right)
at $\phi=\pi$



Midplane profiles

(blue is toroidal average)

EHO MHD

Next steps

- Magnetic tangle and stochasticity are margnally resolved in simulation
  - Very small scales; especially near X-point, where grid has difficult shape
- Two-fluid model appears important for plasma edge
  - Two-fluid numerical stability problems – needs work!
- Nonlinear evolution differs from linear eigenmodes, even with free boundary – better linear model?
- Toroidal rotation + two-fluid effects, etc: V&V
  - Need better data (waiting on a number of cases; Edge joint milestone 2011 should help)
- (Not CEMM) Relate tangle to plasma perturbation theory; what is stochastic field for turbulent transport?

Physics so far

- Edge instabilities in a plasma with magnetic X-points on a freely moving boundary experience strong nonlinear effects (ELMs, ELM-free MHD oscillations)
  - Magnetic field develops near-Hamiltonian tangle-like structure, stochasticity
  - Tangle effects tend to be stabilizing nonlinearly
- Tangle introduces nonlocal connection, global effects
- Nonlinear evolution differs from linear eigenmodes, even with free boundary
- Potential coupling of edge instability to large, low-mode-number internal mode at low toroidal rotation
  - Reduced by two-fluid+rotation, not rotation alone