Reduced-ELM and ELM-stable regimes-rotation and two-fluid effects

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C-Mod/NSTX Pedestal Workshop
7-8 Sept 2010
PPPL

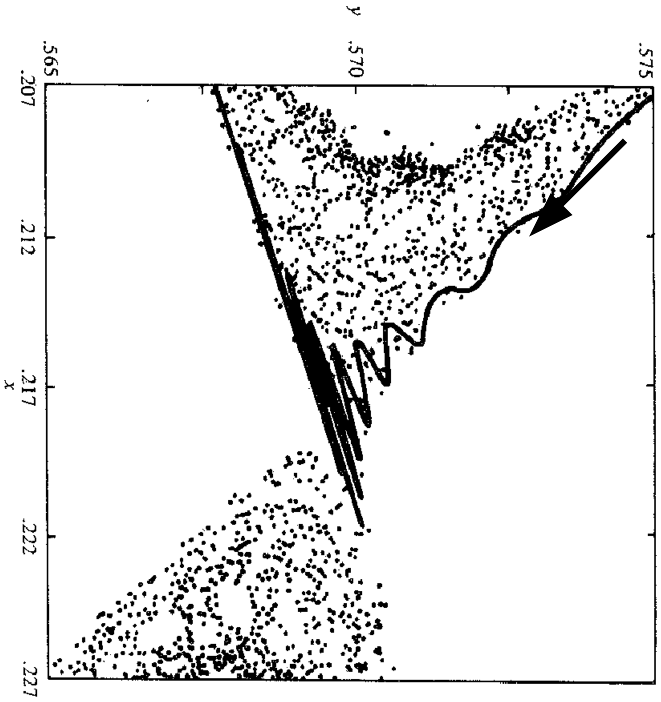
Topics

- Large ELMs: MHD nonlinear simulations with the M3D code
  - “Homoclinic-like” magnetic tangle and magnetic chaos in the plasma edge exists; important effects on nonlinear ELM
- Reduced and stabilized ELMs – preliminary results
  - MHD density evolution
  - Toroidal rotation
  - Two-fluid effects
- Comments on requirements on experimental data for simulation and analysis

Type I ELM Simulations

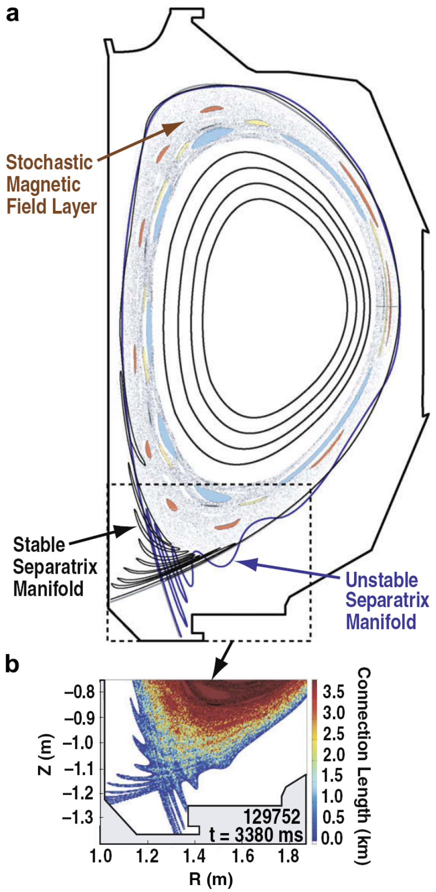
- MHD and extended MHD simulations of large Type I ELMs in DIII-D carried out with the M3D code; RMP stabilization
  - Discharges 119690 and 126006; 200-300 hours on 432 cores, Cray XT-4
  - L. Sugiyama et al, *Phys. Plasmas* June 2010; L. Sugiyama, SciDAC 2010; APS-DPP invited talk 2009; *J Phys: Conf Series* 2009 (SciDAC).
  - Earlier work: H.R. Strauss, et al. IAEA 2006 ELMs; IAEA 2008 and *Nucl. Fusion* (2009) RMP stabilization of ELMs
- Identified the role of the freely moving plasma boundary in D-shaped plasmas with magnetic X-points
  - X-points on or near the plasma boundary (magnetic separatrix) allow the nonlinear magnetic field in the plasma edge to form homoclinic-like magnetic tangles (mathematically robust!)
  - Tangle allows (1) penetration of the initial ballooning type instability deeper into the the plasma interior and (2) can destabilize a secondary inboard instability that also expels particles and energy to the divertors, (3) role of interchange instability instead of tearing reconnection
  - ELM has quasi-periodic, partly stochastic behavior

Perturbation of X-point produces asymptotic field line splitting → "homoclinic" tangle → chaotic field



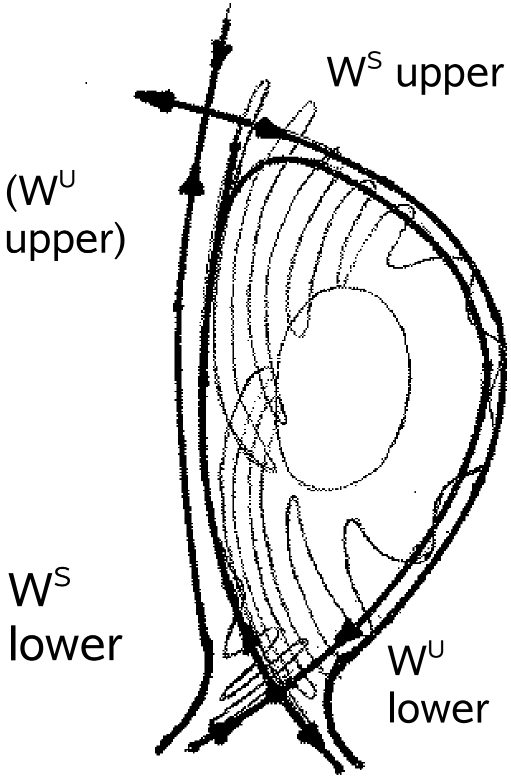
Exact Hamiltonian (perturbed pendulum)

Lichtenberg & Lieberman, Regular and Chaotic Dynamics (1992).



DIII-D with RMP vacuum field
δB/B ~ few x 10^{-4}

T. Evans, et al J. Nucl. Mat. (2007)



ELM schematic

- Toroidal field is a Hamiltonian system with 2 degrees of freedom
- Mathematical perturbation theory is well-developed for 2 d.o.f.

(eg, Lichtenberg and Lieberman 1992)

Many features match experiment (DIII-D ELM)

- ELM crash, initially on outboard side, later involves inboard (Cases were initially ballooning unstable in MHD)
  - Ballooning fingers outward form helical ridges along the magnetic field; rapidly saturates by reduction of near-midplane *density* gradient
  - Temperature profile less affected than density
  - Direct losses of particles to divertors from near X-points
  - Secondary inboard instability and inboard losses; quasi-periodic pulses
  - Slower healing to near-original configuration
- Time scales of stages approximately match experiment (10's to 100's μsec)
- Helical filaments aligned with equilibrium field are a robust nonlinear feature; toroidal and poloidal asymmetry
- Helical field lines onto divertor roughly follow equilbrium field lines, but evolve in time
- RMP stabilization – fast onset RMP field changes the plasma edge almost like a 'mini-ELM', reduces density gradient, stabilizes ELM

Lack of detailed data for verification!

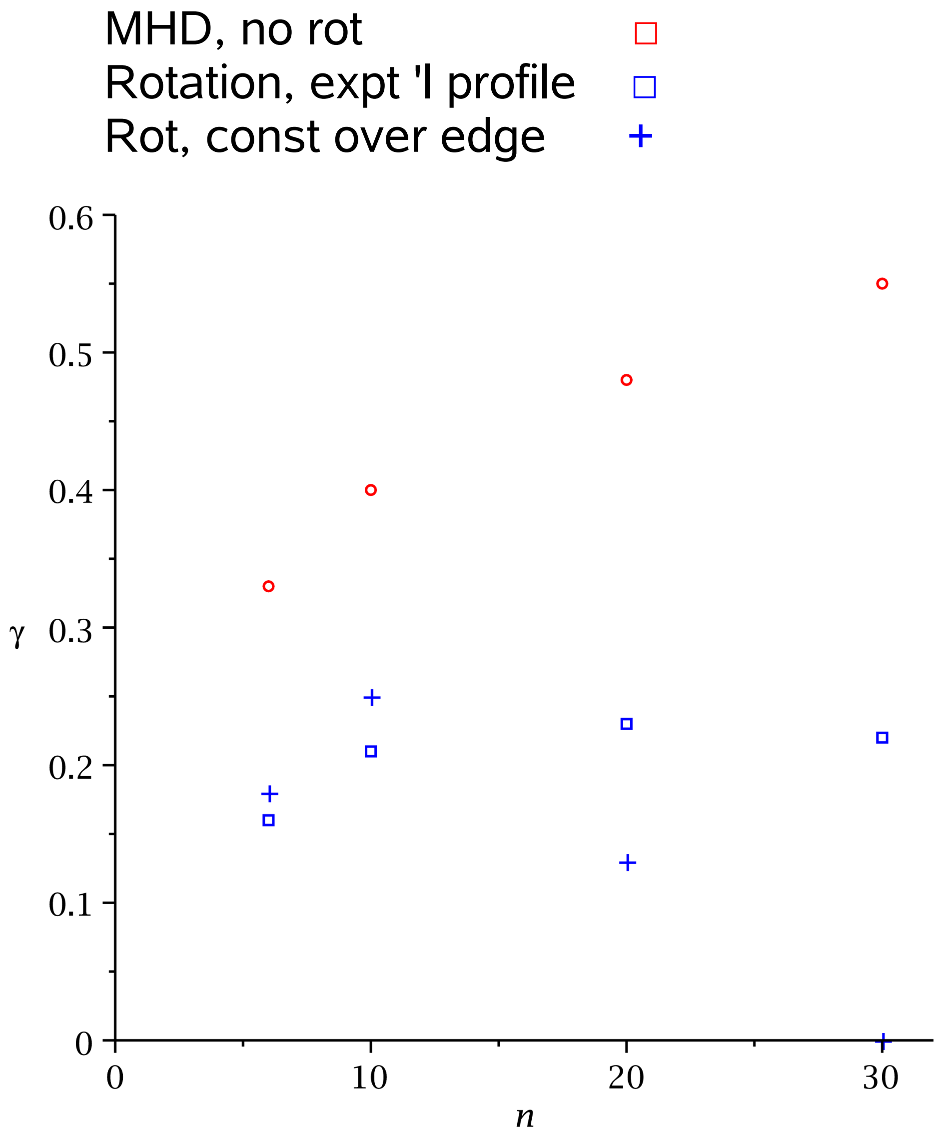
- The Type I ELM cases were well analyzed experimentally, but do not have sufficiently detailed fast pictures of plasma edge or divertor region to compare to simulation results
  - Magnetic stochasticity means that time-history will not match in detail
  - Approximate plasma edge data (tanh fits to density, pressure profiles; toroidal rotation near edge is uncertain; poloidal rotation exists?)
  - Many features of the simulation can't be measured directly: need collaboration on new expt'l measurements and code diagnostics combined with 3D visualization of both expt and simulation
- Large ELMs in simulations interact with the plasma interior!
  - 119690 had q=1 sawtooth or partial sawtooth (also seen in expt)
  - 126006 with no toroidal rotation had large q≈2 mode (not standard island; interacts with wall). Exp't saw large internal mode when toroidal rotation was lowered deliberately.
- ELMs, linear and nonlinear, interact with the surrounding wall.
- Instead of waiting for data, consider factors that reduce ELM growth rate or produce non-ELM MHD oscillations

General results

- Results for a number of cases show that large and medium sized ELMs have fairly typical nonlinear behavior (Type I, III, ...)
  - Details differ depending on strength, configuration; smaller ELMs are less extreme than the Type I cases
- Strong nonlinear consolidation of toroidal harmonics leads to relatively low mode numbers in MHD; growth rates not linear ones
  - Poloidal, toroidal asymmetry makes it hard to define mode numbers
- Resistivity increases linear and nonlinear growth rate over ideal MHD (expected for ballooning), down to actual levels in experiment
- Resistive MHD can be too unstable compared to experiment
- Complicated interactions depend on parameter regime, mode size
  - Toroidal rotation, two-fluid effects, density evolution

Example: RMP stabilized DIII-D ELM

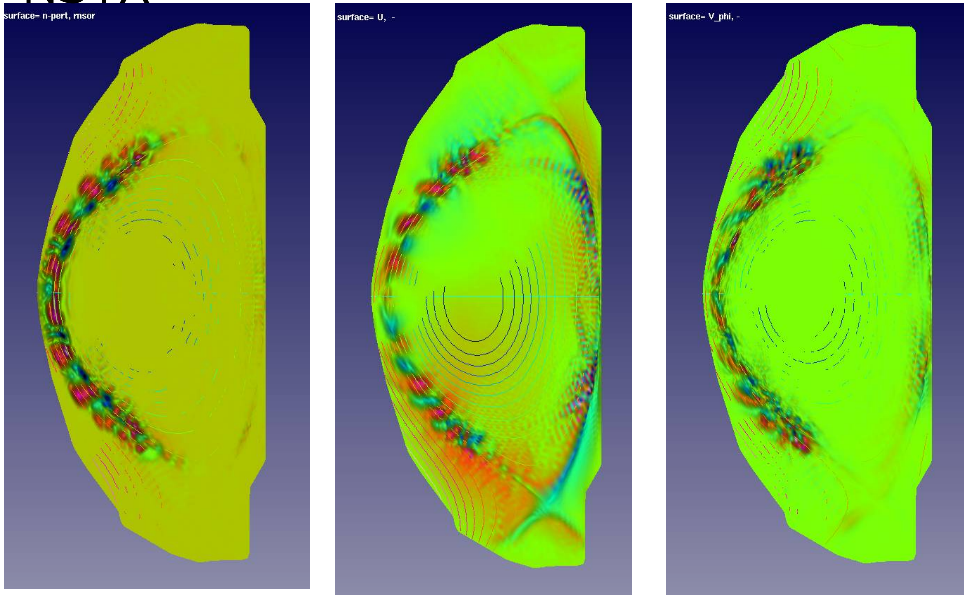
- Discharge 126006 data was taken from RMP ELM-stabilized part of discharge, but simulation showed a large ELM in resistive MHD at ≈ 5x resistivity (but weaker than no-RMP case 119690)
- Linear perturbation shows strong stabilization by toroidal rotation
  - Not rotational shear at higher n: compare expt'l profile with shear or constant rotation near edge (over ψˆ= 0.7 - 1.0)
- In NL, two-fluid effects alone are not sufficiently stabilizing to ELM at the lower n-numbers seen in the nonlinear instability
- Two-fluid+rotation more stable
  - Interaction of edge with interior macroscopic modes is also reduced by the combination



Linear growth rate
vs toroidal mode number

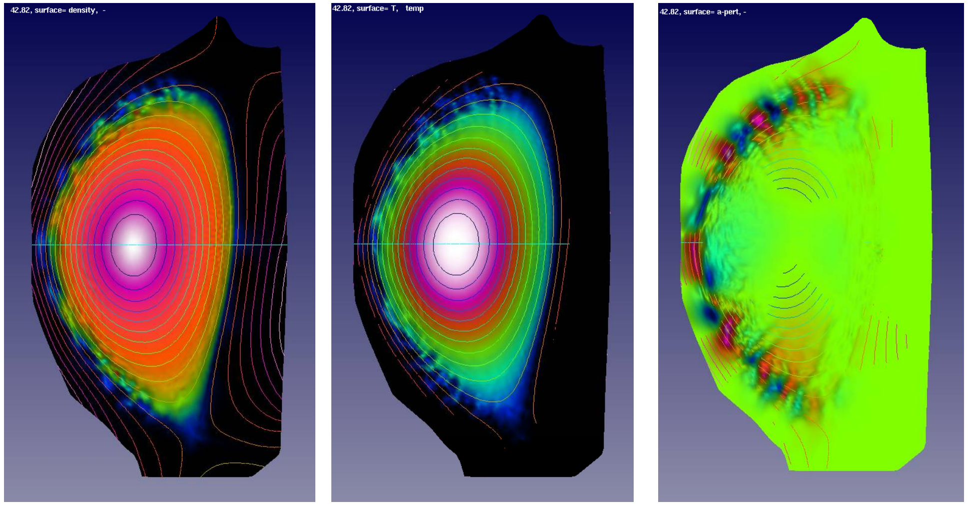
NSTX ELM differs from DIII-D: geometry

NSTX



n-pert U v_ϕ

DIII-D



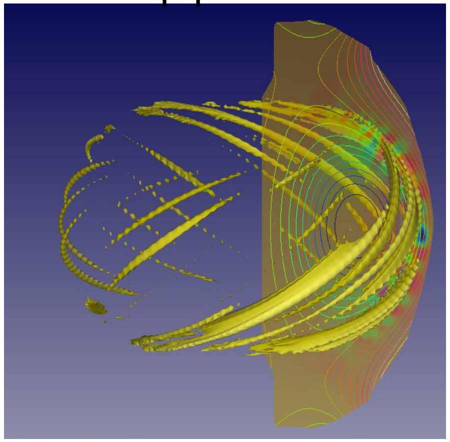
n T ψ-pert

NSTX upper X-pt is closer to plasma; early ELM is more restricted near mid-plane, more symmetric about midplane

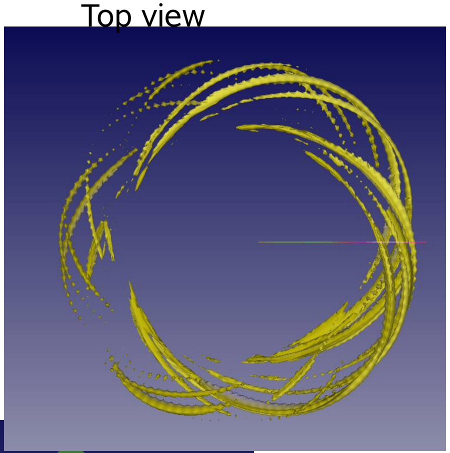
NSTX strongly toroidally asymmetric

Reason NSTX ELM is *de*stabilized by n=3 midplane field?

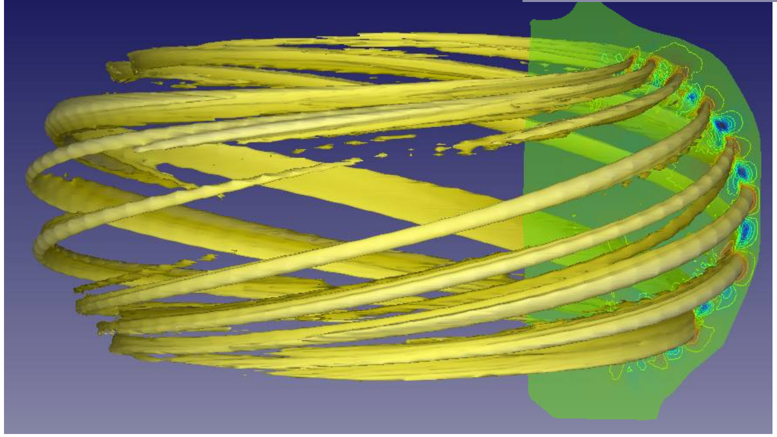
NSTX ψ-pert



Top view



DIII-D 119690

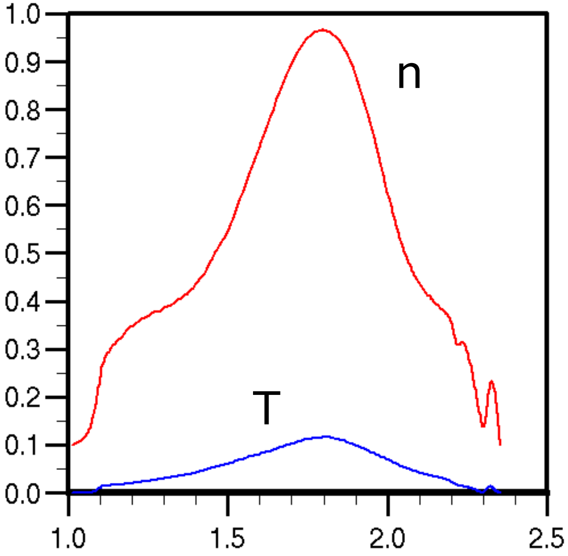


Smaller or no ELM cases

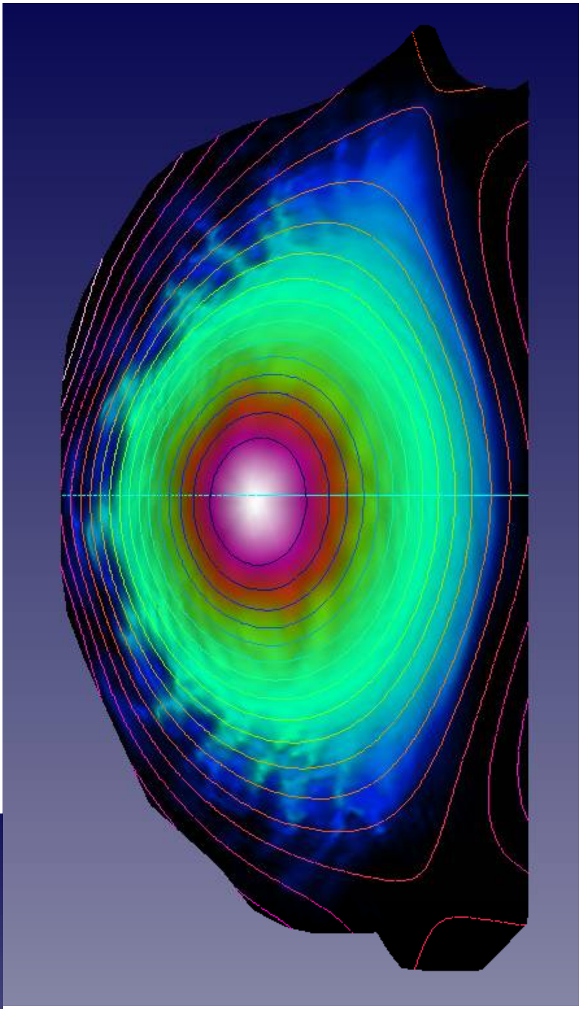
- DIII-D 126006, ELM stabilized by applied RMP
- NSTX ELM stabilized by liquid lithium divertor
- DIII-D EHO (no ELMs)
- C-Mod EDA with QCM oscillation (no ELMs)
- All these cases have smaller growth rates (linear or nonlinear) than DIII-D large ELM cases;
  - MHD oscillations give nonlinear edge losses smaller than for ELMs
  - Potential for strong internal modes in MHD, not always in expt.
- Stabilizing effects
  - Density evolution (continuity eqn; strong thermal $\kappa_\parallel$ or $\kappa_\parallel$=0)
  - Toroidal rotation (including DIII-D RMP case)
  - Two-fluid effects may be stabilizing or destabilizing

DIII-D EHO

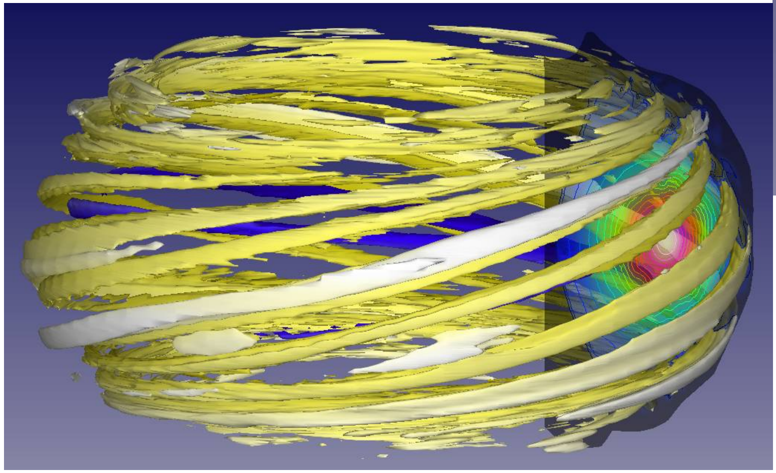
- Edge instability exists
- Smaller growth rate than ELM
- Density 'ribbon' (wide poloidally, narrow radially) peels off to outside, largest near midplane
- Ribbon in MHD, 2F, rotating cases



n



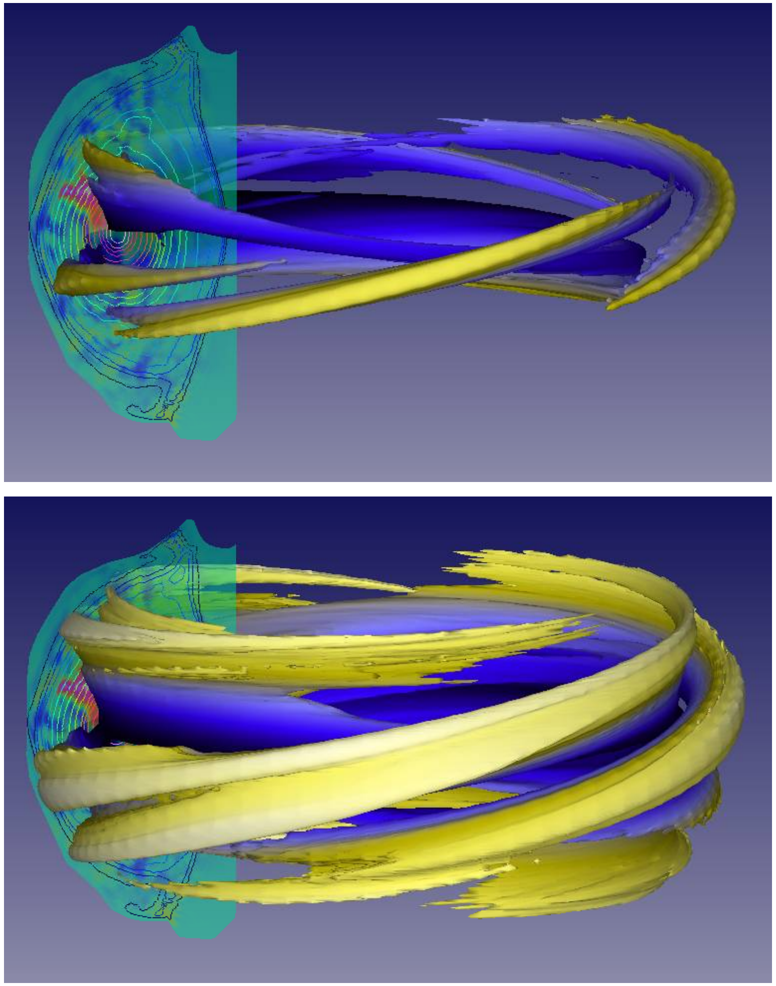
n-pert



128542
Tor rotation

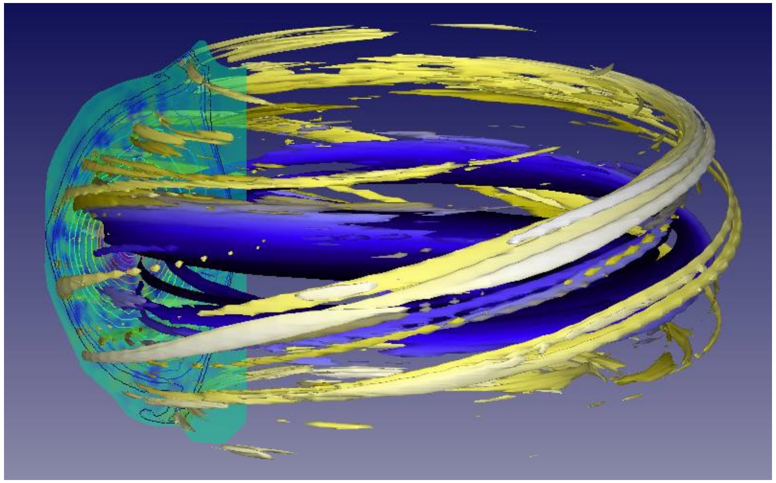
But, DIII-D EHO case shows strong interior MHD mode at later time! Strong interior losses, *not* seen in expt.

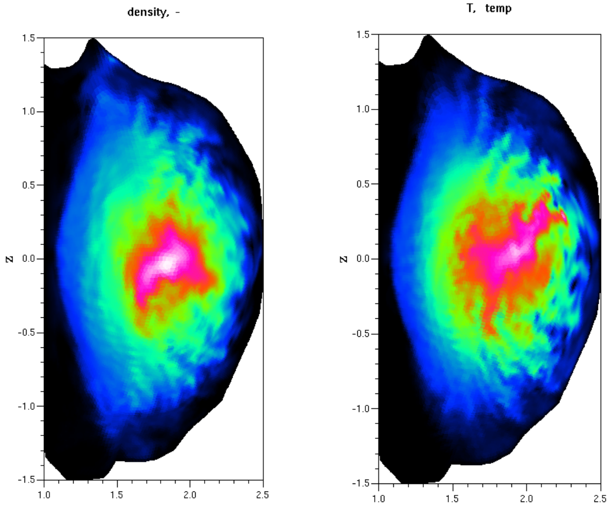
Perturbed poloidal flux contours, colored by total pol flux: 0.0015 top, 0.0004 bottom



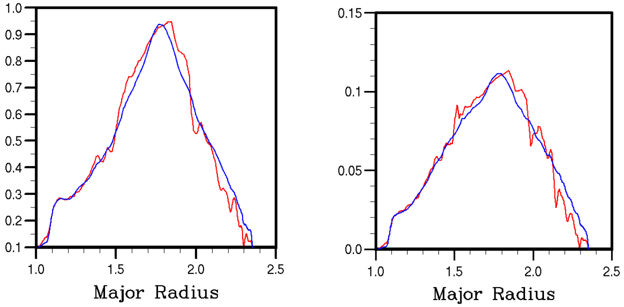
MHD $\eta=3\times10^{-8}$, factor 24x high

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





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

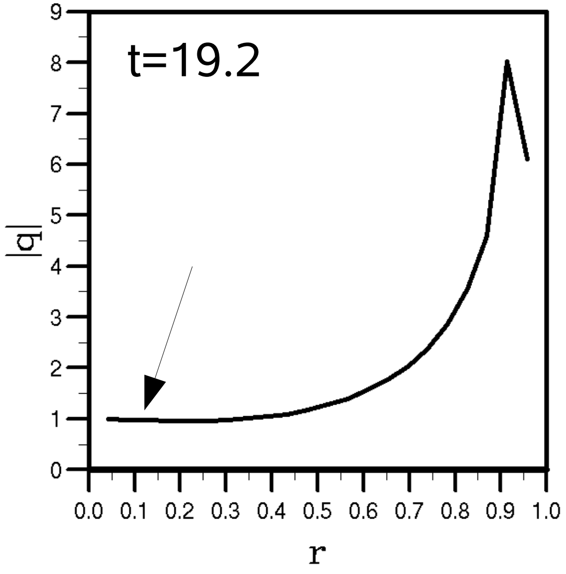


Midplane profiles

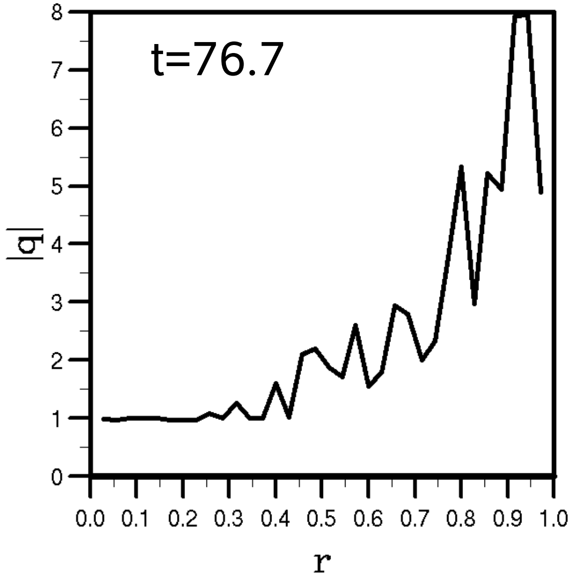
(blue is toroidal average)

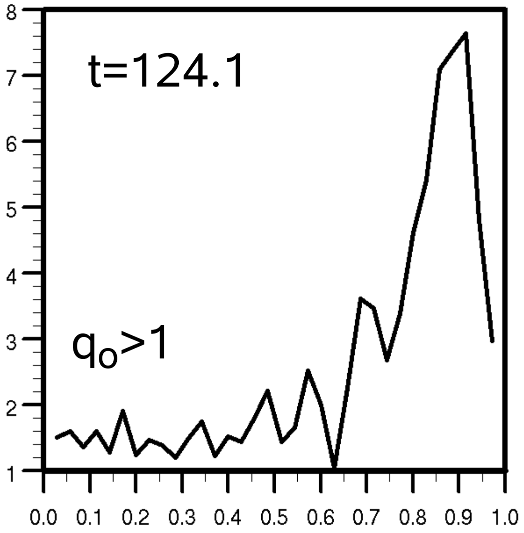
Equilibrium reconstruction: interior may not be accurate

- Central q ≈ 1 leads to large macroscopic interior modes that grow on slightly longer scales, but eventually couple to, and dominate, the edge mode
- No sawtooth crash: q_o rises above 1



Early time ≈ equilibrium
EHO

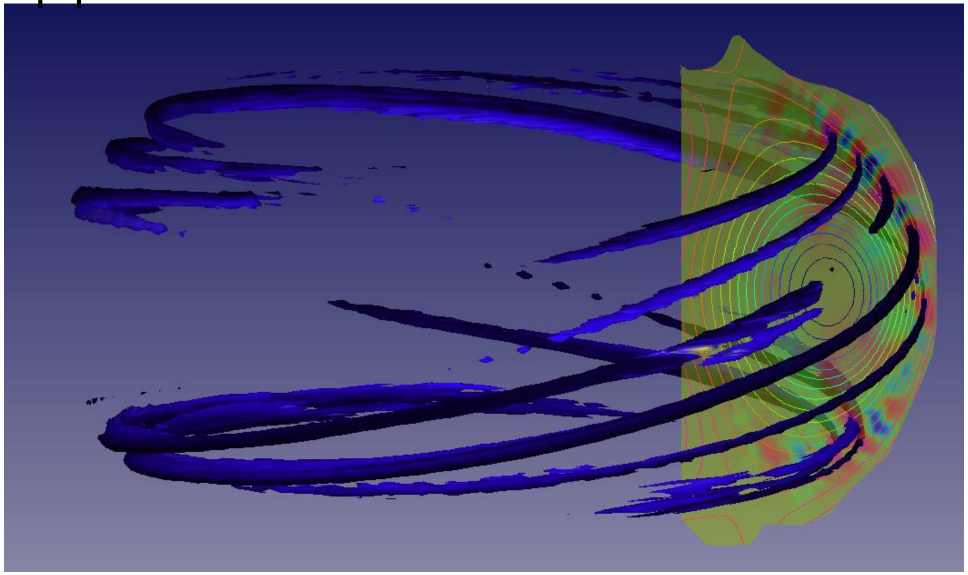




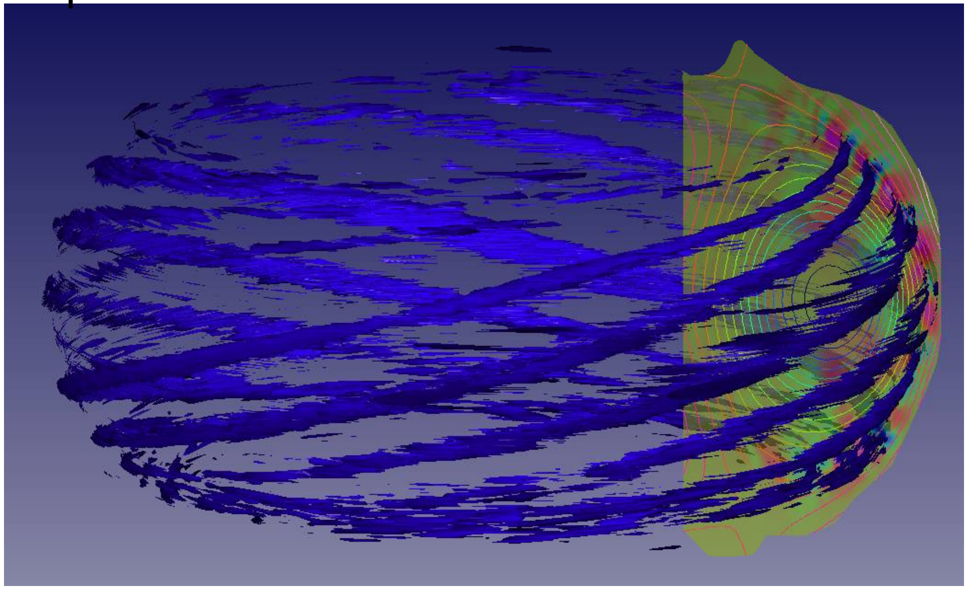
Two-fluid effects reduce edge and interior modes

- MHD has rather strong edge mode, later develops large interior mode
- Two-fluid effects reduce edge mode to a something closer to an EHO
  - Shape different from ELM
  - Single main helical ribbon of density moves out of plasma edge to wall; n-pert >> ψ-pert
- Toroidal rotation alone may *increase* growth rate of edge and interior mode slightly at actual $v_{\phi o}$ for strongly unstable cases. (Also seen in large DIII-D ELMs.)
- Two-fluid combined with toroidal rotation reduces strength of interior mode, also coupling to edge
- Suggests error fields may also contribute (not considered yet.)

ψ-pert



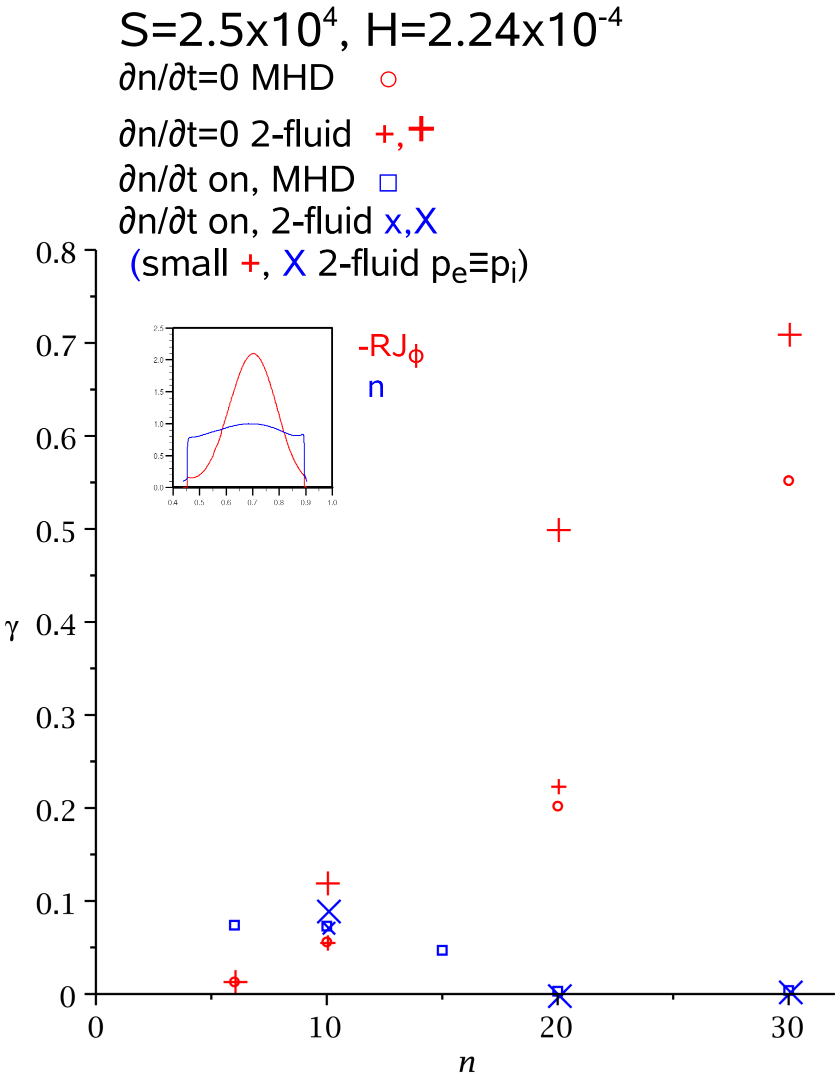
n-pert



EHO t=77.7

C-Mod EDA

- Alcator C-Mod EDA discharge 108032102
  - Two-fluid $H=c/R\omega_{pi}=0.224$ is large
  - Diamagnetic EFIT reconstruction; the measured $n \approx n_e$ and $Ti \approx T_e$ profiles are applied at start of simulation; no I_{BS}
- Resistive mode: Actual resistivity η is $\eta^{-1}=S=1.31\text{x}10^7$. MHD stable or nearly so at $S=1.64\text{x}10^6$; Unstable at $S=2.46\text{x}10^4$, 1/540x actual, shown
- Unstable, but growth rates mostly small compared to high beta, large ELMs
- Density evolution is stabilizing at high n!
- Two-fluid at very small $H=2.244\text{x}10^{-4}$ can be destabilizing for fixed density, high n. Full H probably stable.
- Edge instabilities interact strongly with interior perturbations, in various ways



Linear growth rate vs. toroidal harmonic n (units $[\tau_A=1.42\text{x}10^{-7}\text{ sec}]^{-1}$)

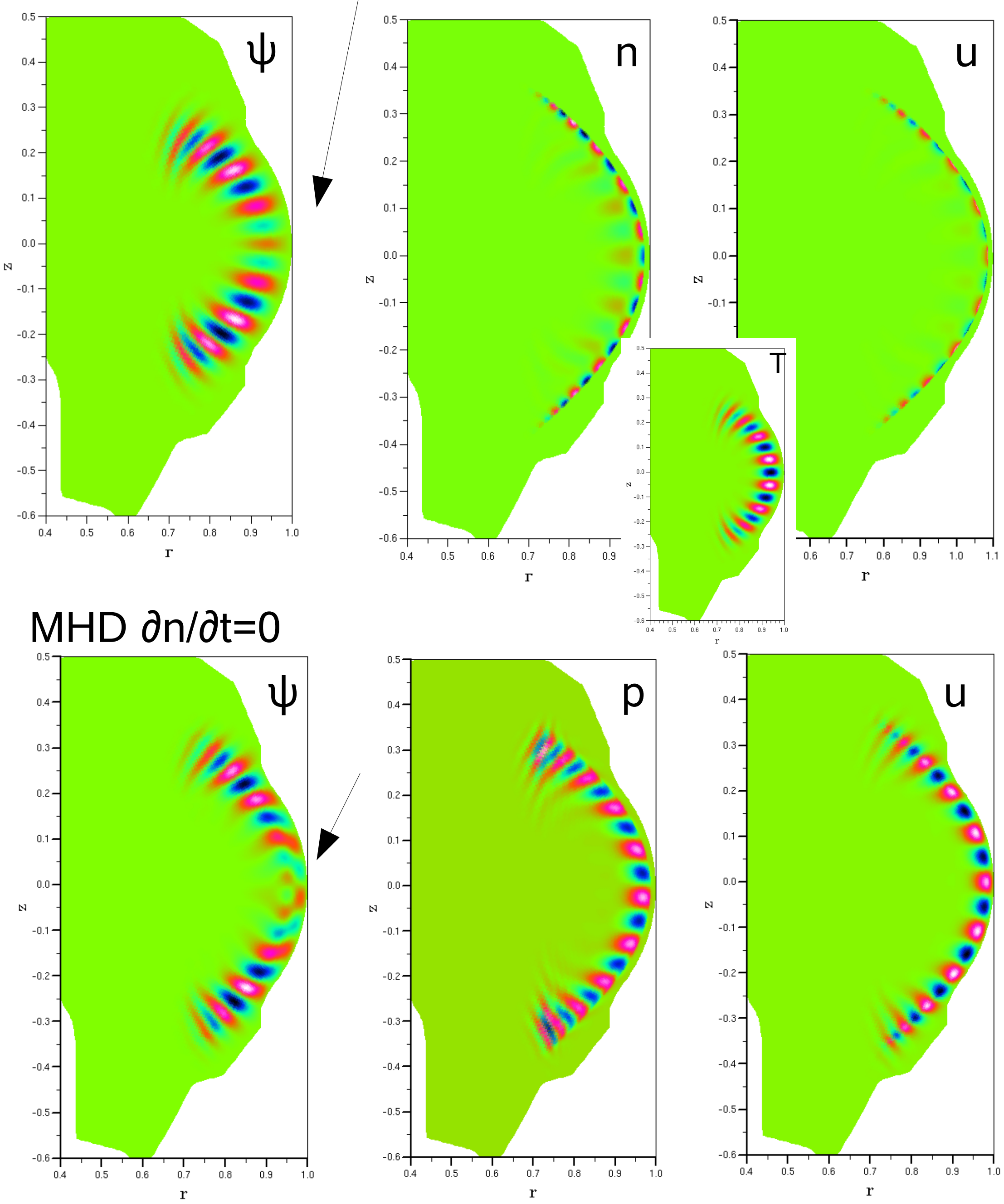
n=10 linear perturbation

- Lower n couples edge to interior plasma modes more strongly
  - Coupling is reduced or interior mode suppressed by ∂n/∂t (large $\kappa_\parallel$ in both cases; in p for ∂n/∂t=0, T for full eqs)
- Small two-fluid H has little effect at n=10, but larger effect at high n
- Magnetic perturbation extends beyond plasma to wall; density barely perturbs separatrix.

MHD ∂n/∂t

Note small ampl of ψ-pert on midplane

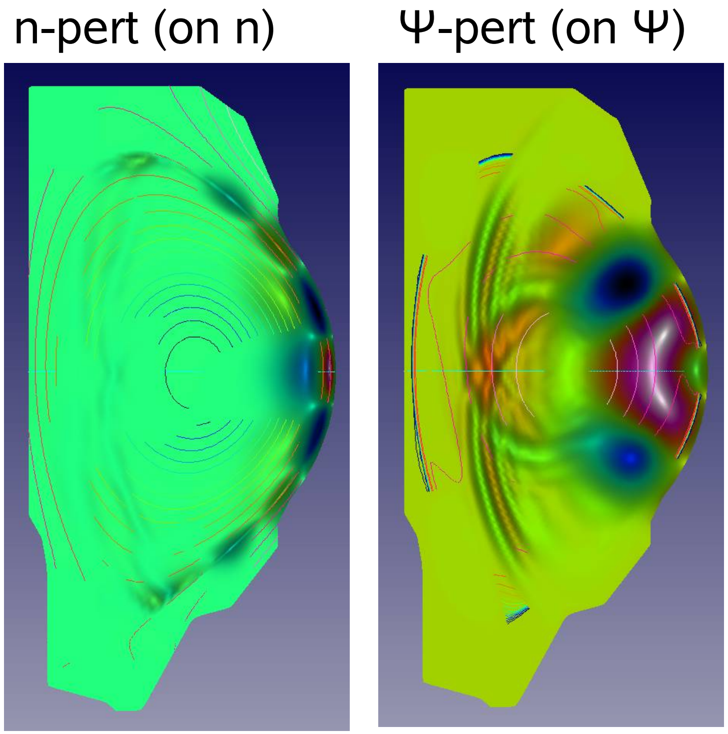
MHD ∂n/∂t=0

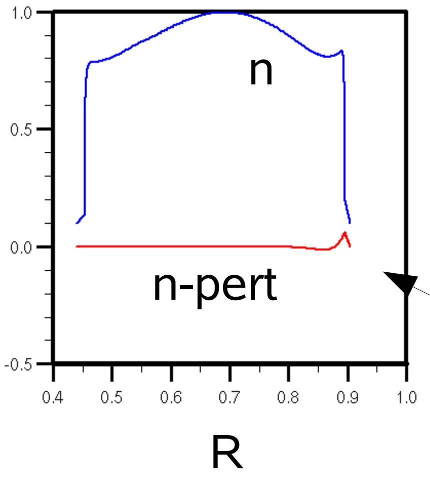


C-Mod EDA

Nonlinear evolution

- Nonlinear evolution with density evolution
  - Strong thermal $\kappa_\parallel$
  - Upwind advection diffusion in n,p and v_ϕ (not in linear perturbation)
- No toroidal rotation.
- Start with full spectrum of toroidal harmonics n≤23.
- Some features are characteristic of ELM-stable, edge MHD oscillations
- Strong nonlinear interaction of harmonics; strong toroidal asymmetry
  - Early single helical band in density; peels off near midplane towards wall
- Low n's dominant, n=1-4, up to 6, despite largest linear growth rate at n≈10
  - Actual experiment has higher n.





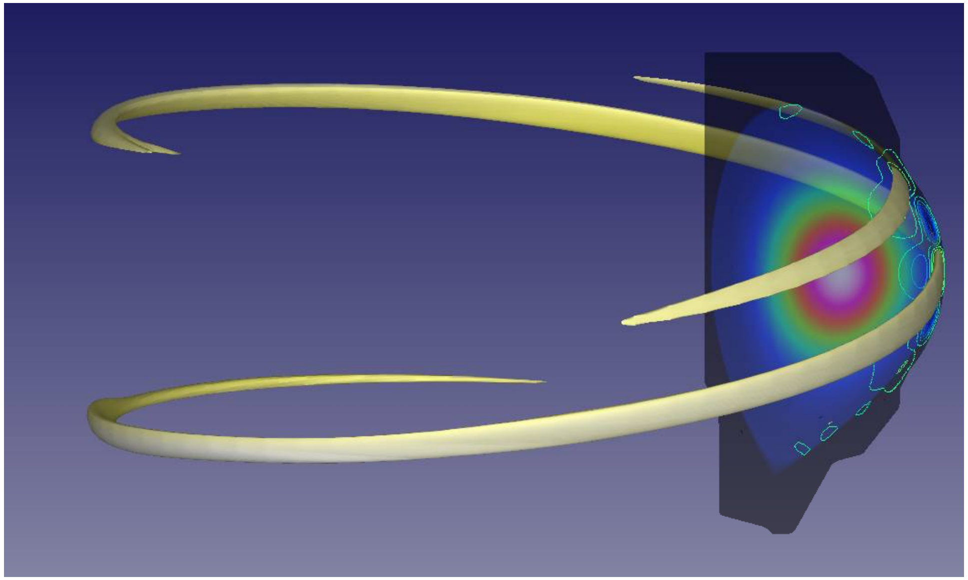
t=140.9
still developing,
γ rising

n-pert peak in pedestal or outside separatrix; small dip inside the peak.

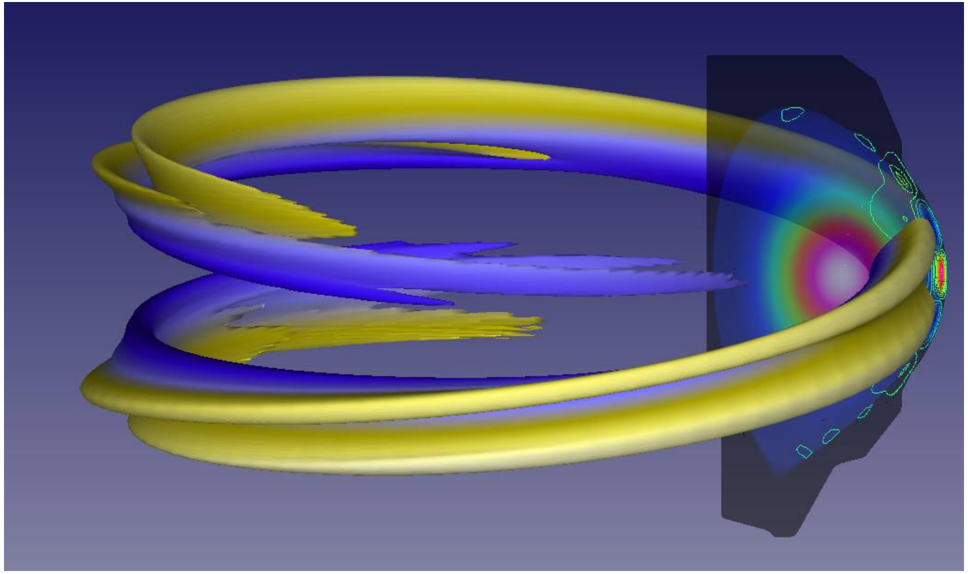
Nonlinear evolution

- NL early growth is slower than linear perturbation growth rates
  - Nonlinear mode interactions
  - Magnetic tangle effect is stabilizing
- 3D contours show single dominant helical band in perturbed n and Ψ.
- Density expelled on mid-plane:
  - n-pert forms radially-thin ribbon with largest amplitude on midplane on outboard side, moving out of plasma; moves out
- Ψ-pert also forms helical band, but has a substantial interior component and perhaps more m/n=2/1 helical winding. It is also largest on midplane outboard.

n-pert t=140.9



Ψ-pert, colored by equilibrium Ψ



Simulation status

- Better experimental data needed
  - DIII-D 126006: RMP and error fields beyond just n=3 RMP
  - DIII-D EHO – better interior equilibrium reconstruction with central q >1
  - C-Mod EDA - kinetic equilibrium reconstruction and rotation profile.
  - Accurate edge toroidal rotation from the pedestal to the separatrix
  - Wall in the equilibrium reconstruction is 'solid wall'? BC's?
- Principal numerical/simulation difficulties
  - Actual (very low) resistivity for nonlinear simulation
  - Two-fluid model has relatively poor numerical stability; do the extended MHD fluid-based models contain all the important effects???
  - High resolution runs for accuracy – large size runs are hard to run for the long wall clock times required for complete ELM crash
  - NSTX: spherical torus at tight aspect ratio and close inboard wall is more difficult than DIII-D
- Theoretical: what sets minimum length scale with magnetic tangle? Kinetic effects – couple to particle model?

Summary

- Simulations of large Type I ELMs show role of magnetic tangle
  - Tangle is a robust perturbation of magnetic X-point – not just in ELMs
- Smaller ELMs (partly stabilized) and no-ELM MHD oscillations
  - Toroidal rotation stabilizing on modes with weaker growth rates
  - Two-fluid mixed effect on linear modes
  - Combination can be strongly stabilizing nonlinearly; decouple edge from interior modes
- Interior modes important – need good experimental data, equilibria for entire plasma
- Need experimental case with both global and fast local data for checks of model
- Standardized data formats would be very useful!
- Complex combination of effects - others such as error fields, resistive walls, ..., may be important