Simulation of ELMs: The real ELM?

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CEMM Workshop
APS-DPP 2009
Atlanta GA

Summary

- ELM at realistic resistivity
  - Freely moving plasma boundary with X-point
  - Magnetic tangle interacts with field-aligned ballooning-type plasma instability
- Multistage ELM crash
  - Initial ballooning burst outboard
  - Main density and energy loss to divertors direct from X-point regions, not outboard filaments
  - Important interior and inboard component
  - Stochastic magnetic field with partial structure
- Implications ... second talk, this workshop

Magnetic X-point

- H-mode in D-shaped plasma with one or two magnetic X-points on plasma boundary
  - Steep edge pressure gradient; power threshold to enter H-mode
  - Periodic edge instability (ELM) driven by gradient
- Toroidal magnetic field at each instant is a 2 degree of freedom Hamiltonian system, since $\nabla \cdot B=0$. X-point is hyperbolic saddle point.
- Roeder (PoP 2003): X-point should lead to a homoclinic tangle when perturbed from axisymmetry. T. Evans has developed idea for RMP nonaxisymmetric field, to stabilize ELM.
  - See expt'l evidence of tangle structure in divertors; match using vacuum RMP field is incomplete
- Hamiltonian or near-Hamiltonian perturbation theory valid for “small” perturbation; mostly qualitative.

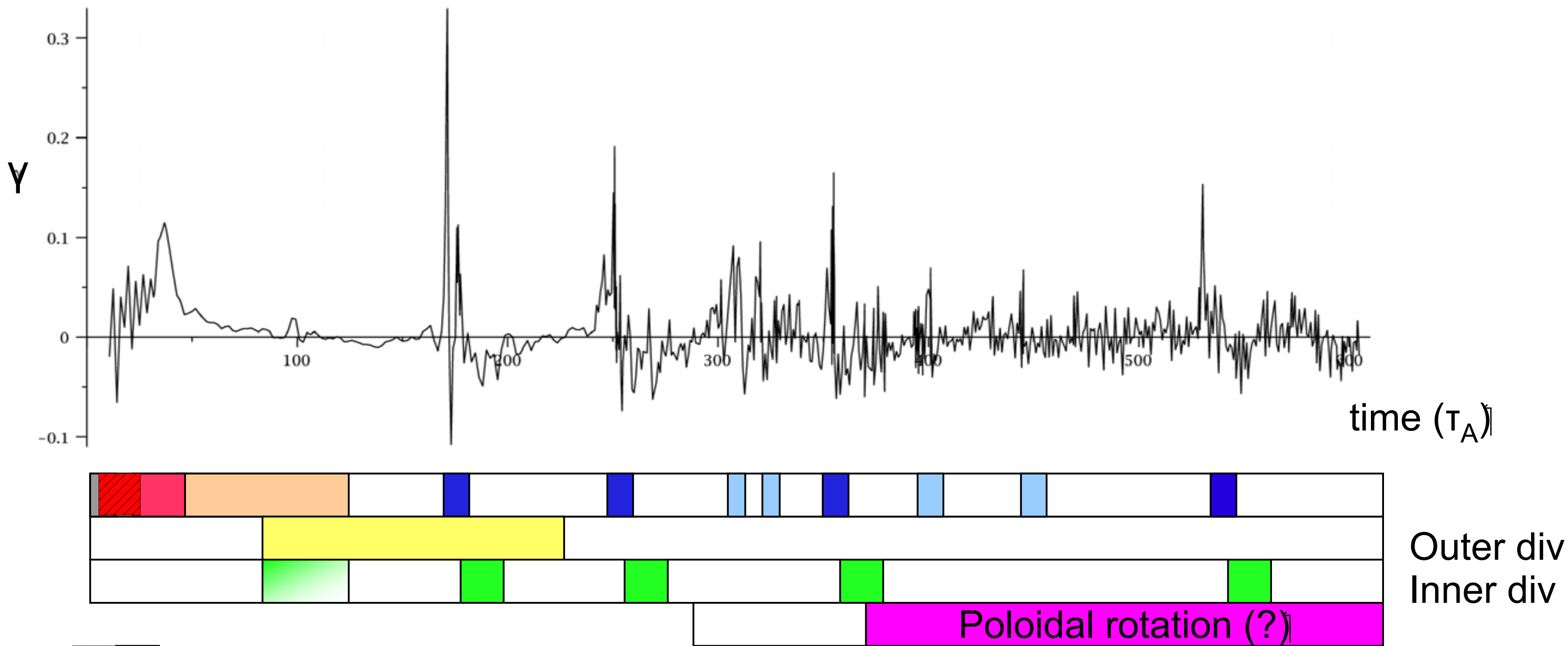
Magnetic X-points -2-

- Local stability theory for hyperbolic saddle points predicts
  - Asymptotic field splitting into two limits as field lines approach or depart from X-point (“stable” and “unstable” manifolds)
  - “Unstable” field line makes increasingly narrow, increasingly long loops about the “stable” one, which remains close to unperturbed
  - Chaotic field due to multiple intersections
  - X-point is a fixed point
- Global structure - Homoclinic (both manifolds connect to same X-pt) or heteroclinic (different X-points)
- Plasma does not allow ideal Hamiltonian magnetic tangle
  - Plasma can slip through field, also push or pull field
  - Plasma response does not allow infinities in time evolution
- Magnetic structure is a perturbation of state with infinities?
  - PDE theory acknowledges most solutions have singularities

Simulation

- Realistic value of resistivity is important
  - Large local current density if magnetic reconnection
- Potential infinities in 'unperturbed' field
- Weak solution (against test functions v: $\int uv\,dx = \int F(u)v\,dx$)
  - Weakest finite element (volume): linear
  - No hyper-resistivity or hyper-viscosity
- Full MHD or diamagnetic 2F
- S to 3.3×10^{7}, Spitzer-like η”☎$T/T_o)^{-3/2}$, $\mu=6\times10^{-6}$, $\kappa_{\square}=D_n=10^{-5}$, $\kappa_{\square}=3.53(R_o/a)$
- Diffusive part of upwind advection in n,p (dt*v) and v_φ (dt*v^2)
- MHD resistive vacuum: Large resistivity $S_{vac}=10^3\rightarrow$near-zero current; p=T=0, finite density $n_{vac}/n_o=0.1$ (mostly)

Multi-stage ELM – DIII-D 119690



Outboard ballooning: NL mode consolidation and strong growth

Plasma burst outboard, midplane □n reduced

Density to outboard divertor from near X-point

Inboard edge instability

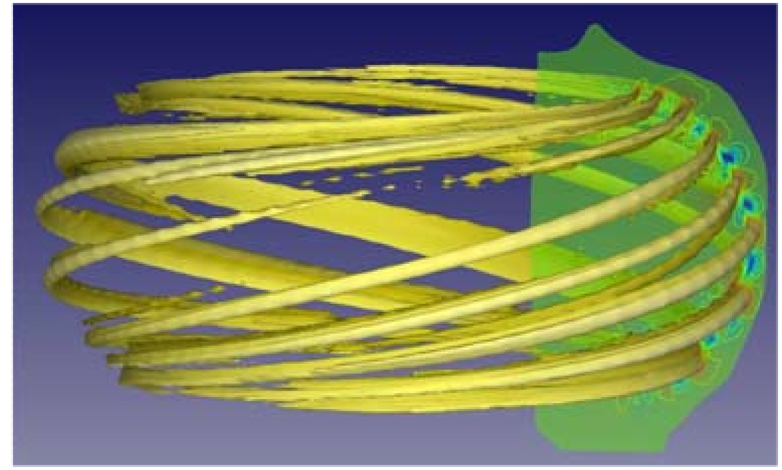
Density to inboard divertor

Nonlinear harmonic consolidation

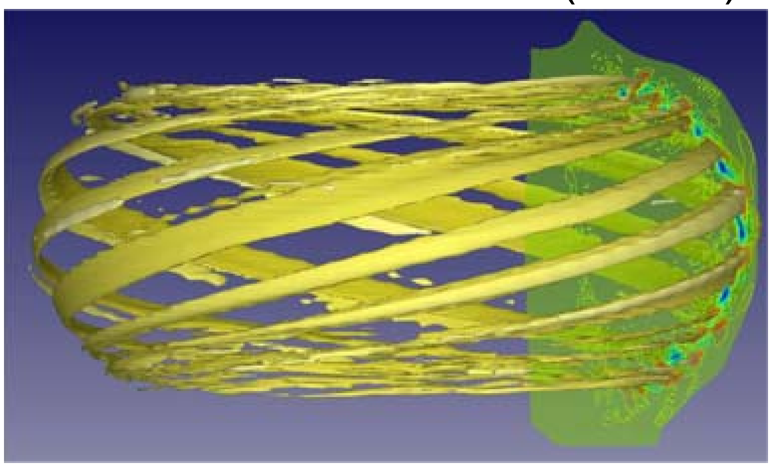
Rapidly leads to lower-n field-aligned mode ``filaments'' (n=6-10 at t=43)

Poloidal magnetic flux ψ has sharpest structure.

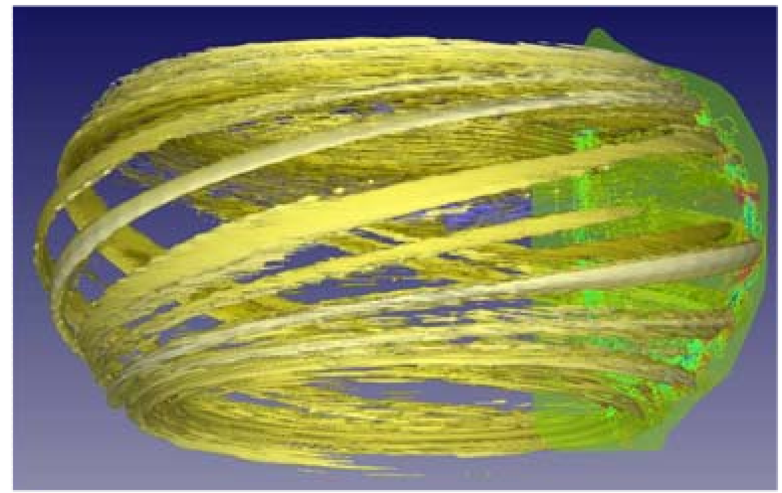
Total T resembles total n (bottom).



ψ-pert



n pert



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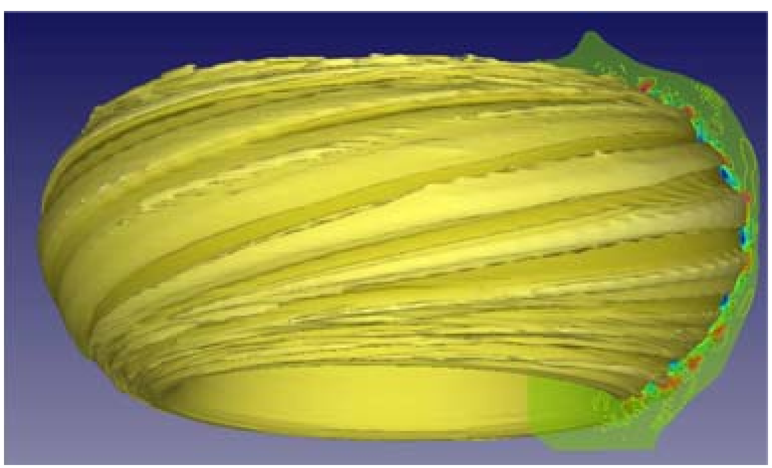
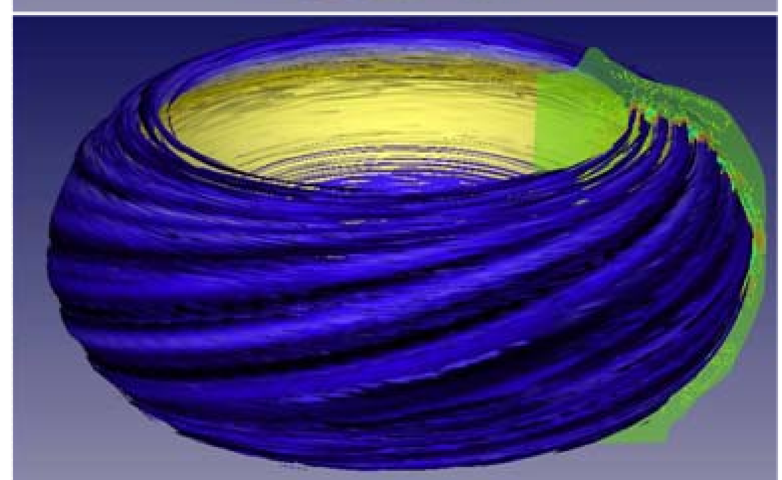
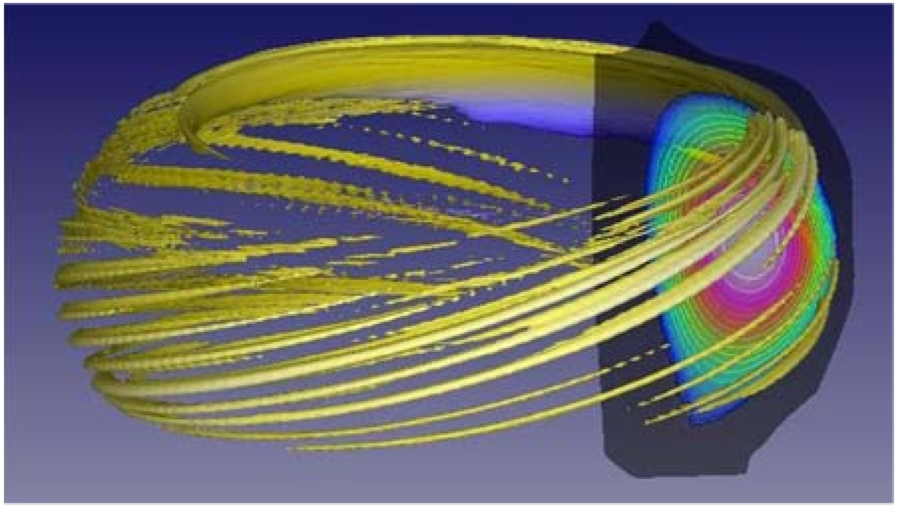
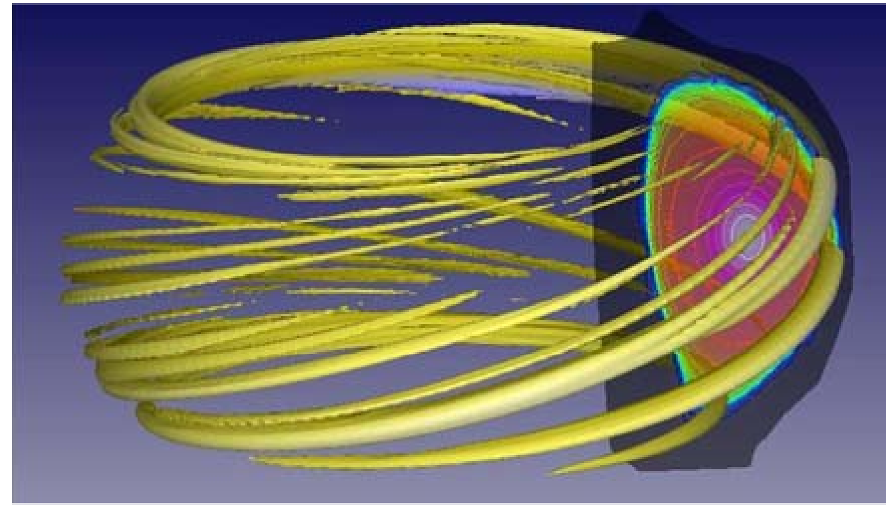


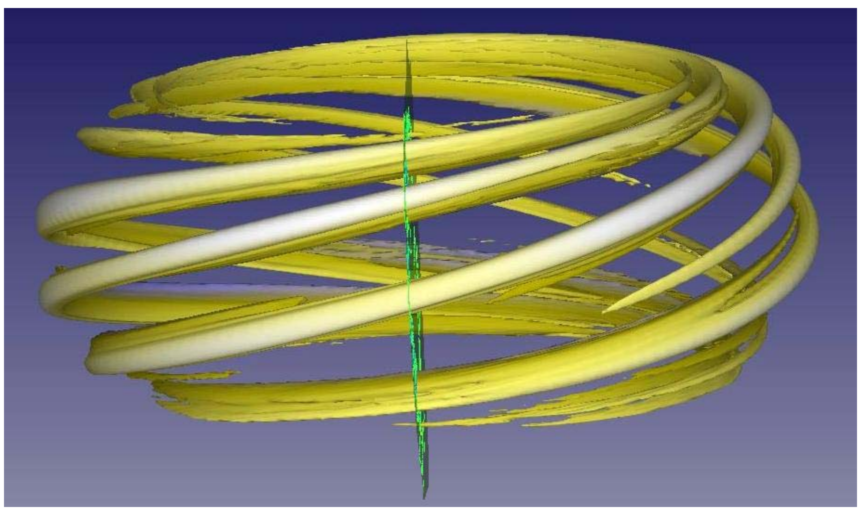
n

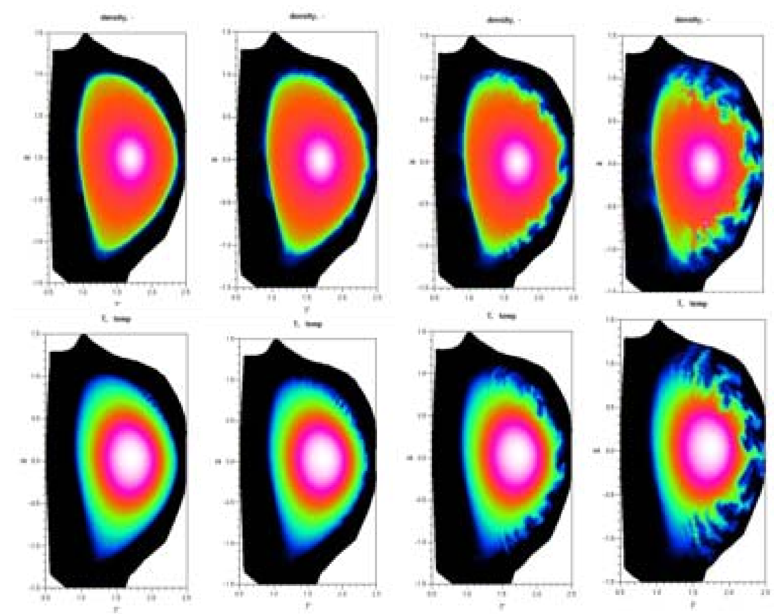


RJ_φ









n

T

t=26 39 52 65

Higher harmonics (n ≤ 47) also show strong nonlinear consolidation of initial random perturbation to lower mode numbers, with low n envelope.

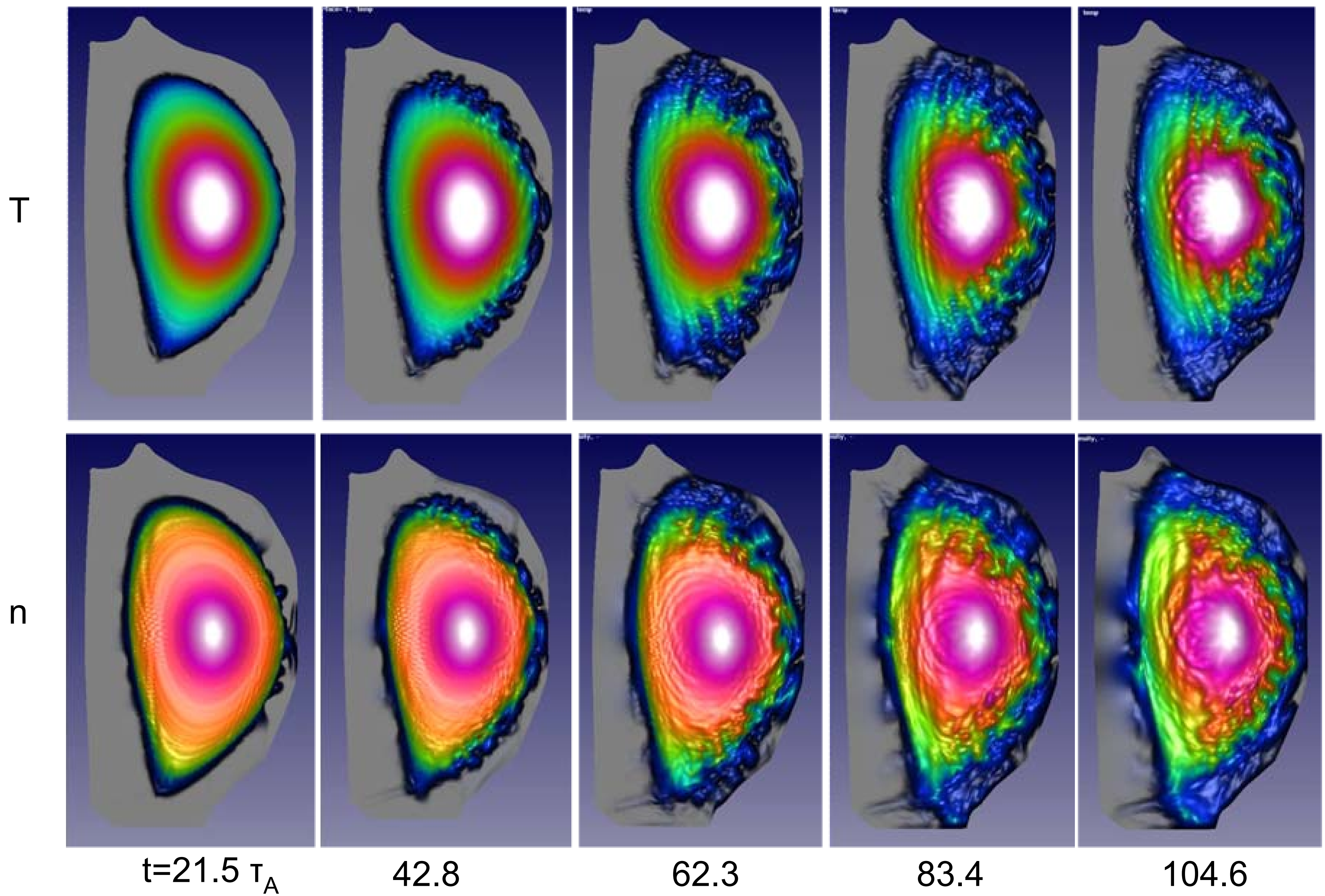
Two-fluid, qualitatively similar to MHD.

Two-fluid ELM

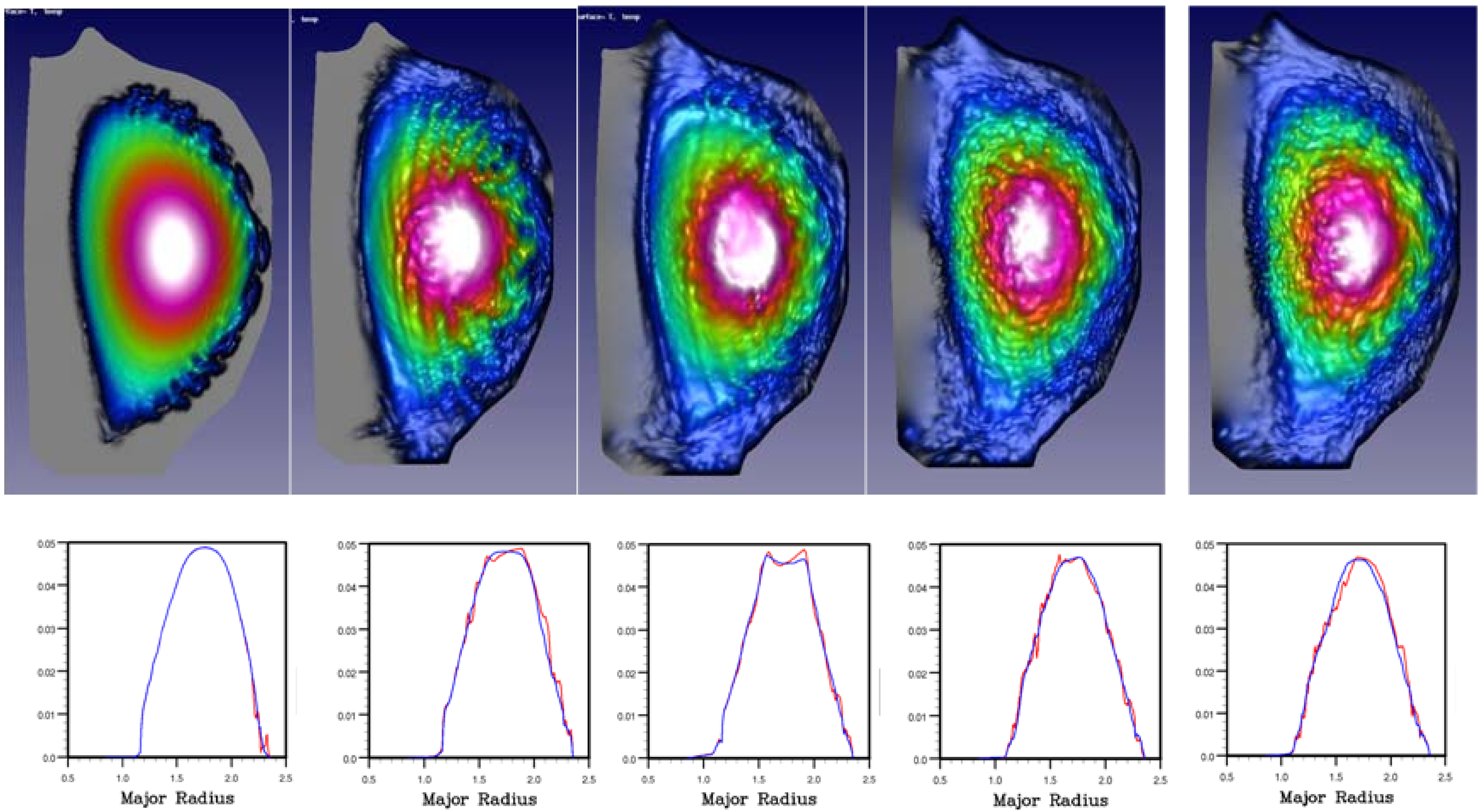
$S=3.3\text{x}10^6$

DIII-D 119690, M3D

Early time: T and n ballooning in rapid burst

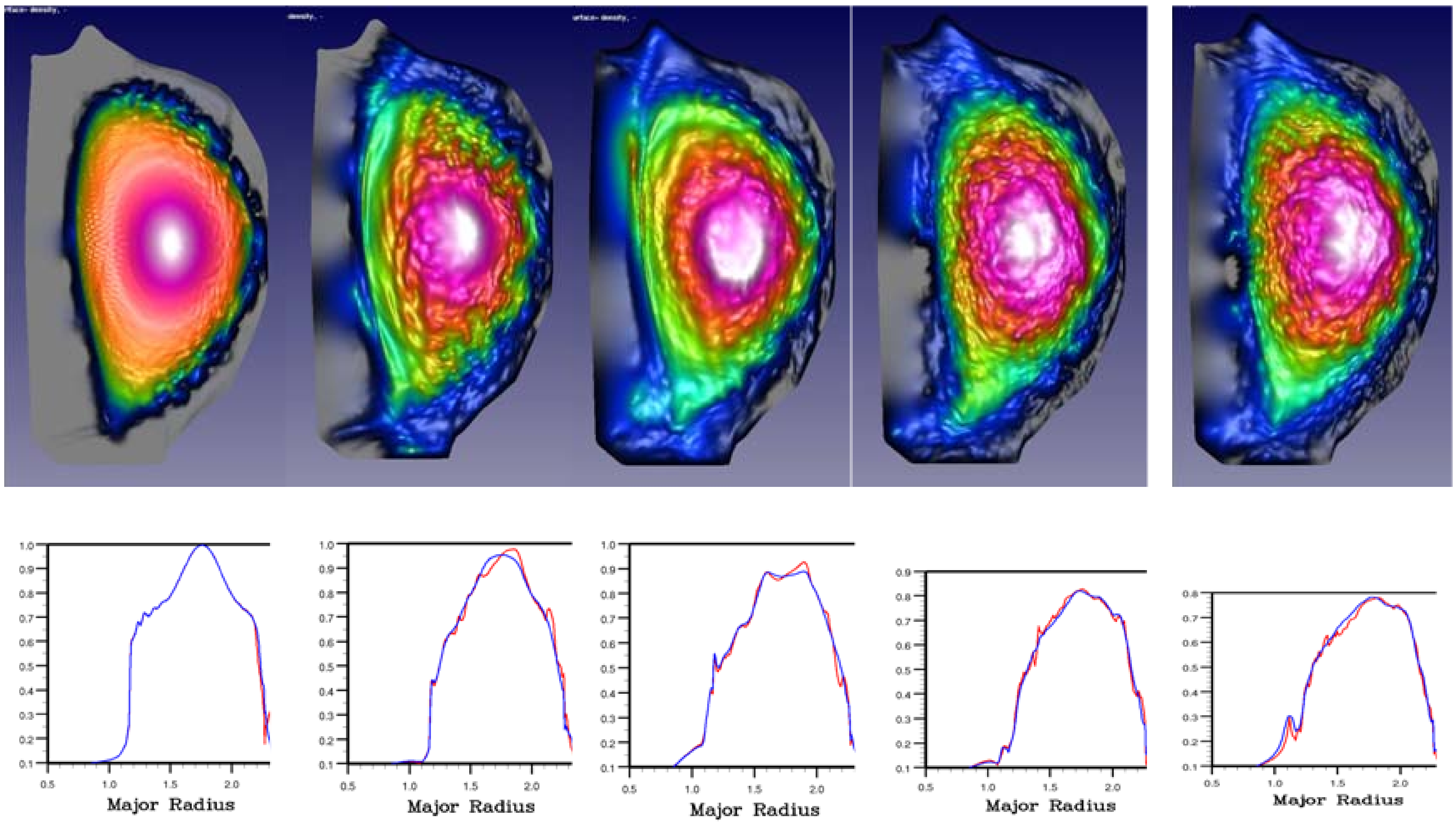


Longer time: T



t=43 126 227 461 529

Longer time: n



t=43 126 227 461 529

Toroidal harmonics in time

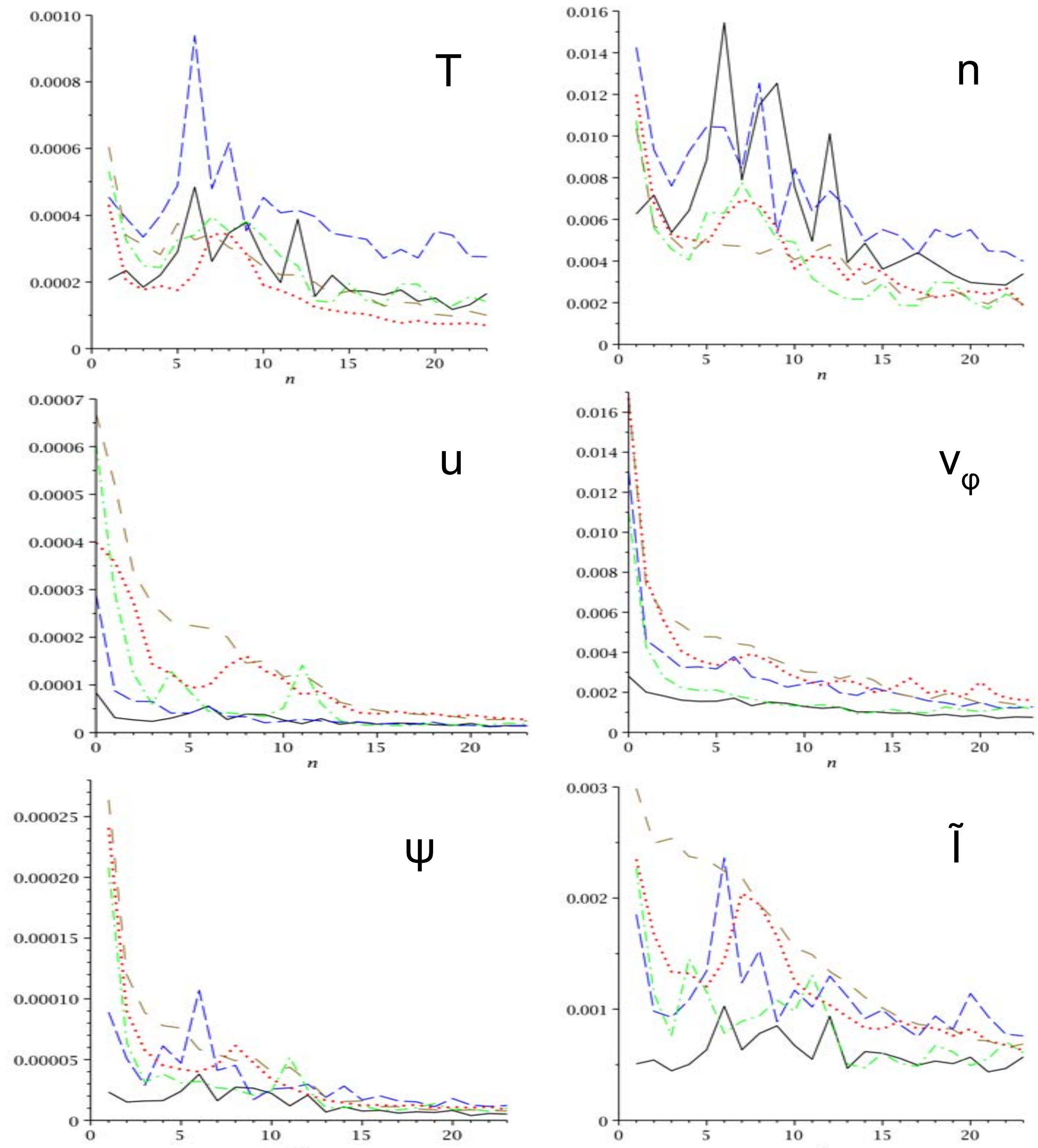
t=43, 126, 227, 461, 604

n=6-12 initially

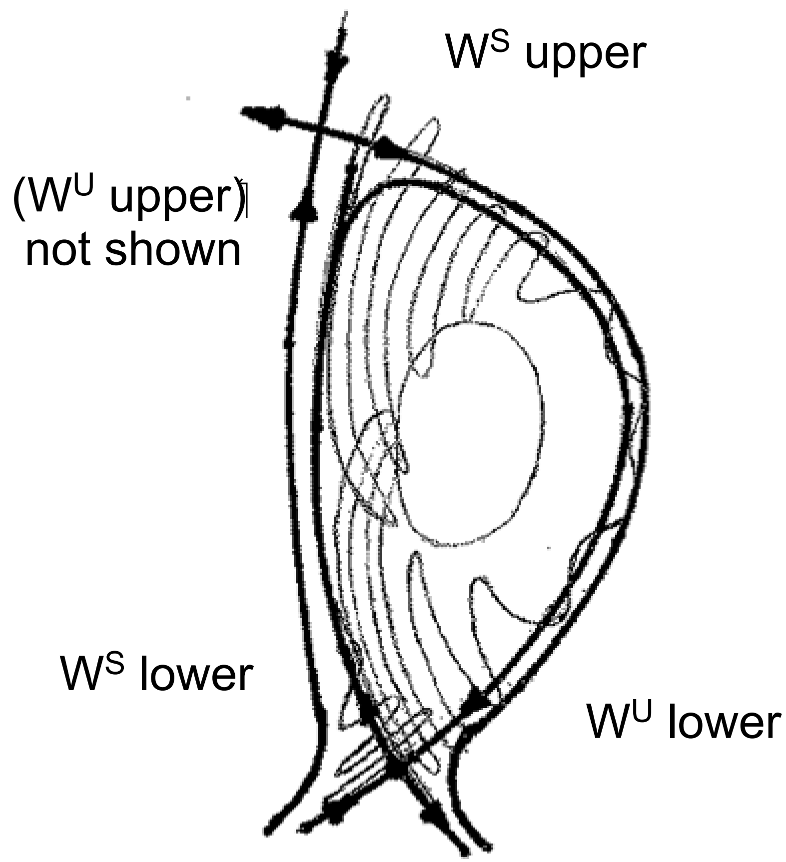
Grows, then decays except for n=1 (island) and rotation

n=0 for n, T, ψ, Ĩ is large, not shown.

n=0 for u, v_φ shown ½ size.



Magnetic tangle - schematic



Asymptotic magnetic field splitting.
Where loops intersect, chaotic field.

Homoclinic tangle plus upper X-point heteroclinic effect.

Different inboard field loop shapes at different times.
Initially aligned along inboard plasma bdy, away from core. Later, curves inward toward core.

Midplane disturbance expands toward plasma boundary. When bdy reached, an inboard instability is triggered. Density blobs are expelled along bdy.

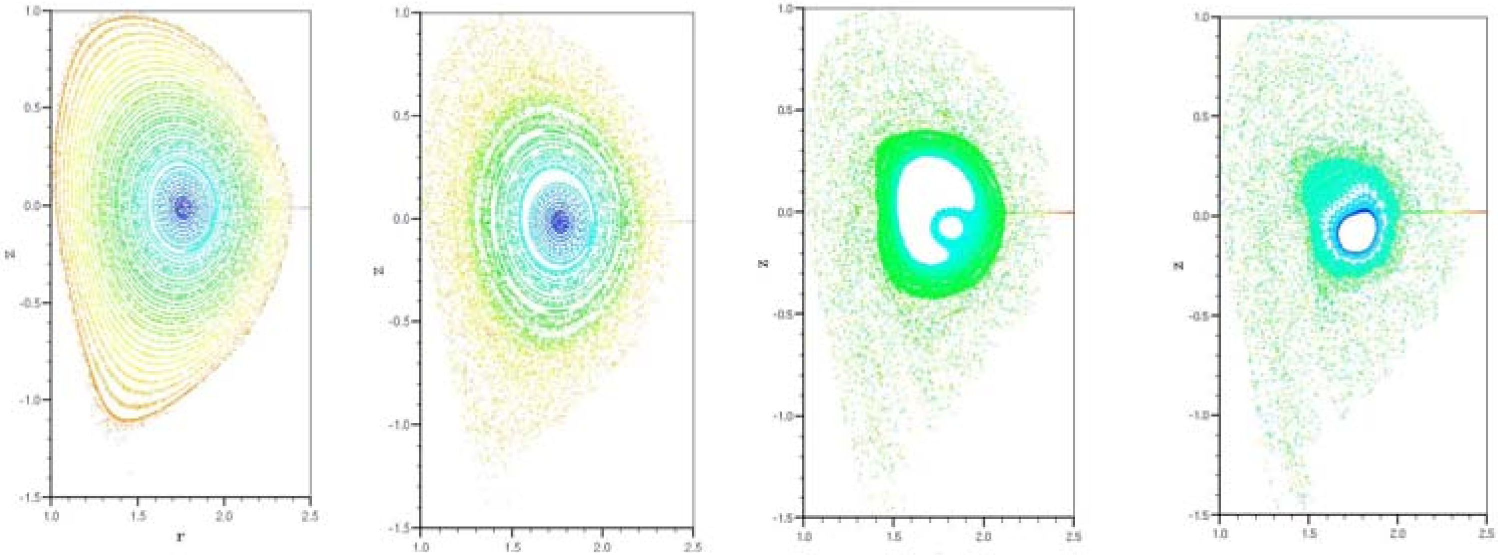
Inner limit of loops and stochastic field is a low order rational surface?

No evidence of field lines connected to full extent of plasma fingers outside plasma

Magnetic tangle creates superficially chaotic magnetic tangle. Field lines in opposite directions match expected homoclinic 'stable' and 'unstable' manifolds.

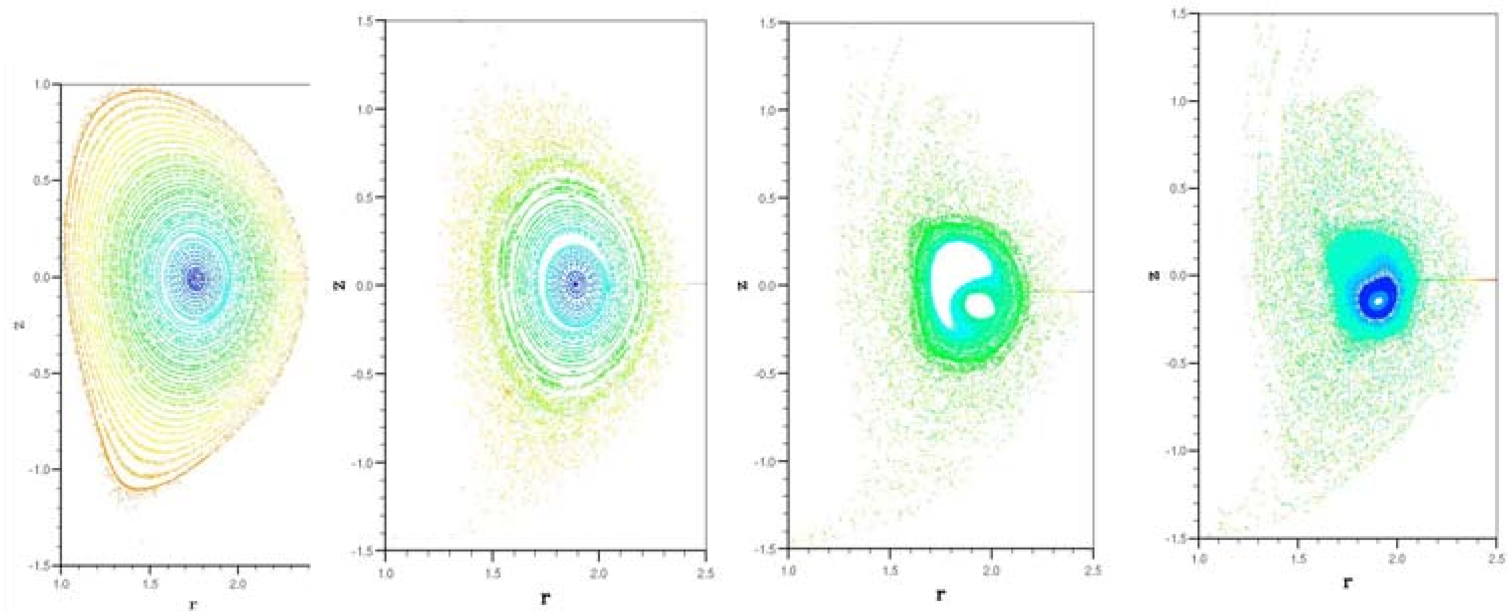
+φ

lower X unstable



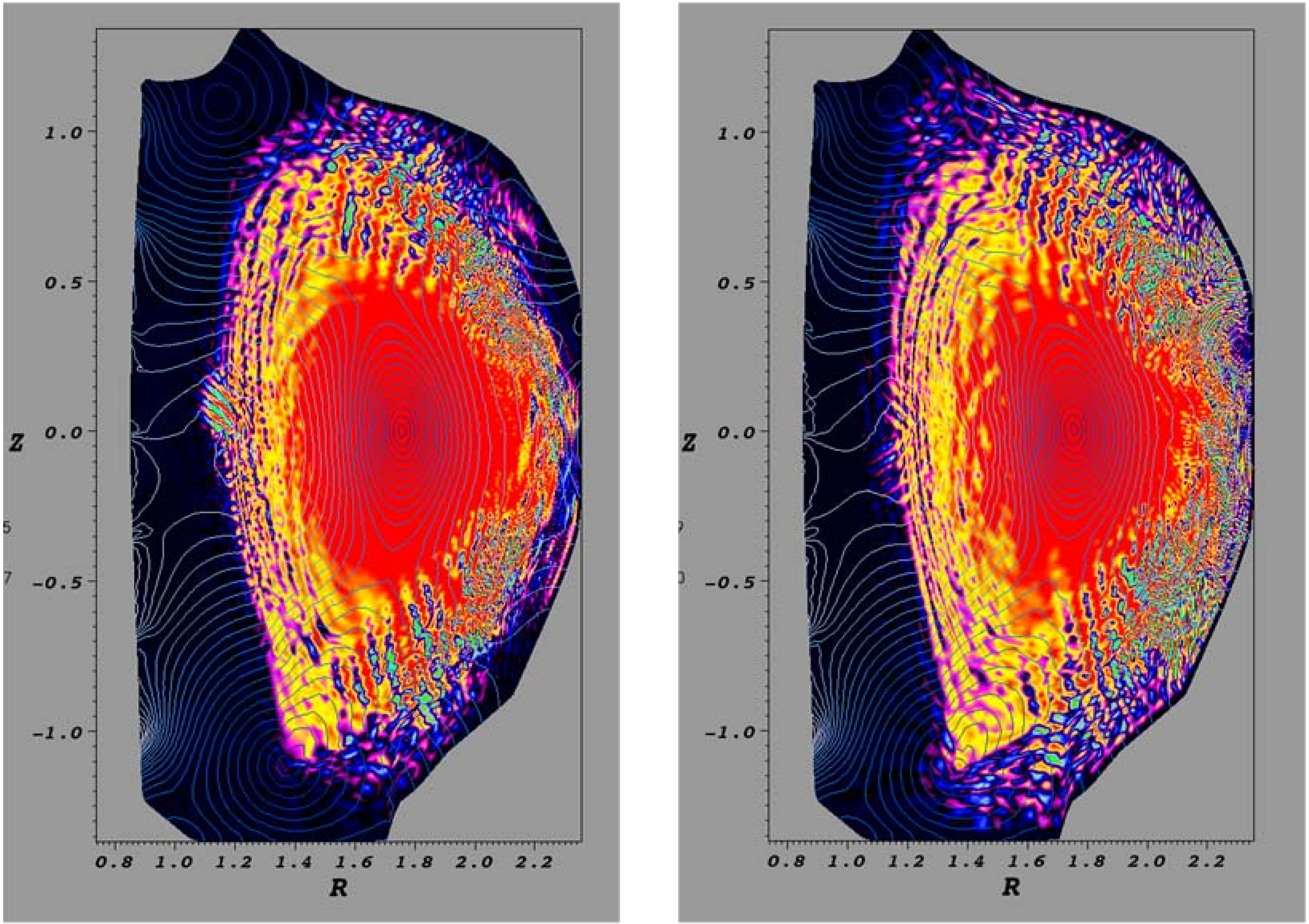
-φ

lower X stable or upper X unstable



S=10^6, strongly unstable, SciDAC2009

C=-RJ_φ shows tangle like structure (colored to max/min +/-1.0)



t=52.6

t=136.2

Movies

- 119690 (ITER-similar shape, very steep edge pressure gradient)
  - Actual resistivity
- 126006 (RMP stabilization case)
  - Resistivity within 5x
- 72 poloidal planes with 2/3 dealiasing in φ, 72x400 radial x poloidal resolution in poloidal plane (80x400 for case 126006)
- Movies done in Visit with help of Dave Pugmire, NCCS
  - M3D interface to the HDF5 output files already existed
- Movies were essential to really understand the ELM dynamics

Results

- Multistage ELM due to interaction of magnetic tangle with plasma instability, initially driven by edge pressure gradient or current
- Nonlinear consolidation of toroidal harmonics to low/medium n early
- Initial burst on outboard
  - Density lost direct to outboard divertor from near X-pts
- Instability penetrates deep into plasma interior
  - Stochastic field over region
- Secondary inboard instability causes loss to inboard divertor
- Periodic pulses of outboard density 'blobs' and inboard losses
  - Poloidal (and toroidal?) rotation of interior and edge
- Slow relaxation toward axisymmetry, original configuration
- Interior islands may grow in 'chaotic' field (Here, type matches experiment.)