ELMs, Magnetic X-points, and Chaotic Fields

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Topics

- X-point on the magnetic boundary of a D-shaped fusion plasma creates a chaotic magnetic tangle
  - Field-aligned plasma instability drives a large ELM with stochastic magnetic field and interior component
- MHD simulation shows a multi-stage ELM
  - Outboard instability
  - Inboard instability
  - Quasi-periodic pulses after main ELM crash
  - Relaxation toward axisymmetry, original shape
  - Poloidal plasma rotation
- Implications

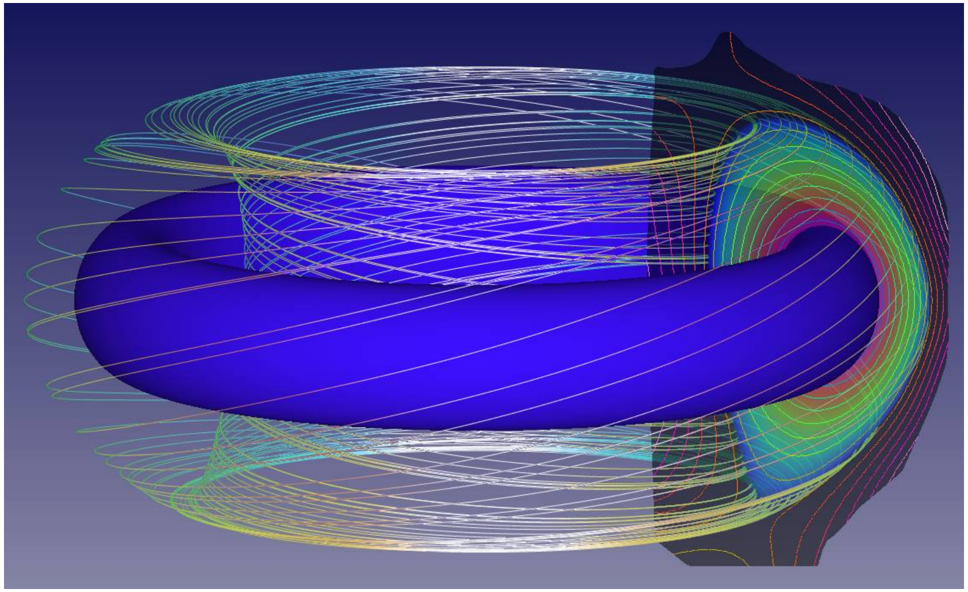
Earlier results: L Sugiyama, J. Phys: Conf Series**180** 012080 (2009)
Acknowledgements for visualization: J. Jacobsen LBL/NERSC, D. Pugmire ORNL

Magnetic X-point

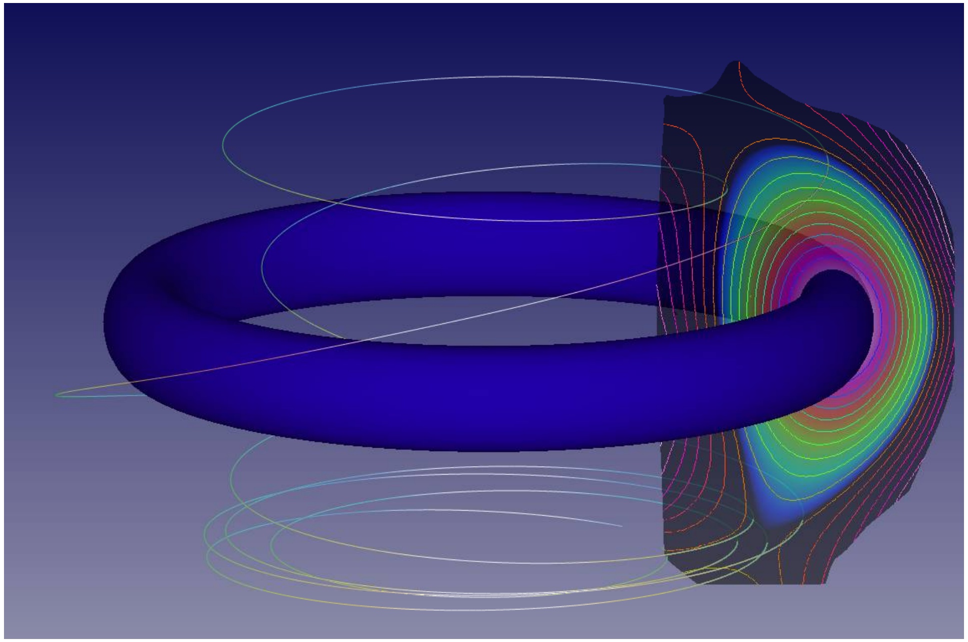
- D-shaped toroidal plasmas have one or two magnetic X-points on plasma boundary. H-mode confinement regime has:
  - Steep edge pressure gradient; minimum power to enter H-mode
  - Periodic edge instability driven by gradient (ELM or oscillation)
- Toroidal magnetic field at each instant is a Hamiltonian system with 2 degrees of freedom, since $\nabla \cdot B=0$. (A. Boozer, PF 1982,1983)
- Roeder et al. (PoP 2003): X-point is hyperbolic saddle point and should lead to a homoclinic tangle when perturbed from axisymmetry. T. Evans has developed the idea for applied non-axisymmetric RMP fields, to stabilize ELMs.
  - Experimental evidence for tangle-like structure in divertors in RMP and ELMs. Matched to vacuum RMP field only, so far.
- Hamiltonian and near-Hamiltonian perturbation theory has been developed for "small" perturbations; mostly qualitative.

Equilibrium magnetic field determines important tangle and ELM properties

Confined flux surface near the separatrix has densely packed field lines near X-pt and at top inboard, due to upper X-point.



Field lines outside the plasma separatrix wrap once toroidally over the height of the plasma, wrap one or more times at top, bottom



Confined field lines also wrap approx'ly once toroidally over outboard side. Little radial shear.

DIII-D 119690

Local/global stability theory shows that a magnetic X-point with small magnetic perturbation undergoes asymptotic field splitting

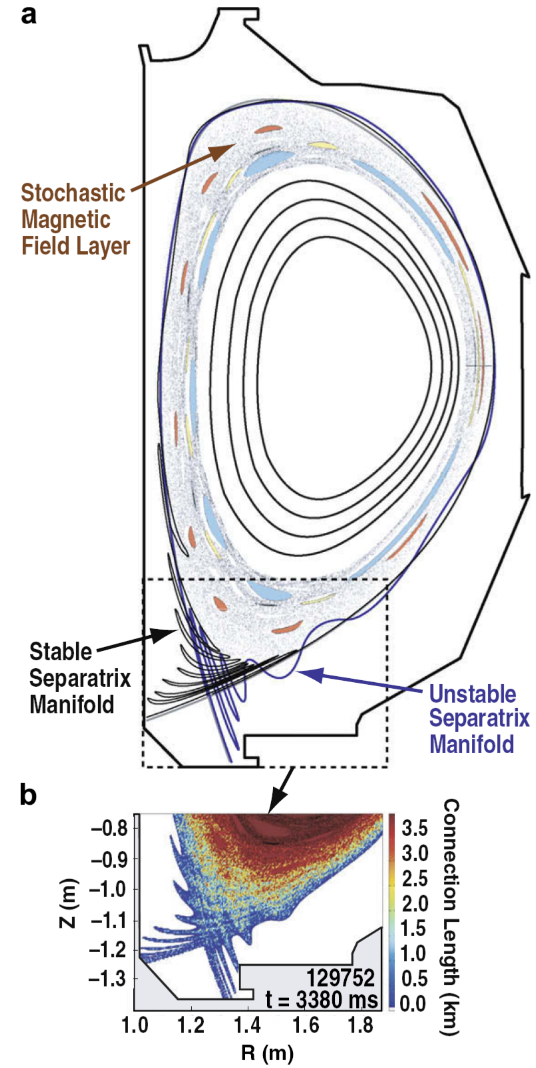
Magnetic field splits into two different limiting surfaces (smooth manifolds), defined by the limiting location of the field lines when traced infinitely in each direction relative to X-point.

X-point is a fixed point.

“Stable” manifold remains close to the original flux surface for field line traced away from the X.

“Unstable” manifold forms loops around the stable surface as field line moves toward the X-point. Loops become infinitely long/thin as line approaches X-point.

Field becomes chaotic where the two manifolds intersect (a magnetic tangle). Homoclinic: manifolds connect to same X-point, heteroclinic: to different X-points



RMP field in DIII-D ($\delta B/B \geq 10^{-4}$)

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

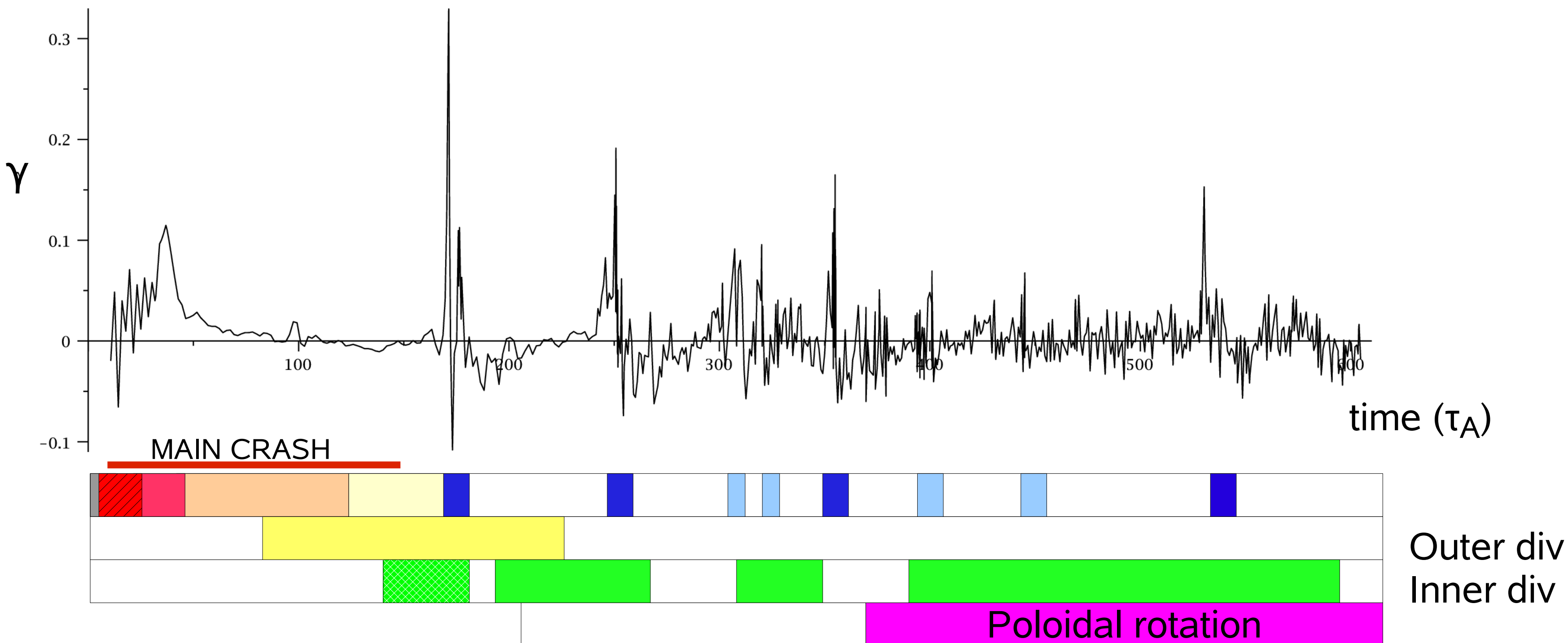
Plasma creates non-ideal magnetic tangle

- Plasma time evolution does not allow an ideal (near)-Hamiltonian magnetic tangle, but the field *wants* to approach the ideal tangle
  - Plasma can slip through field, also push or pull on the field (low η)
  - Plasma response does not allow infinities in finite time evolution
  - In simulations, the discrete spatial grid also prevents infinities
- Plasma magnetic structure is not a perturbation of the original axisymmetric equilibrium. Does the 'averaged' state exist and does it contain infinities? Theory says that it may not exist in 3D.
- Simulation shows that field-aligned plasma instabilities, like ballooning or interchange modes, can interact with the “unstable” manifold
  - Coherent growing instability, despite superficially stochastic field!
  - Stabilizing for early NL ballooning mode (only half of field responds)
  - Allows instability to penetrate deep into the plasma

M3D Simulation

- Full MHD or diamagnetic 2F equations with density evolution
- Plasma separatrix with X-point, freely moving plasma boundary surrounded by a (resistive MHD) vacuum and rigid, partially conducting wall
- Realistic/near-realistic value of resistivity!
  - $S = 3.3 \times 10^7$, Spitzer-like $\eta(x) \sim (T/T_o)^{-3/2}$
- Viscosity $\mu = 6 \times 10^{-6}$, thermal $\kappa_\perp = D_n = 10^{-5}$, large $\kappa_\| = 3.53(R_o/a)$
  - Diffusive part of upwind density advection in n, p $(dt \cdot v_\perp)$ and v_ϕ $(dt \cdot v_\perp^2)$
  - No hyper-resistivity or hyper-viscosity
- MHD resistive vacuum: Large resistivity $S_{vac}=10^3$ (near-zero current), p=T=0, small density $n_{vac}/n_o=0.1$
- Plasma/vacuum/wall initial configuration from experimental reconstructions (GEQDSK). Wall slightly smoothed.
- Linear Finite Elements (finite volumes) in 2D plane, FFT over ϕ-planes

Result: Multi-stage ELM



Outboard ballooning: NL mode consolidation and strong growth

Plasma burst outboard, midplane ∇n reduced | outboard SOL clears.

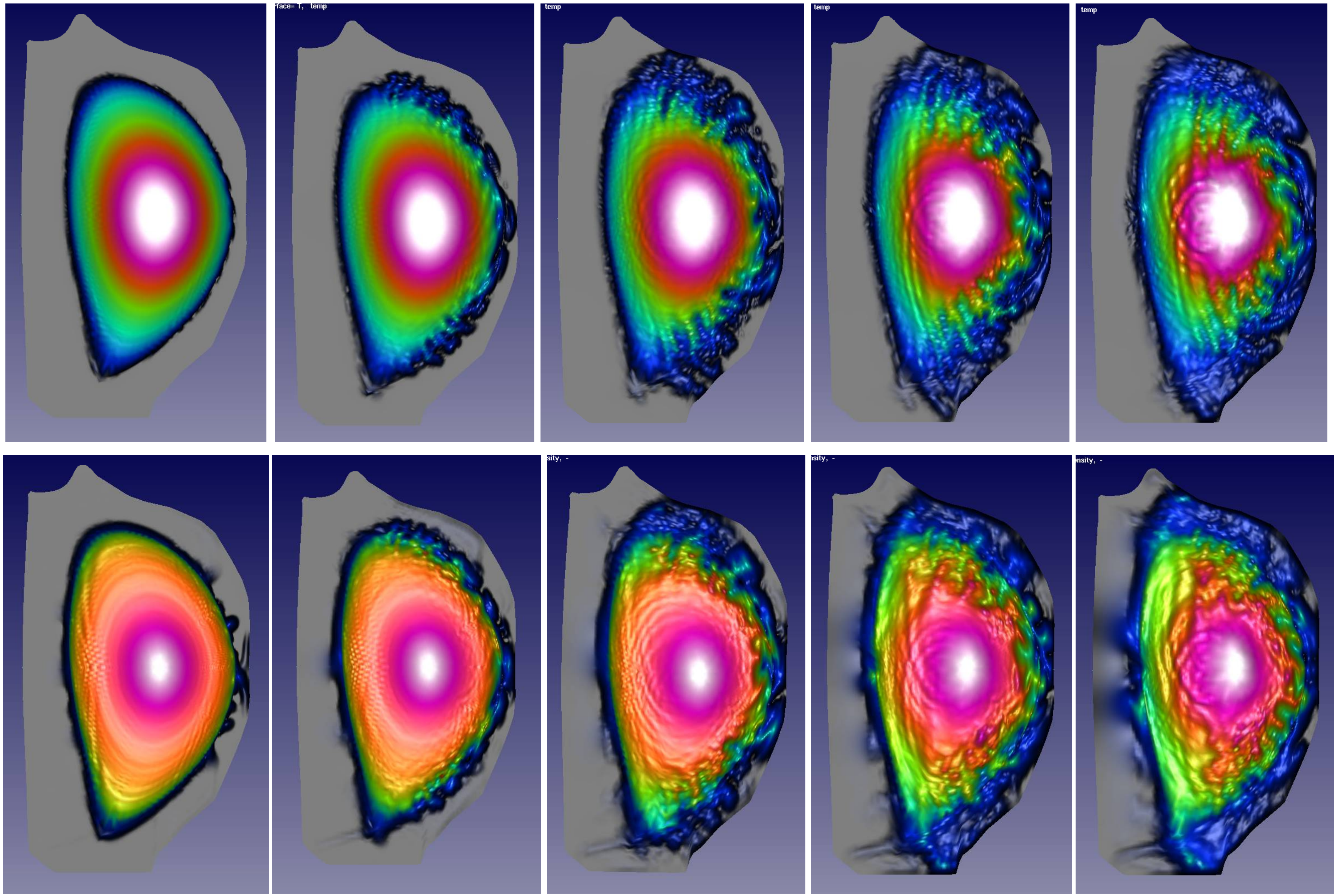
Density to outboard divertor from near X-point

Inboard edge instability

Density to inboard divertor (approx)

DIII-D 119690 at 2656 ms
Growth rate $((\int_{Vol} KE)^{1/2})$ vs time
1 τ_A = 0.78 µs

Early time: T and n over main ELM crash

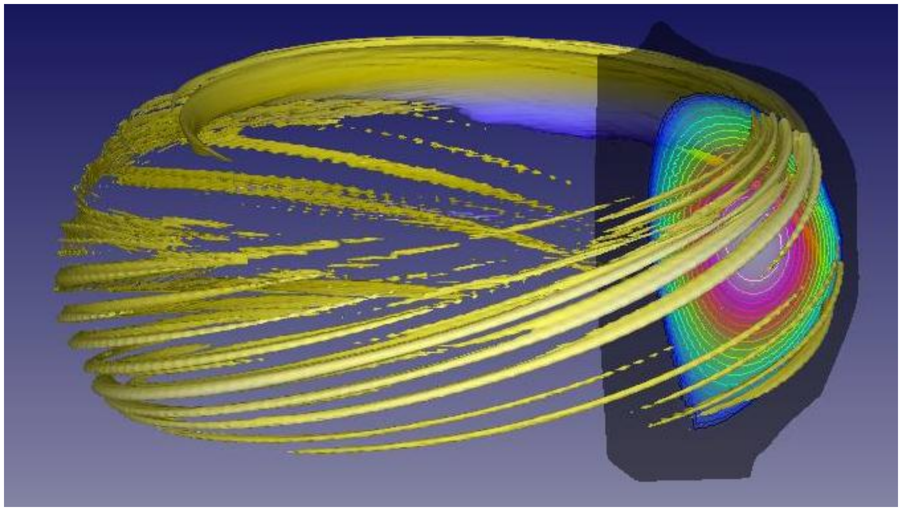


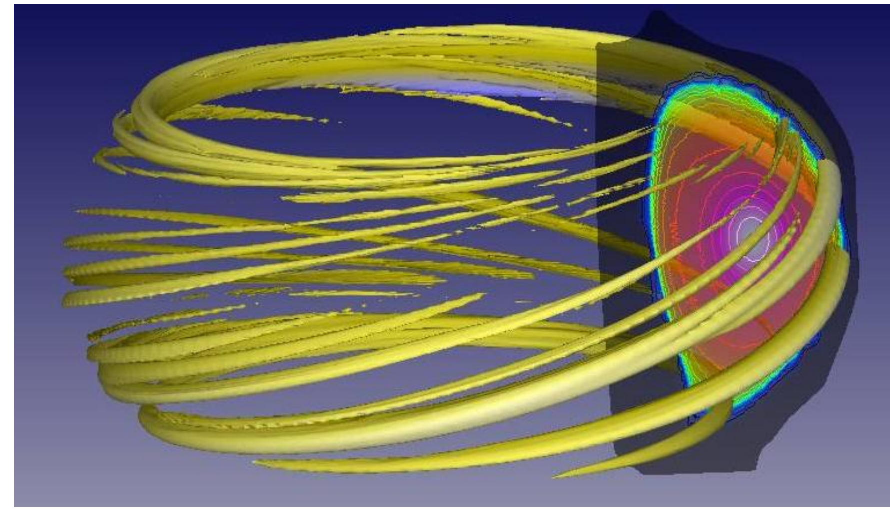
T

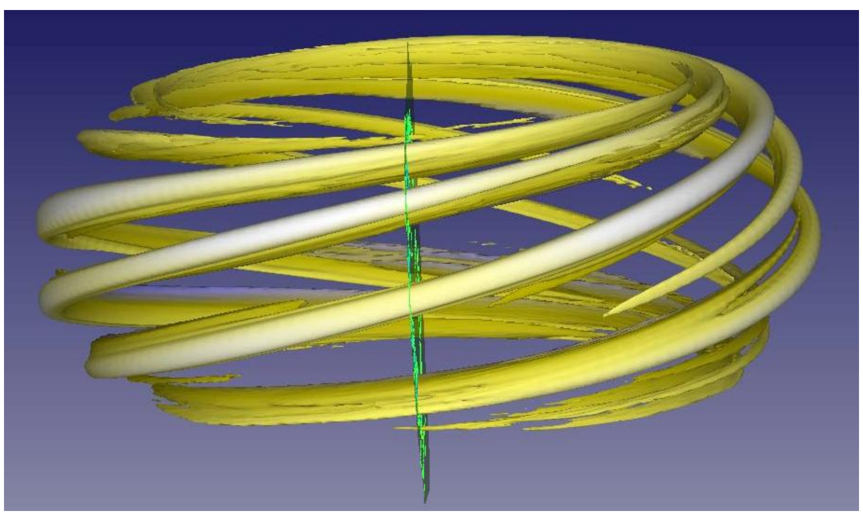
n

t=21.5 τ_A | 42.8 | 62.3 | 83.4 | 104.6

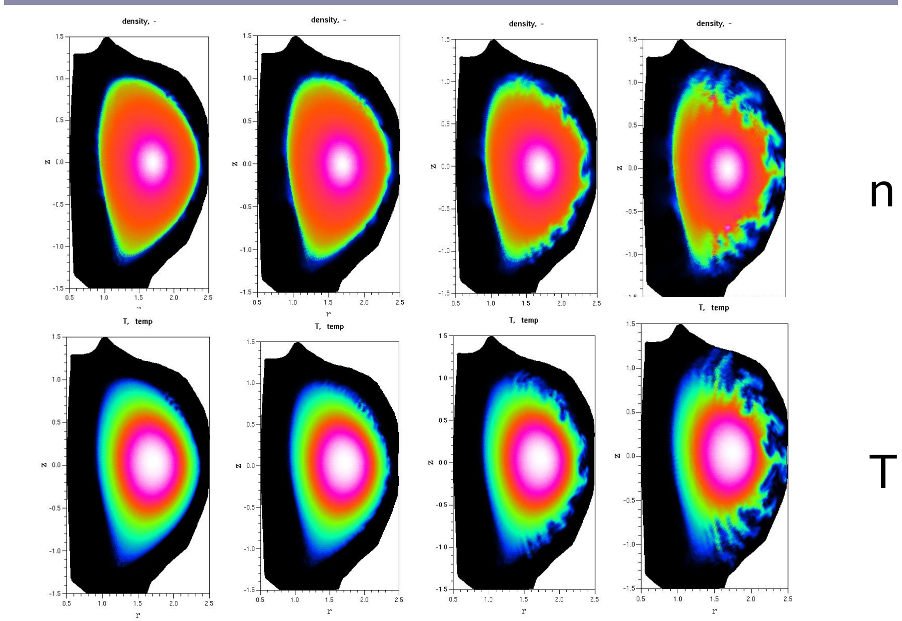
Nonlinear consolidation of toroidal harmonics occurs early
Field-aligned filaments near plasma edge







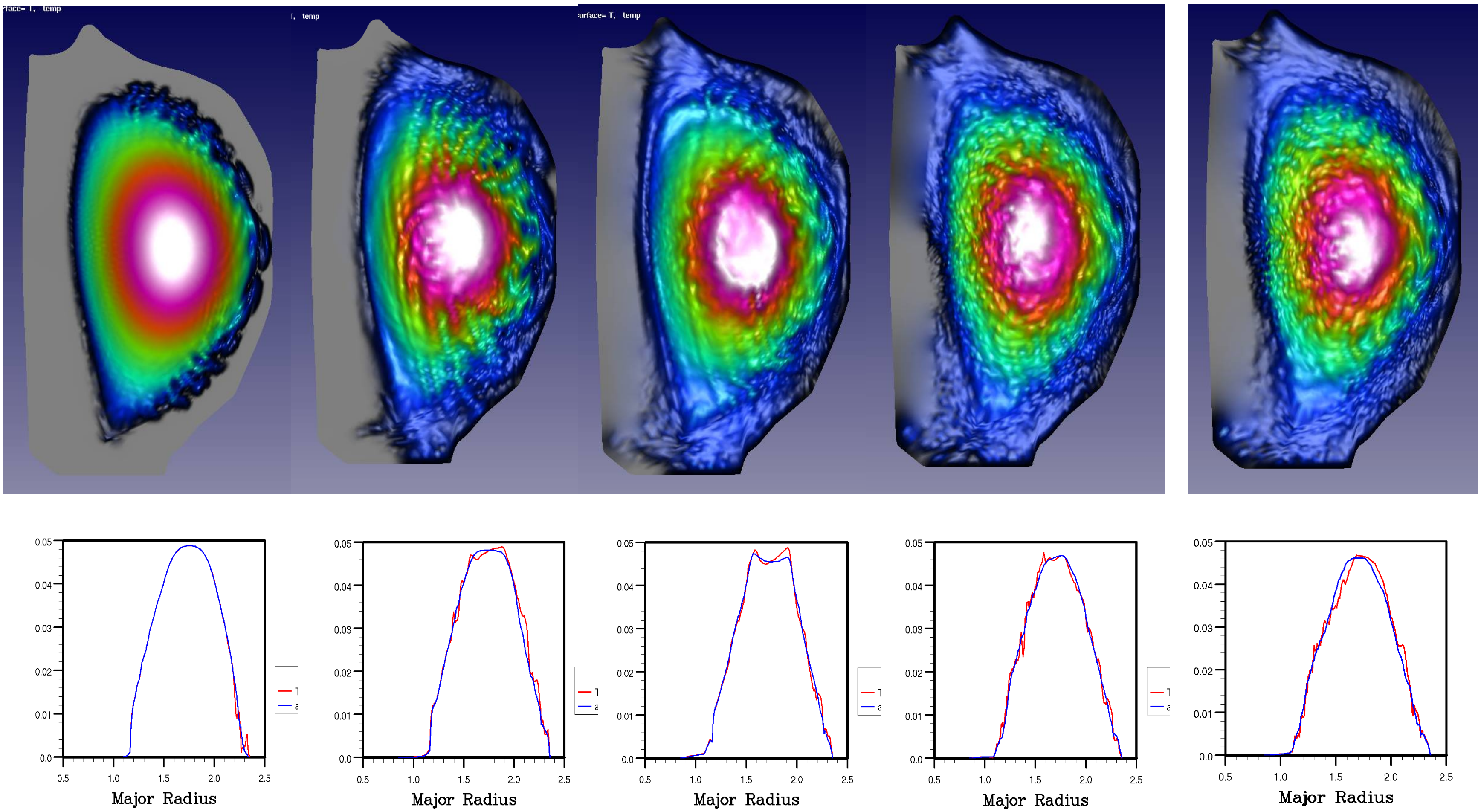
Perturbed ψ for high resolution ($n \leq 47$) two-fluid case, initially perturbed all $n \neq 0$. t=26, 39, 52. No linear mode phase. Qualitatively similar to MHD, lower res.



t=26 39 52 65

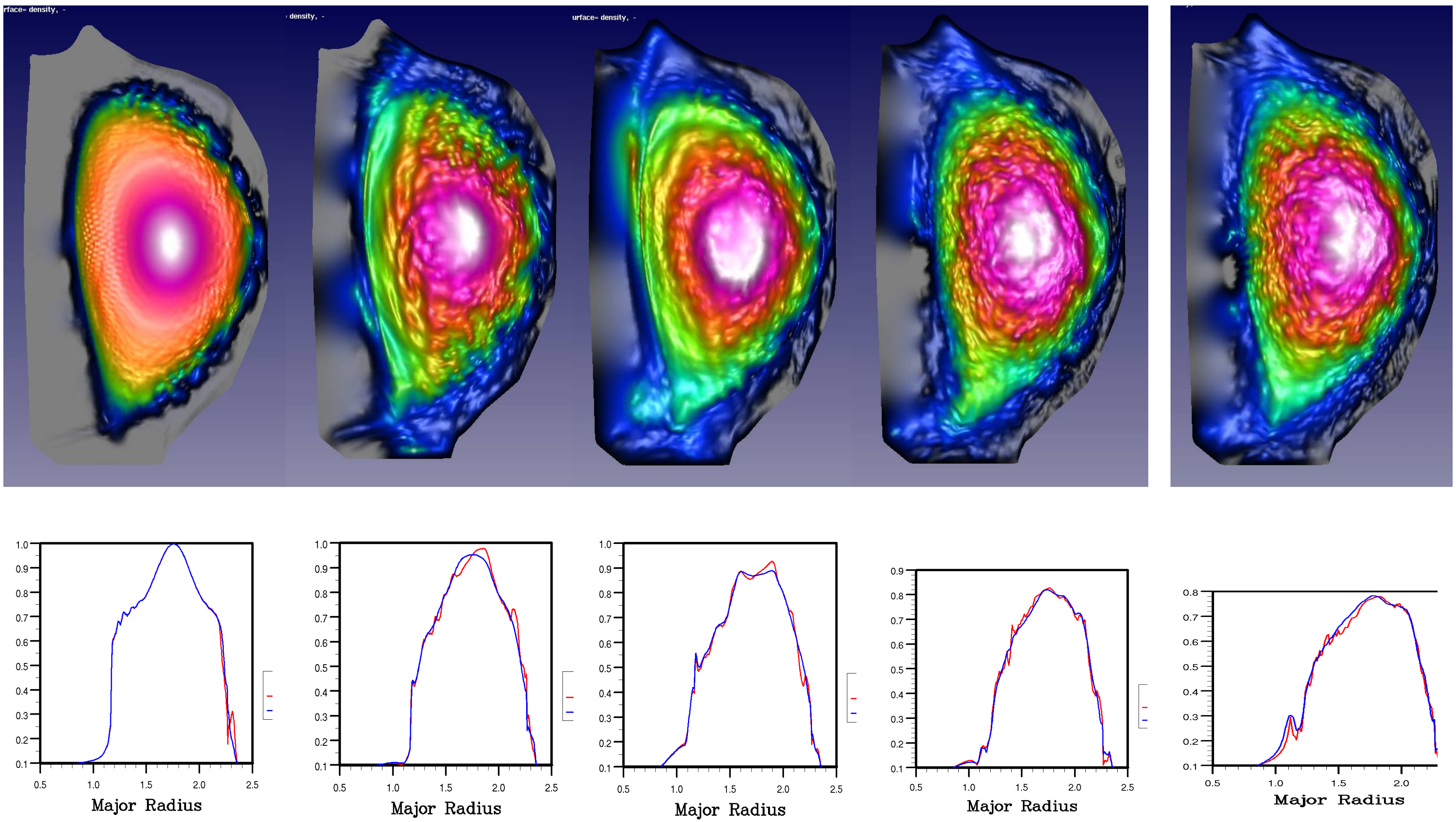
119690 2F S=3.3x10^6

Longer time: Temperature



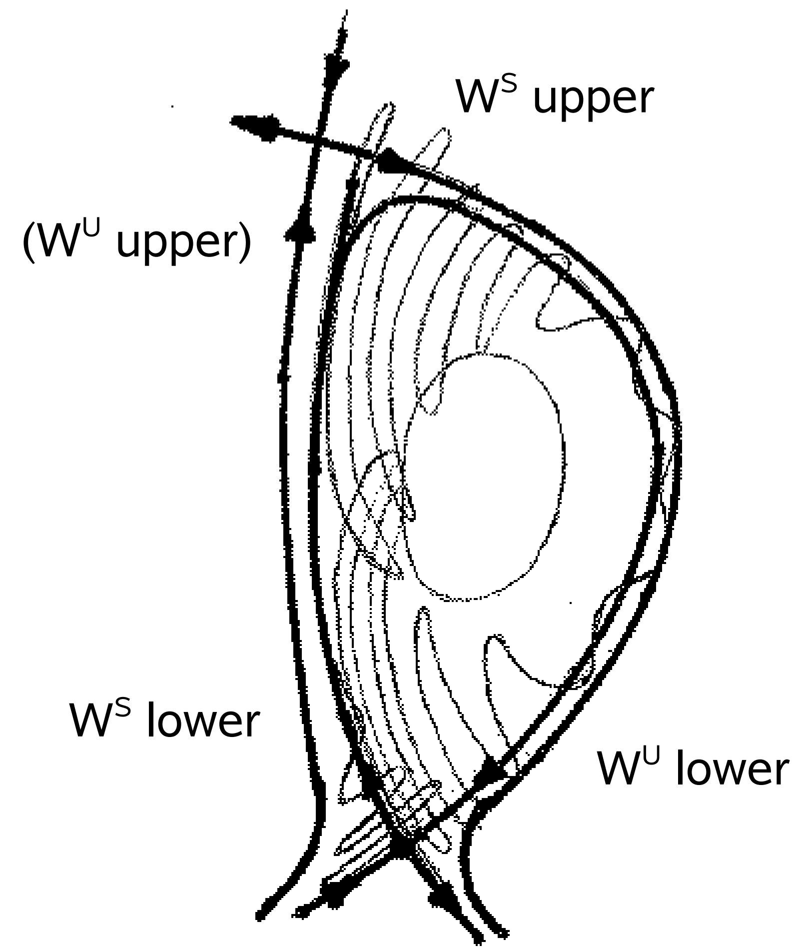
t=43 126 227 461 529

Longer time: n



t=43 126 227 461 529

ELM magnetic tangle - schematic



Homoclinic tangle (single X-point) with some effects from upper X-point, driven by plasma instability. $W^{U,S}$ label equilibrium manifolds, thin lines show perturbed.

Inboard field shape changes in time.

- Initially aligned along inboard plasma bdy, away from core.
- Later, curves inward toward core.

When disturbance expands to plasma boundary, an inboard instability is triggered. Density blobs are expelled up and down along inboard side.

Where loops intersect, chaotic field. *Interchange/ballooning drives field perturbation deep into plasma!*

Loops wider than actual. Diagram is an interpretation of the asymptotic manifolds.

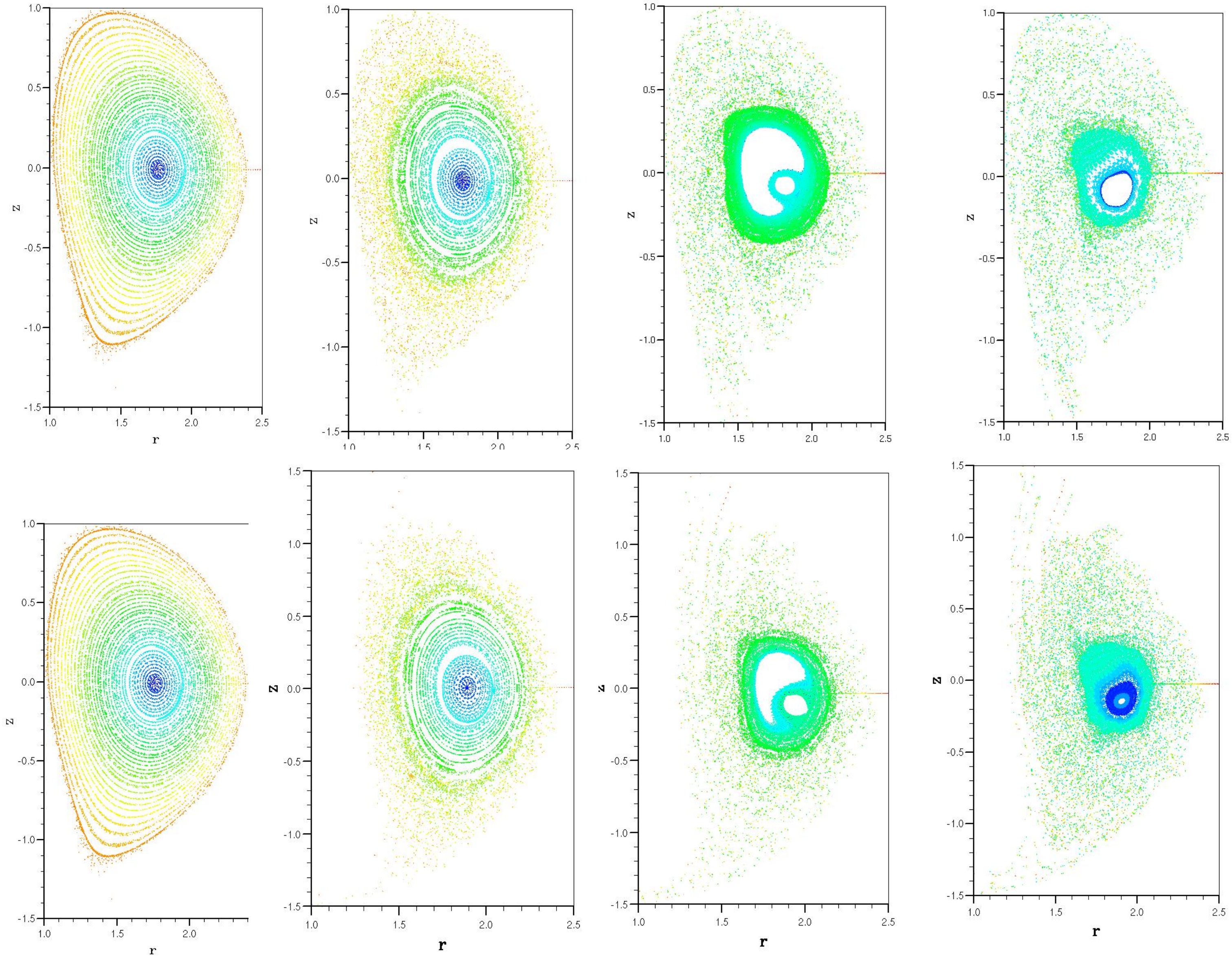
Chaotic magnetic tangle. Field lines have several features of expected 'stable' and 'unstable' homoclinic manifolds.

+ϕ

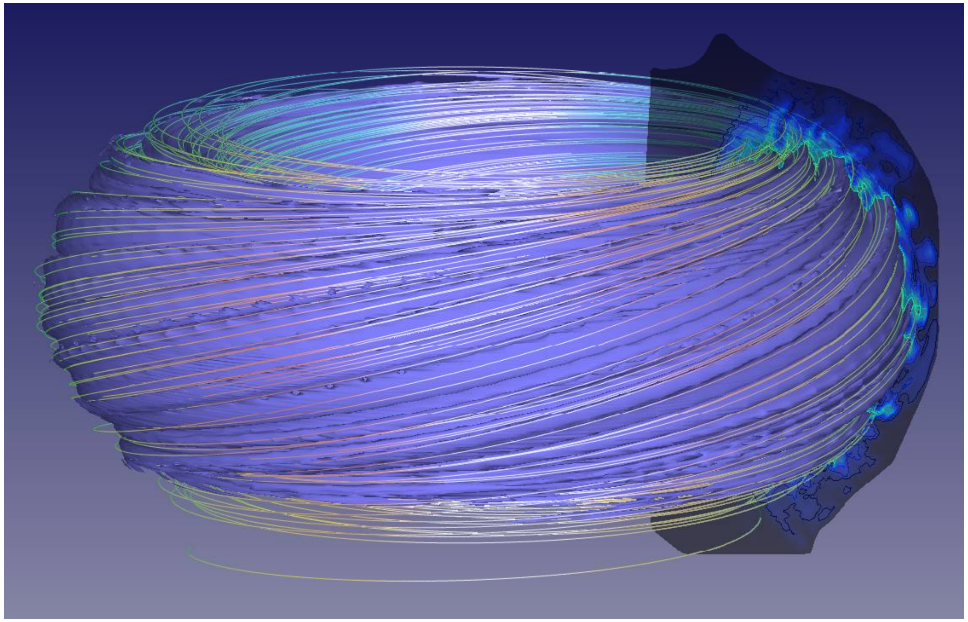
lower X-pt unstable

-ϕ

lower X-pt stable (or upper X-pt unstable)



119690, $S=10^6$, strongly unstable case, SciDAC 2009



Temperature surface near plasma edge shows helical, field-aligned perturbation

Magnetic field line approximately follows temperature for many toroidal circuits (traced $+B_T$), finally lost along (outboard) X-leg

Case 119690 t=83.4

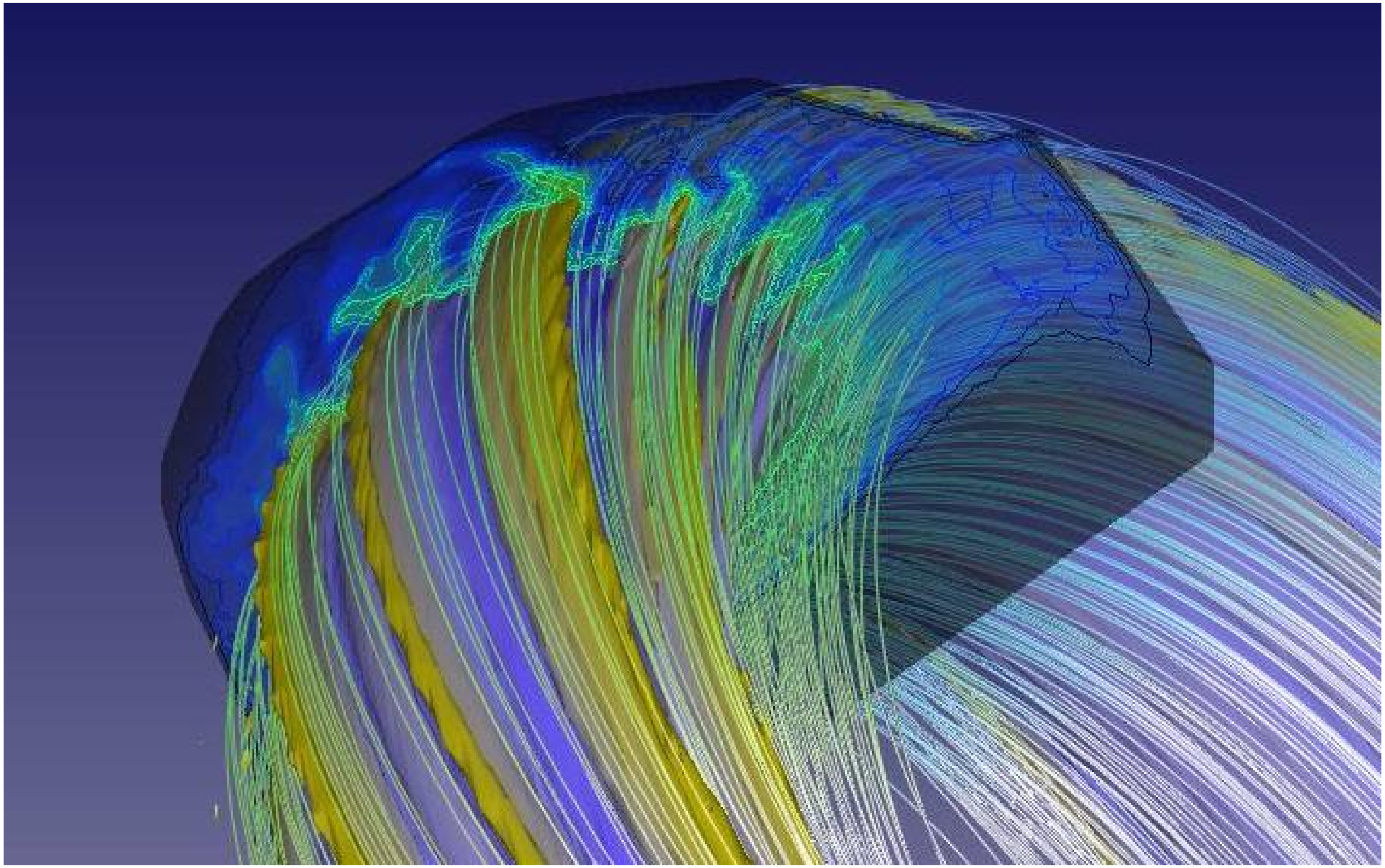
- Plasma filaments are *not* magnetically connected into plasma beyond a small distance outside the original plasma separatrix, except near X-points.
  Field lines outside are rapidly lost to wall.

- Field lines connect deeply *into* the plasma as the alternating lower density fingers grow inwards, with radial excursions. Many lines are eventually lost from near X-points, after many toroidal circuits.

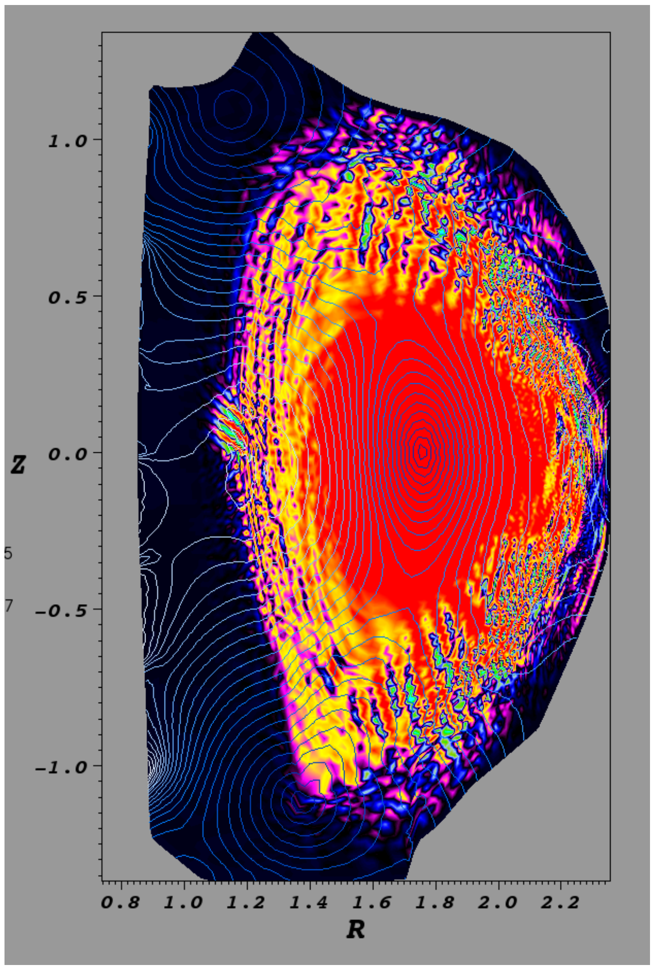
- Some field lines form annular flux “volumes” rather than surfaces.

Magnetic field retains some structure, despite apparent chaos. Confined field lines are mostly helical like equilibrium, approximately follow temperature contours, with Δr excursions.

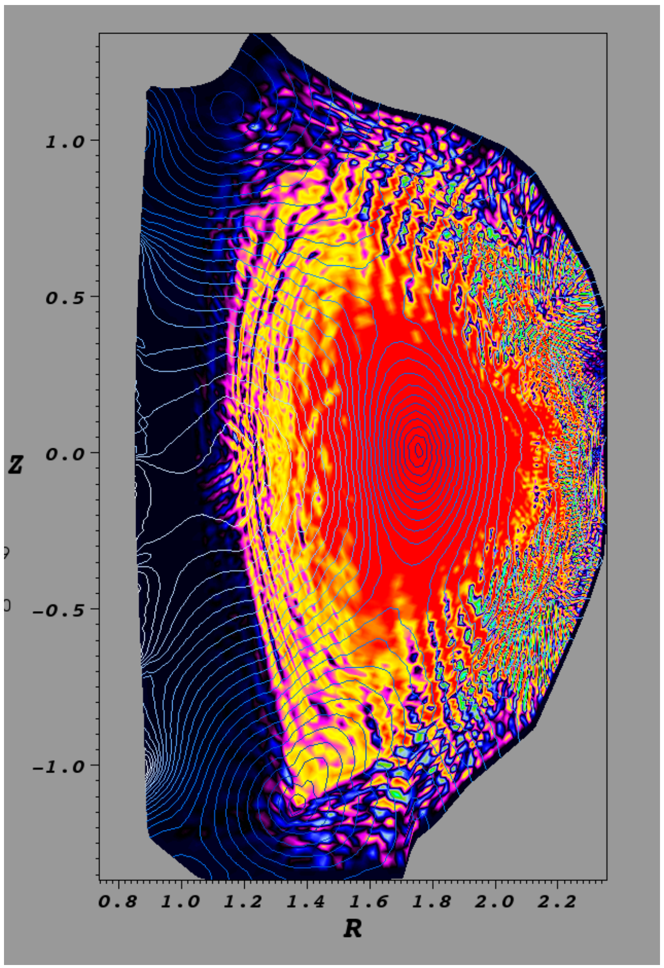
Temperature surface colored by values of ψ, with single field line in $+B_{\phi}$ direction. Tilted to show bottom X-region (119690, different case).



Toroidal current density ($-RJ_{\phi}$) suggests tangle

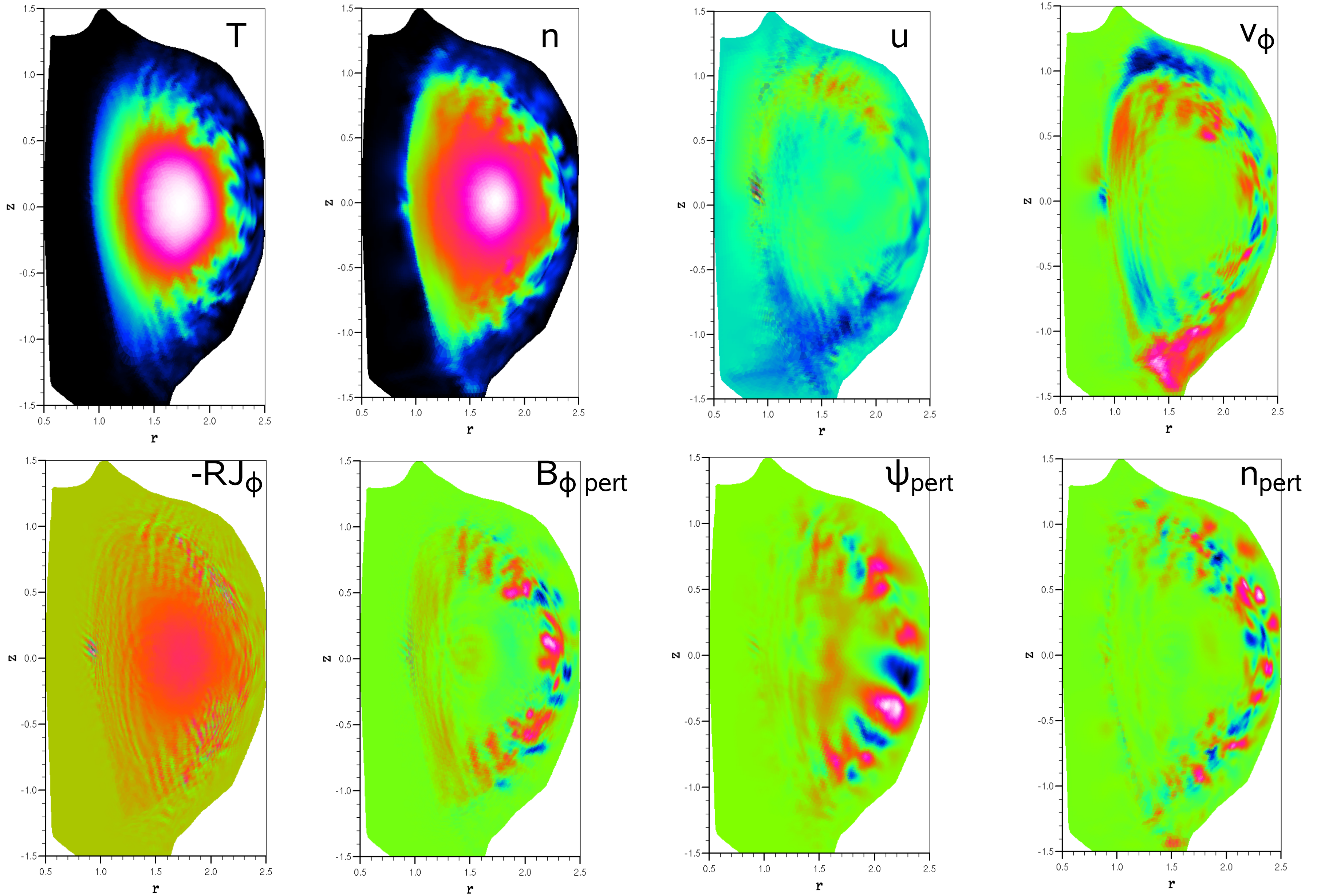


t=52



t=136

Contour lines are $B_{\perp\phi}$
119690



Plasma quantities show some features of the magnetic tangle.

119690 t=83.4

Toroidal harmonics in time

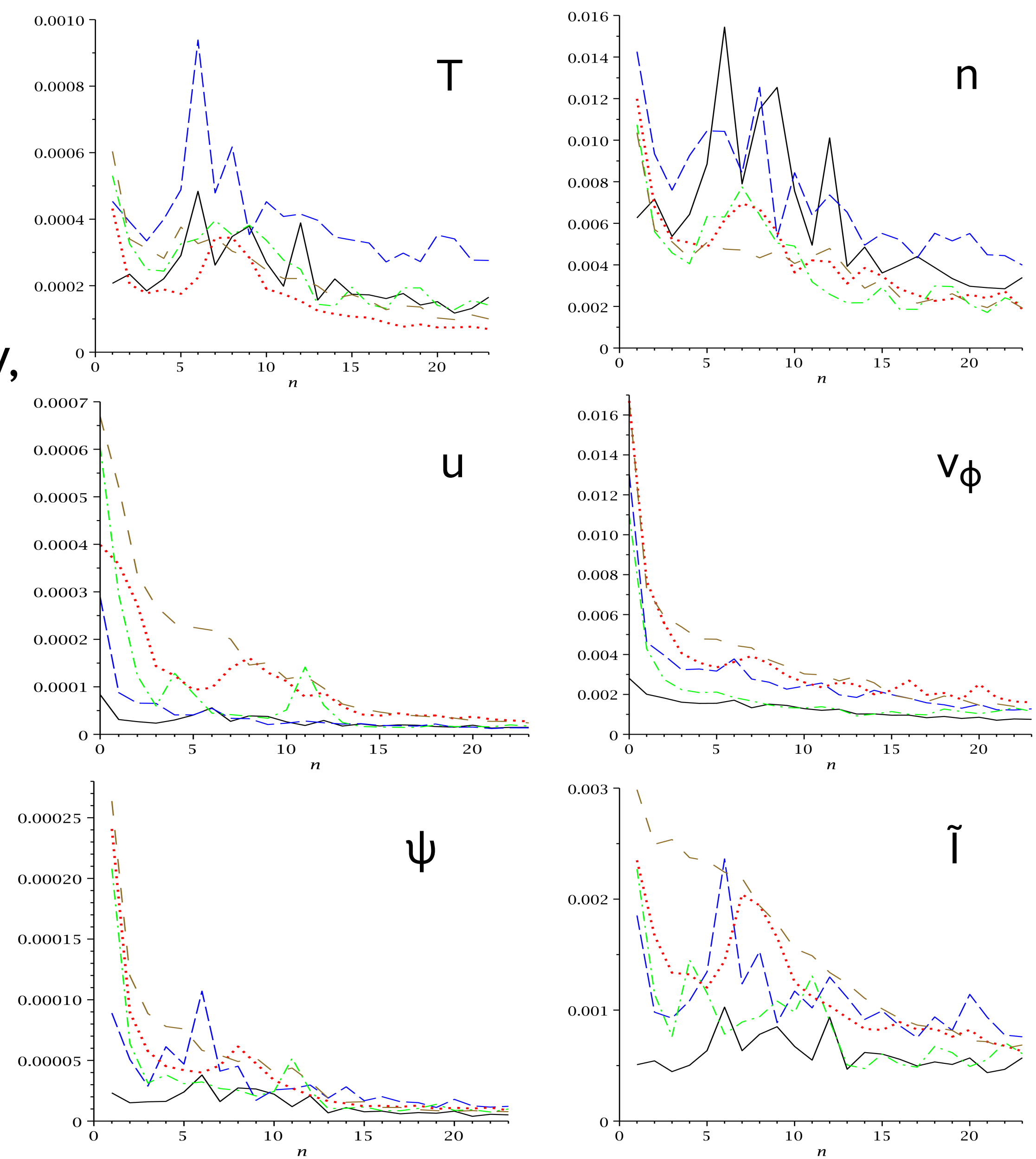
t=43, 126, 227, 461, 604

n, T, ψ non-zero harmonics grow initially, then decay towards axisymmetry, except for a central n=1 structure

n=0 components of n, T, ψ, and $\tilde{I}=(RB_{\phi}/R_oB_o-1)(R_o/a)$ are large, not shown

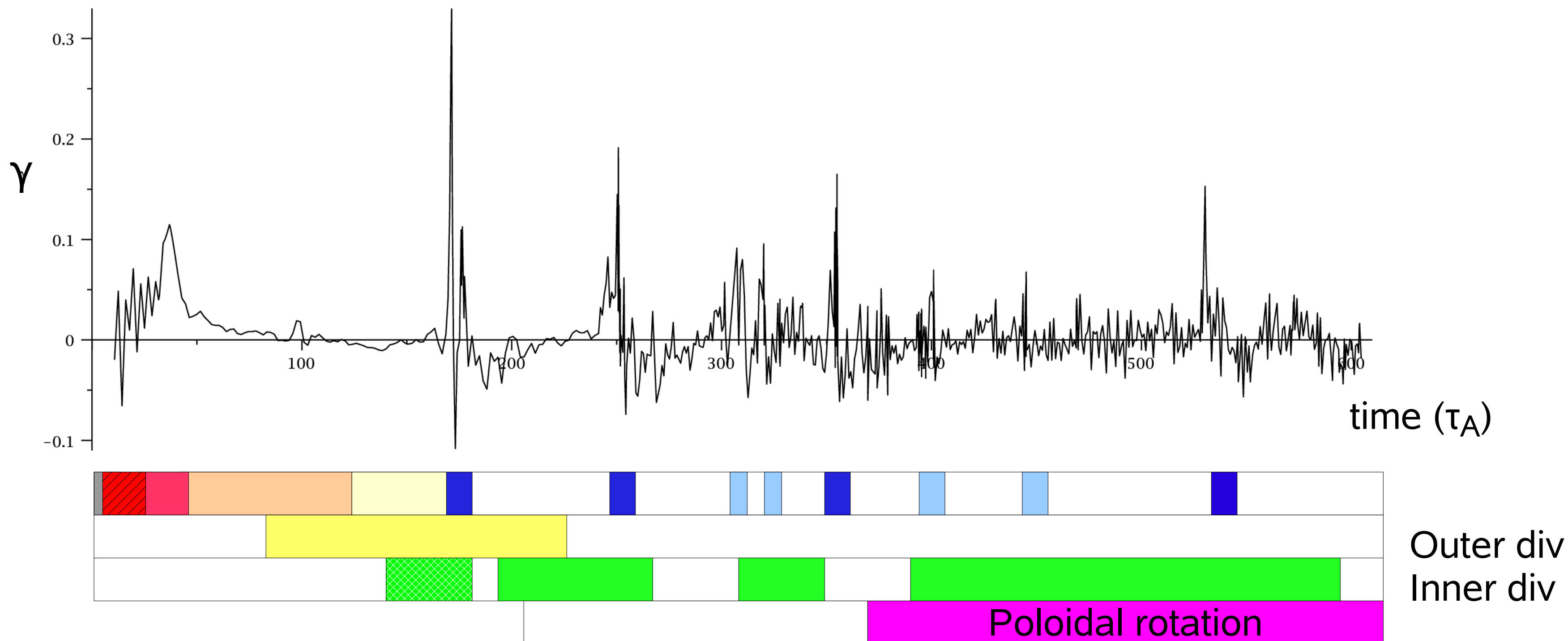
u_0, $v_{\phi 0}$ x (½) shown

(Volume integrated)



119690

ELM Stages: The movies



Outboard ballooning: NL mode consolidation and strong growth

Plasma burst outboard, midplane ∇n reduced; outboard SOL clears.

Density to outboard divertor from near X-point

Inboard edge instability

Density to inboard divertor

DIII-D 119690 at 2656 ms
1 τ_A = 0.78 μs

Movies

- DIII-D 119690 (ITER-similar shape, very steep edge pressure gradient, $q_o \approx 1$)
  (1) 2D pressure (2) 3D density at 2 values
  - Actual resistivity, $S=3.3x10^7$
  - $1\ \tau_A = 0.78\ \mu s$, total simulation time $604\ \tau_A = 470\ \mu s$
  - Movie frame rate $10\ \tau_A = 7.8\ \mu s$ (approximately)
  - 330 wall clock hours on 360 cpus (Cray XT-4 Franklin at NERSC)
  - Inboard wall-plasma distance stretched; 15769 grid points in 2D ϕ-plane
- Initial fast ballooning outburst with large off-midplane fingers; near end, density lost to outboard divertor from near X-point
- Outboard instability subsides, density begins to clear from outboard SOL, then inboard instability (growth rate spike at t=170); density to inboard div.
- Continuing cycles of edge perturbation/blobs. Poloidal rotation develops.
- Central 1/1 island grows starting early, reduces central density and temperature; not complete reconnection. Sawteeth seen in experiment.

Movies -2-

- DIII-D 126006 (RMP ELM-stabilized case)
  (1) 2D density (2) 2D temperature
  - Resistivity within 5x actual ($S=3.3x10^7$)
  - 1 τ_A = 0.43 μs, total simulation time 331 τ_A = 142 μs
  - Movie frame rate 5τ_A = 2.6 μs
  - Inboard wall at actual position; 19441 grid points in 2D ϕ-plane, 72 planes
- Density lost direct to divertor from near X-point. T (and p) shows stronger streaming along B-lines in outboard SOL.
- Less off-midplane initial ballooning than 119690
  - q_o>1, no 1/1 island
  - Low-n interior mode grows eventually (n=2 seen in experiment when toroidal rotation was deliberately reduced; locked to wall, H->L)
- Other features similar to 119690
- Without RMP nonaxisymmetric field, ELM is MHD unstable!

Summary

- ELM represents a new type of plasma instability
- X-point causes chaotic magnetic tangle near plasma edge. Field-aligned plasma instabilities can couple to the tangle!
  - Asymptotic field splitting reduces early NL ballooning mode (Not shown)
  - Later, interchange + tangle penetrates deeply into plasma
  - Tangle easily breaks interior flux surfaces without extensive low m/n island formation (only known theoretical mechanism)
  - Stochastic magnetic field retains some structure
- Multistage ELM has many features similar to experiment
- Main loss to divertor direct from X-point region, or inboard
- Stochastic field may help explain properties of the plasma edge in D-shaped plasmas, including confinement