ELMs: A New Type of Plasma Instability

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Summary

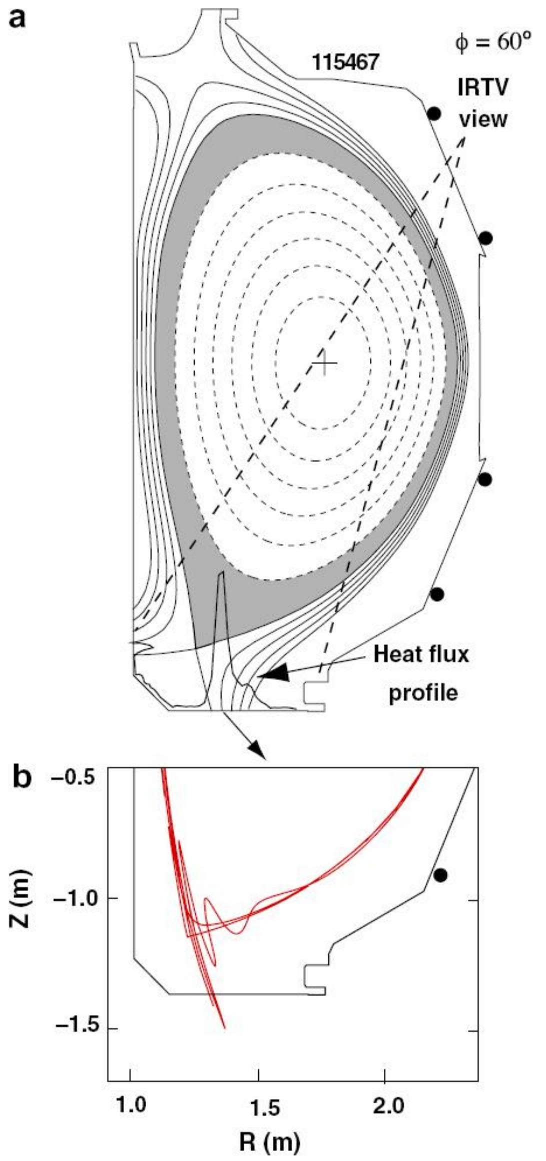
- ELMs are a new kind of nonlinear plasma instability in a free-boundary plasma with magnetic X-point on (near) boundary
  - X-point magnetic boundary surface splits into two asymptotically under small perturbation
  - Coherent MHD plasma instability (ballooning/interchange, field-aligned) couples *nonlinearly* to *part* of the magnetic field
  - Can penetrate to plasma core; stochastic field allows rapid loss of core plasma and plasma loss to outside
  - Original axisymmetric magnetic field is mostly preserved; Plasma eventually heals back toward original shape
- Explains many observed features of ELMs
- All perturbations of plasma edge should see similar effects

Topics

- Axisymmetric toroidal magnetic field as Hamiltonian system
  - Small perturbations produce 'homoclinic tangle'
- ELM: competition of plasma instability and homoclinic field drives nonlinear evolution in multiple stages
  - Initial ballooning/peeling mode rapidly develops characteristic nonlinear shape
  - Interchange instability in competition with field perturbation to core
  - X-point losses
  - Long time healing
- Implications for plasma edge physics

Hamiltonian systems and homoclinic tangle

- Axisymmetric toroidal magnetic field with nested flux surfaces can be described as 1D Hamiltonian system
  - X-point on magnetic boundary is a hyperbolic saddle point
- Theory of small pertubations: X-point surface splits into two, defined as the asymptotic limits of the field lines, that traced infinitely, goes to the X-point in each direction
  - “Stable” manifold near original surface
  - “Unstable” manifold forms loops (bulges) that intersect stable manifold. Loops get narrower as X-point approached. Area preserving property of Hamiltonian means equal-area loops get longer → infinitely, in limit at X-point



T. Evans, et al, Phys Plasmas 2006
Applied RMP field in DIII-D

- Interior nested magnetic surfaces are different:
  - Small perturbation creates magnetic islands, preserves some intermediate irrational surfaces (KAM surfaces). These break down progressively as pertubation size increases.
- Homoclinic tangle breaks KAM surfaces in the region adjacent to primary X-point! (Dragt and Finn, JGR 1976)
  - Answers long standing question for plasmas: How to break KAM surfaces without forming, reconnecting low m,n islands?
- Similar effects if X-point is near, but not on, the surface.
- Exact form of fields depends on the driving perturbation
  - Changes in plasma take a finite time → actual instability is a continual small perturbation of 3D field (also Hamiltonian)
  - Competition between preferred form of plasma instability and desired homoclinic field response
  - What is definition of “small” perturbation? Theory doesn't say.

M3D ELM Simulation

- M3D code rewritten for ELMs in 2008
  - Higher resolution, more accurate, higher Lundquist number S
- Particular H-mode DIII-D discharge 119690 shows instability clearly
  - Very steep, narrow edge pressure gradient (higher collisionality, density)
  - Simulation can use real $S=3.3 \times 10^7$
- Pieces of this picture are visible in previous simulations by M3D and other codes, but significance not recognized.
- Equilibrium toroidal rotation qualitatively similar to non-rotating (not discussed)

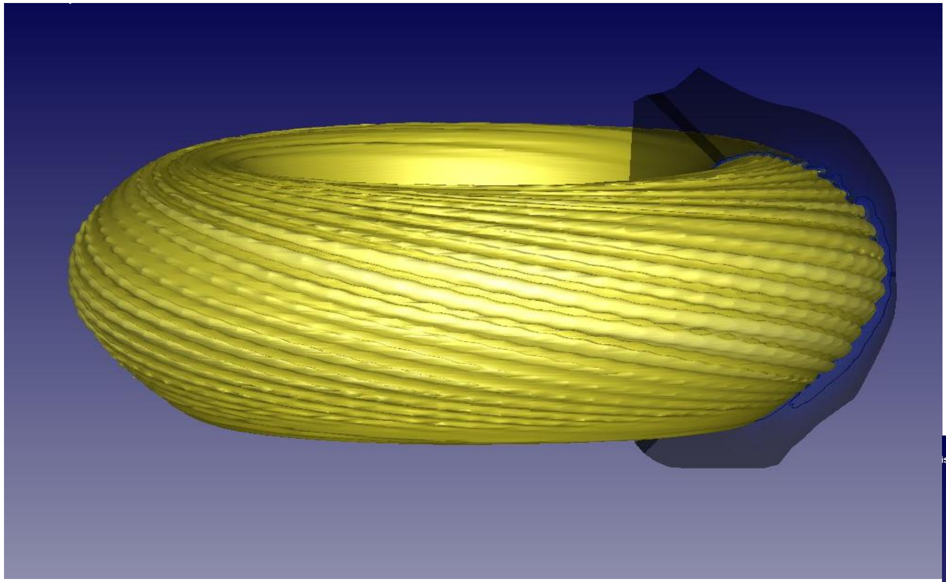
ELM Stages

- Initial: strongly unstable ballooning mode at high-n (approx n=40)
  - Ballooning eigenmode has different shape from tangle → nonlinear beating reduces to lower n=6-10, with strong very low n envelope (n=1,2) →helical stripe along a few field lines
  - Density, temperature edge gradients quickly smoothed (midplane)
- Fingers grow off-midplane (+/-60 degrees), away from X-point
  - Plasma bulges out, vacuum fingers penetrate plasm Resistivity is destabilizing -> nearly ideal interchange?
  - Magnetic field stochasticizes from outside in, following fingers
  - Plasma lost to outboard side from fingers (near top, bottom)
- Plasma core affected; Inboard plasma edge and X-point regions
  - Plasma lost through X-point, to inboard divertors
- Eventually, healing toward axisymmetry, near-original configuration

Early NL ELM perturbation has pseudo- m=1/n=1 shape.

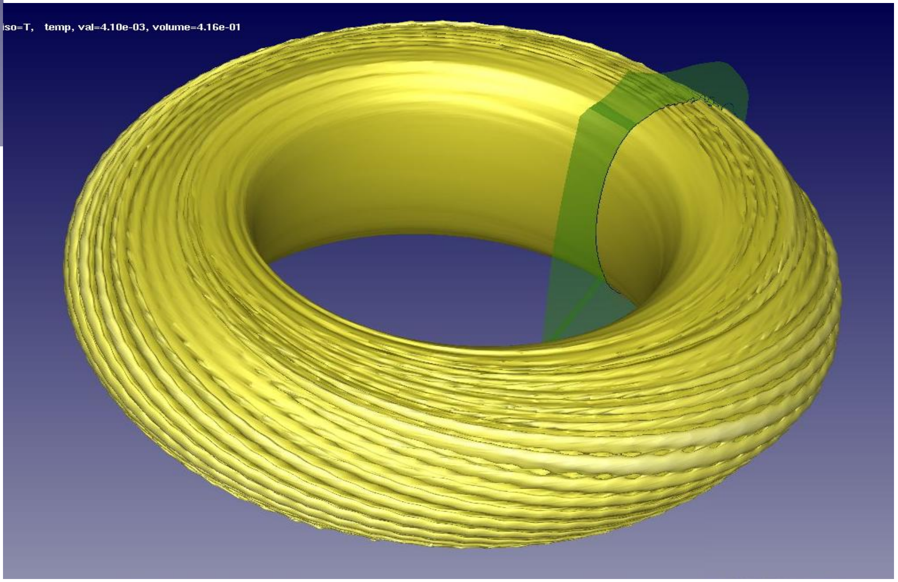
* Perturbation on outboard side of plasma wraps from top to bottom over approximately 1 toroidal circuit, following magnetic field lines.

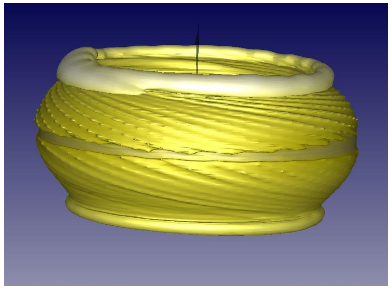
* Characteristic field line geometry in DIII-D H-mode with $q_{95} \approx 3.6$



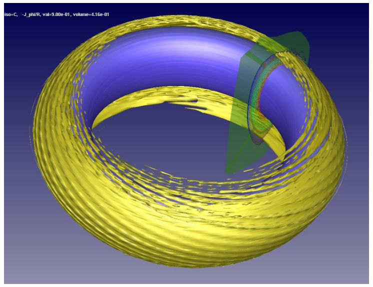
*Temperature, small ELM at $t=131\tau_A$
Side and top view, const T contours approximately follow field lines.

*Toroidal current similar; density also except near midplane





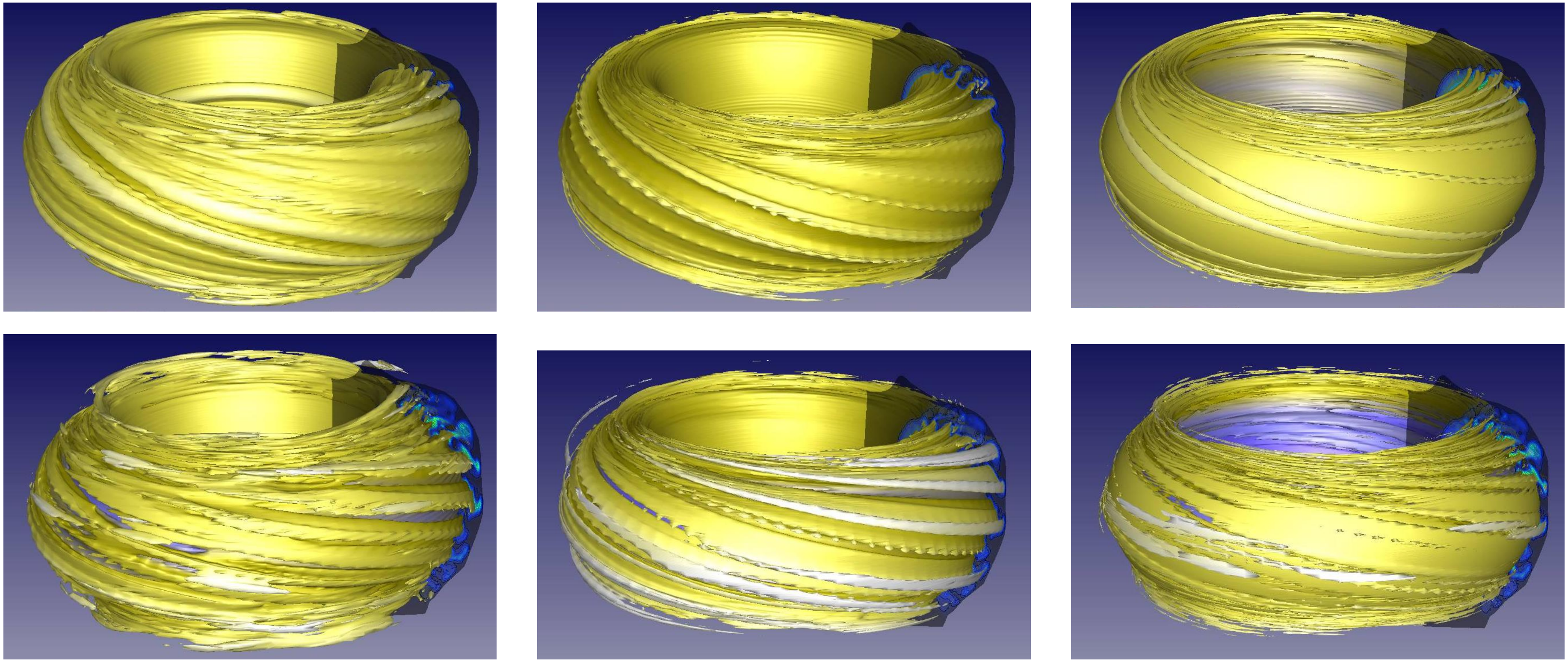
n



$-RJ_\phi$

Toroidal mode number decreases in time

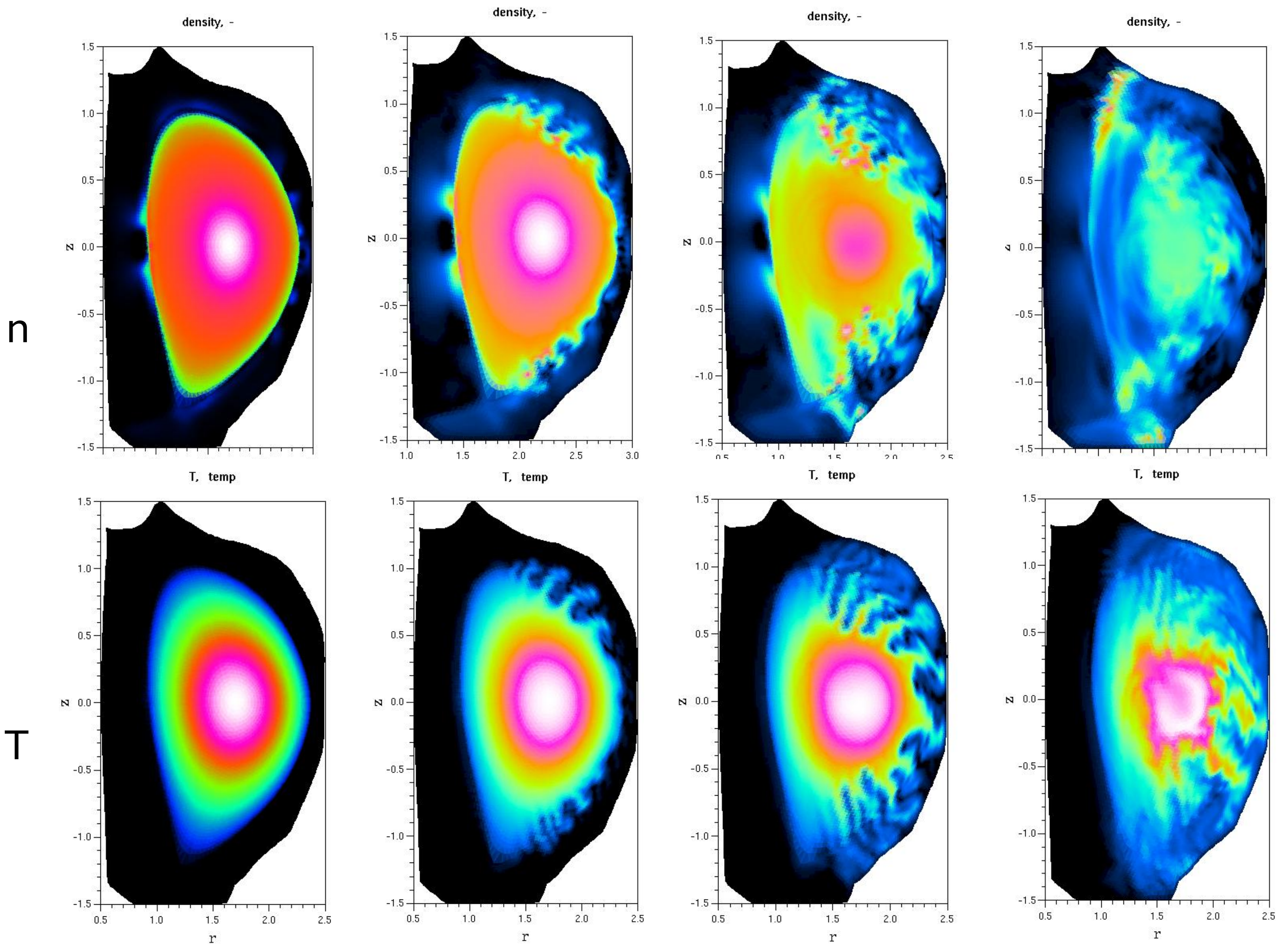
Characteristic, well-defined nonlinear shape with low n=1 envelope as fingers start to grow; becomes more mixed



n T RJ_ϕ

119690

ELM instability



t=66.9 89.3 133.4 178.3

NL shape does not match ballooning eigenfunction; ELM large off mid-plane.

No rotation
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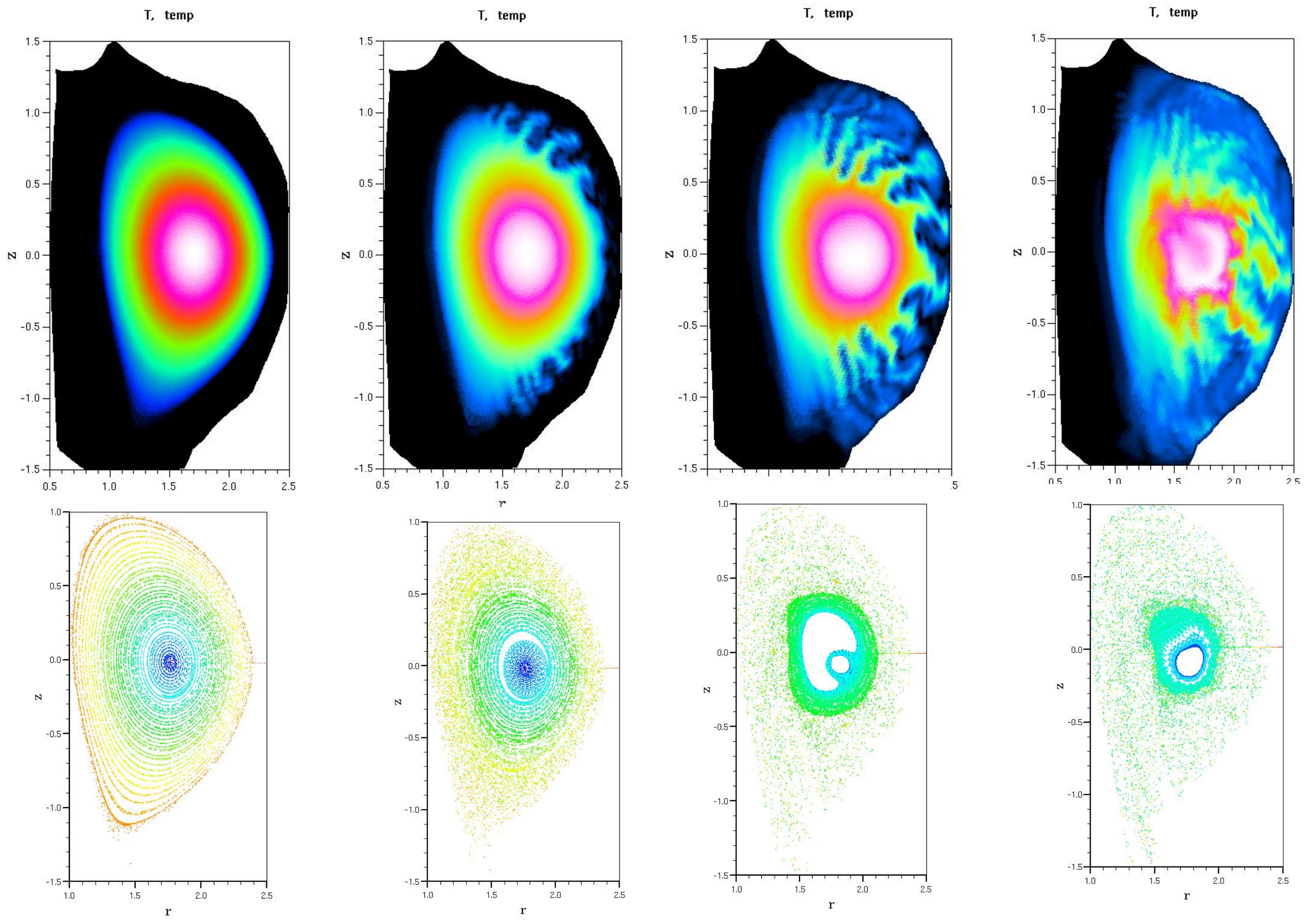
Magnetic field stochasticizes from outside in, following fingers



Plasma temperature in cross section of torus

Magnetic field puncture plot ($q_o<1$)

$t=66.9\tau_A$ 89.3 133.4 178.3

CEMM spring09
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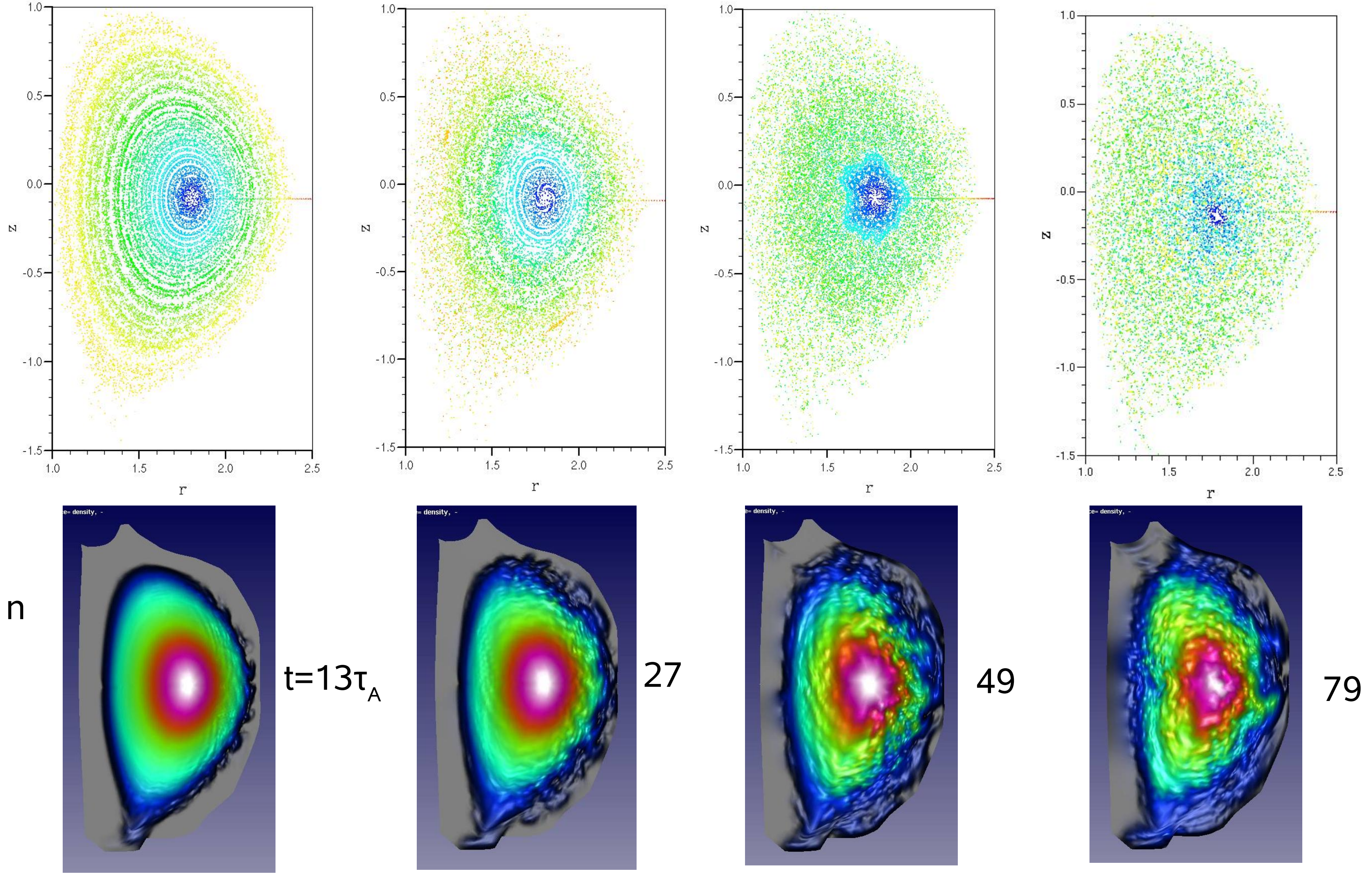
Other ELMs show similar field evolution; fingers less obvious.



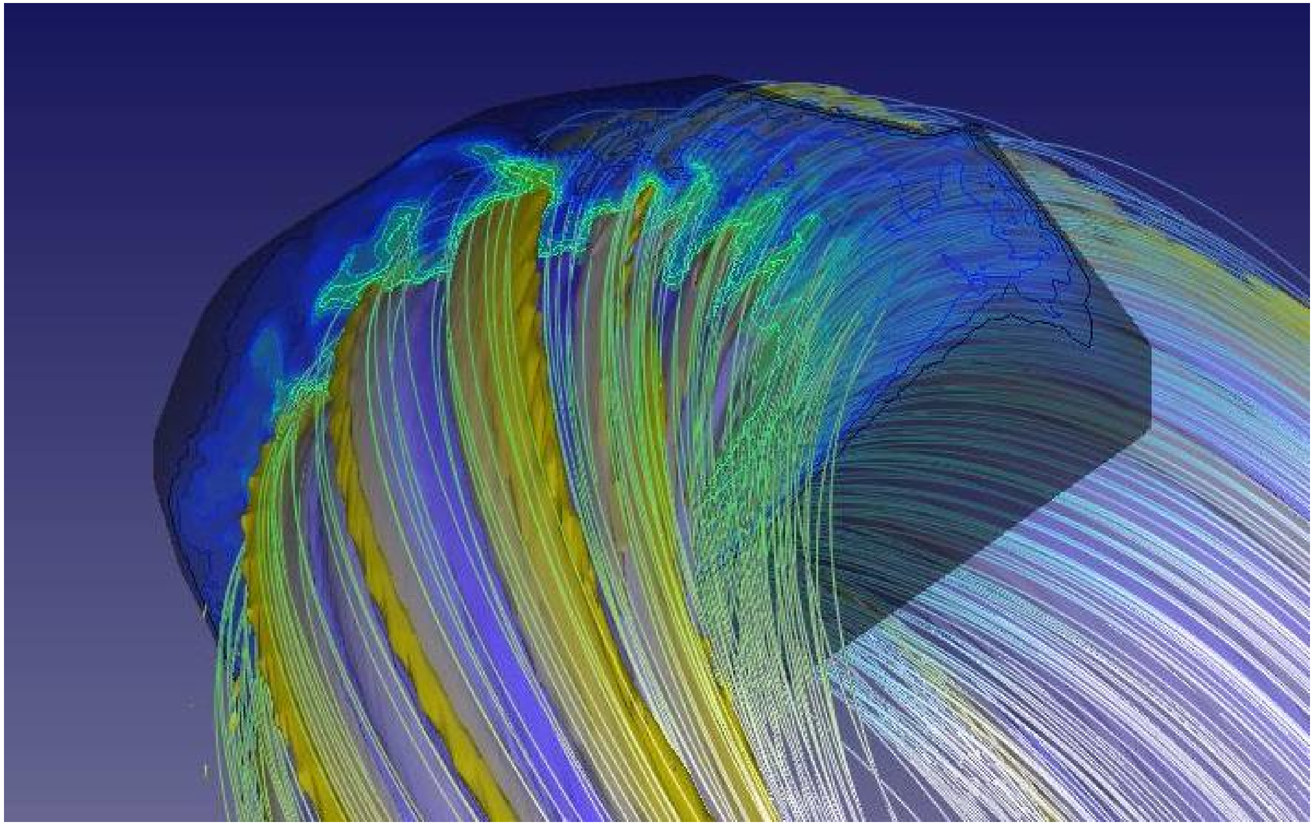
DIII-D rotating

ELM fingers approximately follow the magnetic field, despite its apparent stochasticity, similar to “unstable” side of homoclinic tangle

Plasma fingers (temperature, density) are mostly aligned with field lines, but not exactly.

Field lines have radial excursion, but many are well contained for many toroidal transits, then lost from near X-points. Core well-confined.

No evidence of field tubes deep in vacuum region that connect into the plasma on both ends



Bottom view of plasma, tilted up to show deep T fingers

Temperature levelcontours (surface colored according to values of poloidal magnetic flux ψ, close to equilibrium values) and trace of a *single* magnetic field line.

Properties suggest competition between plasma instability and homoclinic effects

- Plasma fingers grow large some distance from X-point, not at X-point
- Resistivity and tying magnetic boundary surface have opposite effects
- Early stage of nonlinear mode number consolidation
  - Resistivity is stabilizing: Reduces growth of homoclinic field loops
- Growth of off-midplane fingers
  - Resistivity is destabilizing: Partly resistive interchange process
- Constraining the magnetic surface by putting wall close to plasma significantly *increases* growth rate of fingers. Successive increase by:
  - (1) putting wall 20% above upper plasma boundary, cutting off upper X-point, then
  - (2) adding wall just below (1%) lower X-point. In early stage, current builds up in thin layer on plasma boundary in lower finger region, but field bulging greatly reduced (more like ballooning mode).

Longer time (details skipped!)

- Inboard plasma edge changes. Plasma moves to X-points and out to wall; also diffuses into inboard vacuum region.
- Plasma in outer vacuum region disperses early; plasma in divertors may linger.

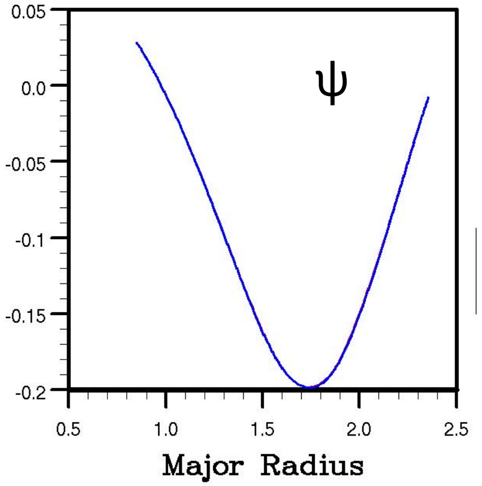
- Slower saturation to axisymmetric profiles with near-original boundary (poloidal magnetic flux ψ is little changed), over several hundred τ_A.

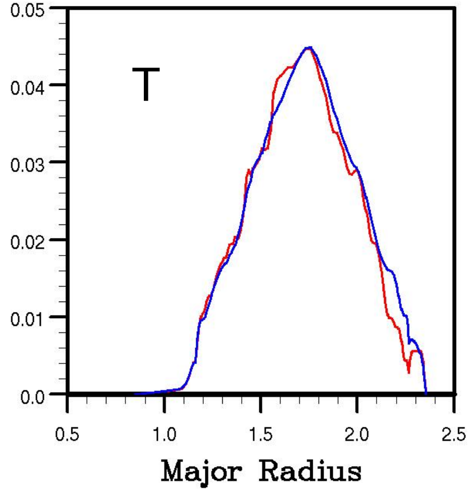
Loss n_o=10-15%, T_o=5-10%

- Question: How long for field to return to axisymmetry (does it completely?)

 Note that standard experimental equilibrium reconstruction methods at this stage would find a good axisymmetric equilibrium!

Long time t=336
red=full,
blue=tor ave

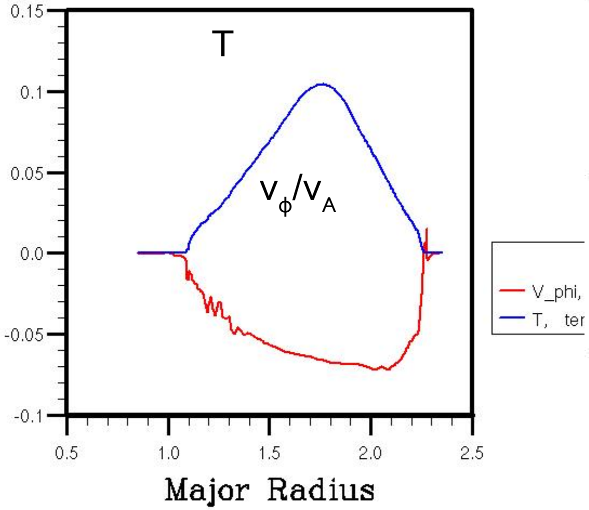


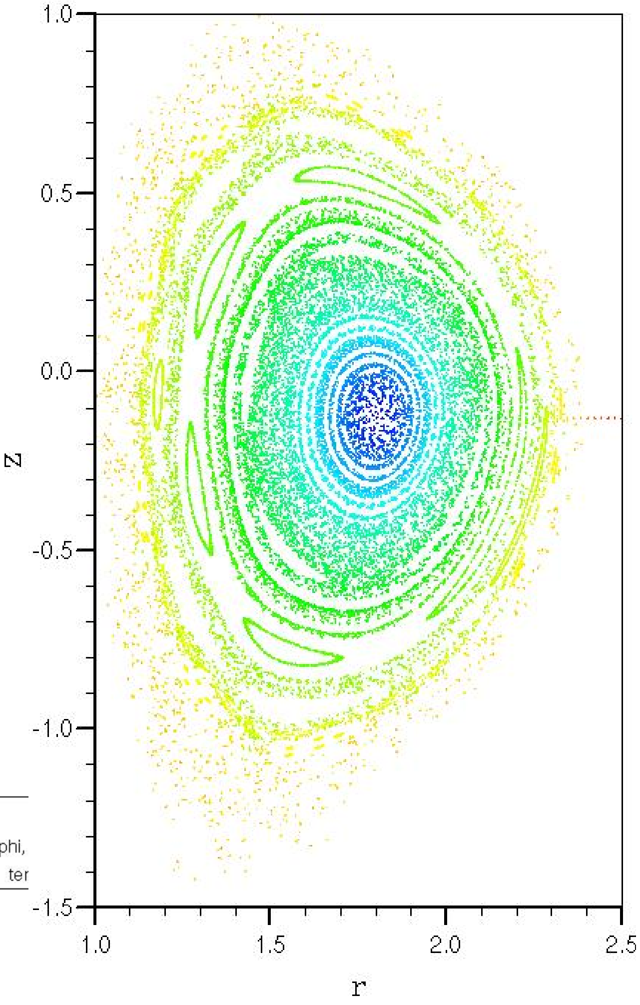


Applied magnetic perturbation also stochasticizes field

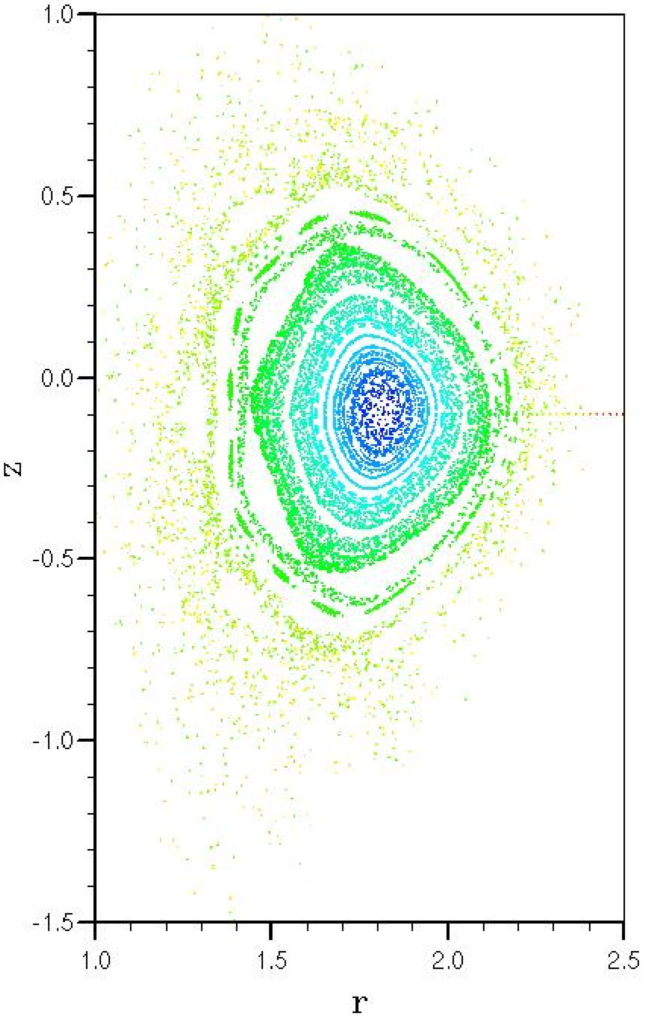
DIII-D vacuum RMP field
from external coils applie
full strength at t=0 to
rotating plasma
(toroidal harmonic n=3)

Scaling with S does not fit simple reconnection theories
(Strauss NF2009)





t=14.5 τ_A



t=28.3 τ_A

Summary

- ELMs are a new type of nonlinear plasma instability that couples *part* of a stochastic magnetic field to a coherent plasma structure
- Plasma magnetic boundary surface with X-point has special properties under small perturbation (Hamiltonian system) → homoclinic tangle
  - Breaks interior magnetic surfaces (KAM surfaces), allows losses from plasma core to outside plasma
  - Preserves original magnetic field; heals back to near-original
  - Magnitude, shape of instability depend on details, driving strength
  - May explain large range of ELM and ELM-free behavior in expt.
- All edge perturbations should allow magnetic field splitting
  - Small error fields and other non-axisymmetries potentially have large effects. Two-fluid, kinetic effects also. Nonlinear!
- Need to rethink H-mode plasma edge confinement and L-H transition