Structure of the ELM crash from numerical simulations

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M3D meeting
PPPL
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Topics

- Extended MHD numerical simulation model (upgraded M3D initial value code)
- Large ELM crash: Older results show “classical ballooning”
- New: Multistage ELM crash, spatial and temporal
  - Midplane outboard ballooning/peeling drives ELM, secondary instability at top/bottom expels plasma to divertors
  - Density moves out by resistive interchange; little change in magnetic field outside original separatrix
  - Many features accord with experimental observations
- Two-fluid effects (preliminary)
- RMP and toroidal rotation (cf. H. Strauss, IAEA FEC 2008)

Numerical simulation model

- MHD or two-fluid equations
- GEQDSK equilibrium, including bootstrap current (257x257 grid)
- Full plasma geometry with X-points, MHD vacuum, wall
  - MHD vacuum: MHD/2F equations with zero current → Large resistivity $S \le 10^3$, p=T=0, but finite density
  - Ideal conducting wall, slightly smoothed from GEQDSK shape
    - No explicit divertors, no particle source/sink or pumping
    - Very strong dissipation right at wall
- Packed grid in ELM region
- Plasma resistivity is Spitzer-like $\eta \sim T^{-3/2}$ between max, min limits
- Large parallel thermal conductivity $\chi_\parallel/\chi_\perp$, so temperature equilibrates rapidly along magnetic field lines
- Results scaled to R_0, v_A, τ_A (Alfven velocity, time)

M3D code with higher order finite elements

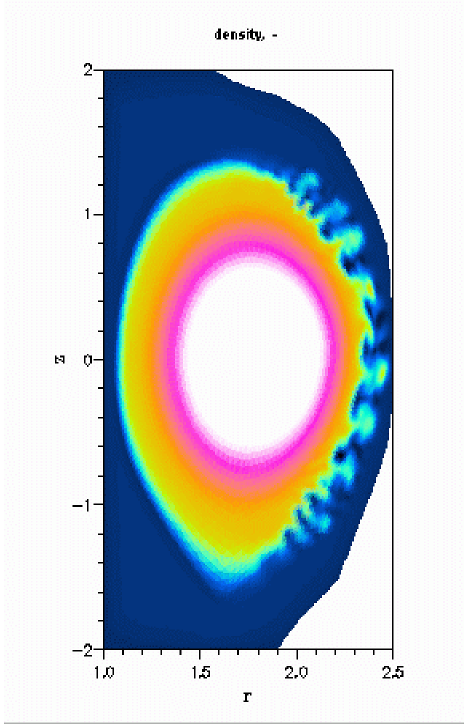
- Over summer 2008, the M3D initial value code was improved to handle higher order finite elements (previously, linear elements only)
  - 2nd and 3rd order, regular and lumped-Cohen triangular elements
  - Extension to higher order
- More grid points in each poloidal plane (ϕ=const) allows
  - Higher resolution, including toroidally
  - Lower, more realistic dissipation (resistivity, viscosity)
- ELM NL simulations (MHD): For same number of grid nodes,
  - 2nd order regular: 2.2x slower than linear per τ_A, 1.41x per Δt
  - 3rd order regular (HO3): 4.5x slower per τ_A, 2.04x per Δt
- 3rd order regular is good compromise between speed, smoothness and numerical stability. Linear FE's ideal for fast scoping.

ELM crash: Lower resolution

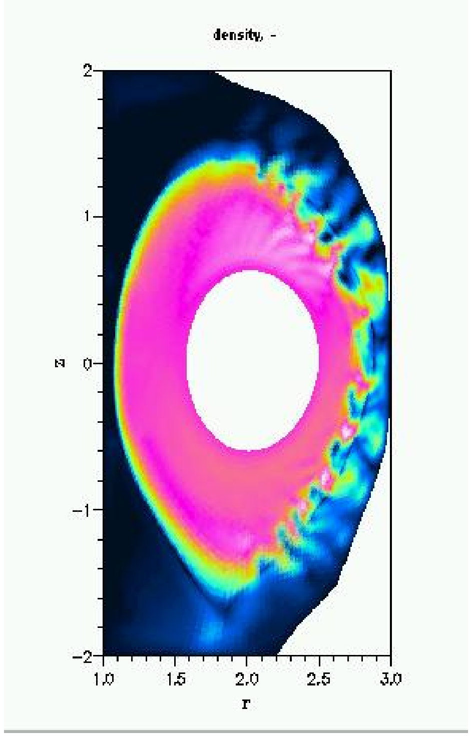
- Older results (2006/7) support a "classical" ballooning mode picture.
  - Low N toroidally periodic (eg, N=3 has modes n=0,±3,6,9, etc, and typical initial perturbation n=9.)
  - Linear FE, ≤8600 vertices in poloidal plane, packed; 32 pol planes
  - Up to $S=10^6$, $\mu = 10^{-5}$ at top of pressure pedestal
  - Plasma annulus
  - Axisymmetric equilibrium, non-rotating, from DIII-D experimental EFIT reconstruction with pedestal bootstrap current
- Ballooning-type NL instability develops over most of outboard region
  - Density and temperature 'fingers' push out into open field line region over the outboard side of plasma; hit wall; mix; over longer time, system heals to near-original plasma shape
  - NL stabilization mechanism is reduction of density gradient over the plasma edge region, reaching well inside original pedestal. Temperature gradient less reduced (Strauss, IAEA FEC 2006)
  - At long times, perturbation reduces to a few dominant field lines.

MHD ELM evolution (2007):

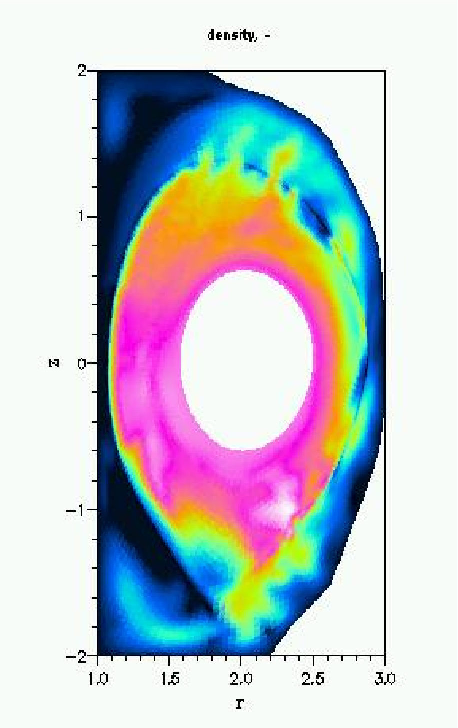
Plasma density shows a) fast ballooning, b) mixing/dispersal, c) long-time healing towards original contours (DIII-D g113317)



t=77 τ A

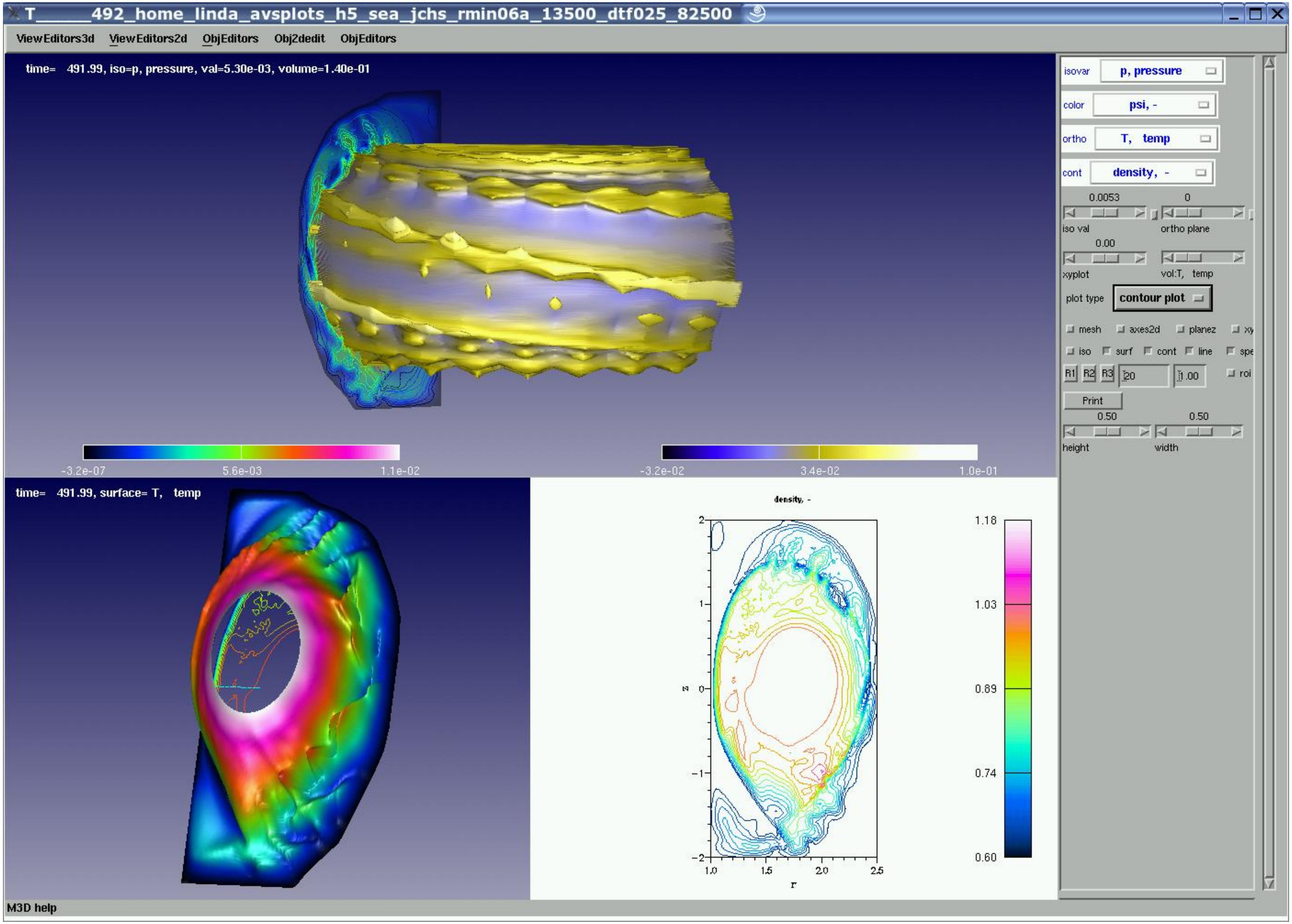


t=99 τ A



t=492 τ A

t=492. Long time saturation and healing to near original configuration. (Small) perturbation at plasma edge concentrates on a few dominant field lines with n=N=3.

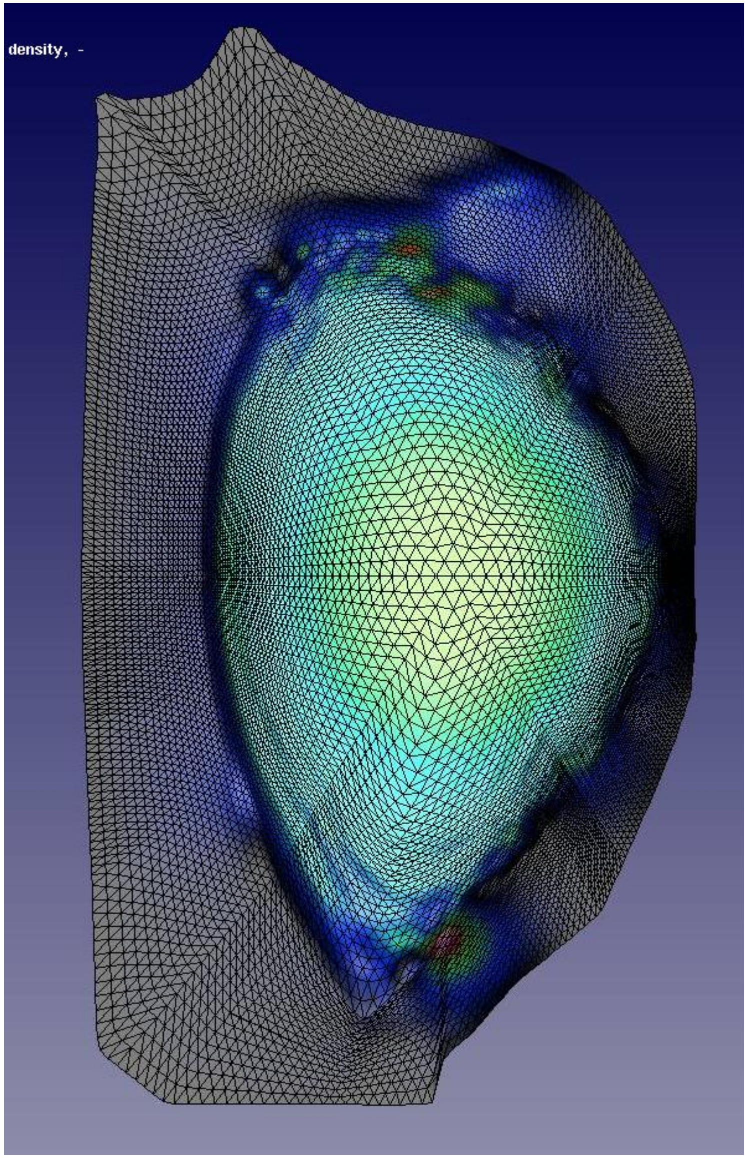


New results

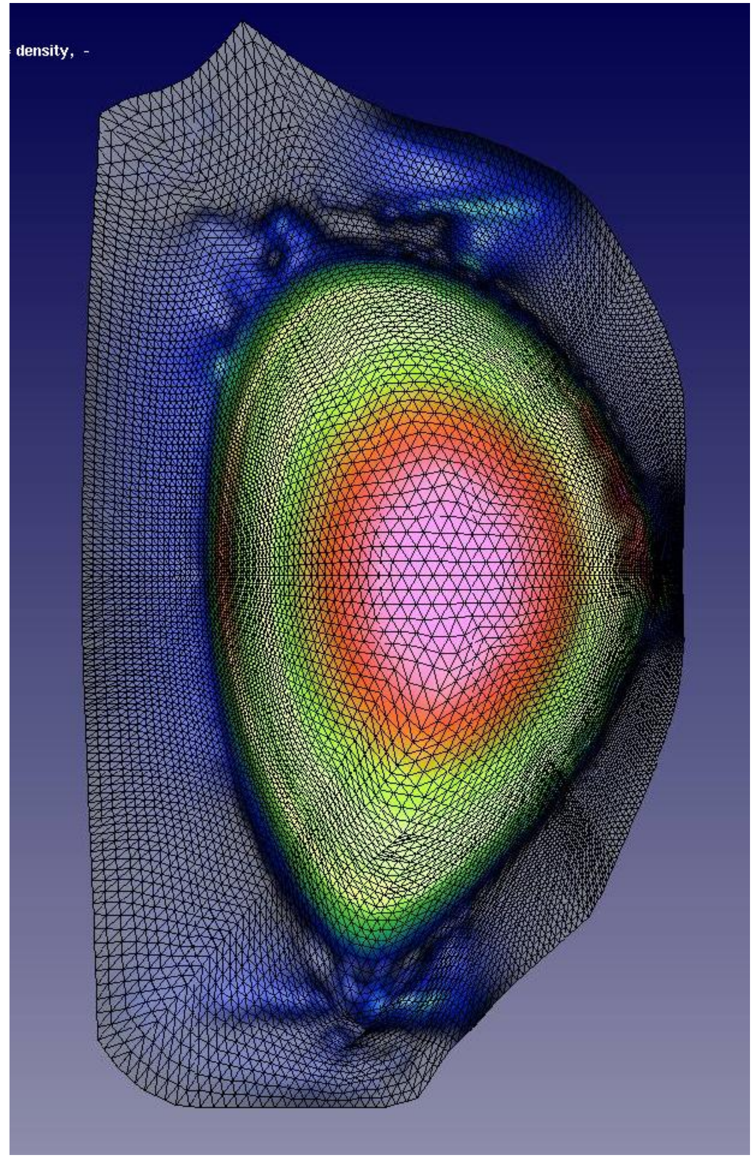
- Higher resolution
  - Finer grid, 10981 vertices/nodes in pol plane vs 7650-8600
  - No toroidal periodicity assumed; 72+ planes or 22+ toroidal harmonics FFT
  - Lower resistivity: Up to $S=10^7$, $\mu= 10^{-6}$ with same $S_{VAC}=10^3$.
  - Bigger computers (Cray XT-4 NERSC, ORNL) regularly available late 2007 → linear FE runs also at higher resolution
- Initial ballooning-type infinitesimal perturbation over outboard region is similar.
  - Initial random perturbation of all toroidal harmonics → higher n mode
  - Growth rate reduced as $\gamma \sim S^{-1/2}$, but increased by higher n
- NL evolution → multiple stage ELM crash
  - More smoothing and/or smaller resistivity reduces magnitude of crash
  - Two-fluid may increase magnitude of crash

Finite element mesh: 10981 nodes

Linear FE

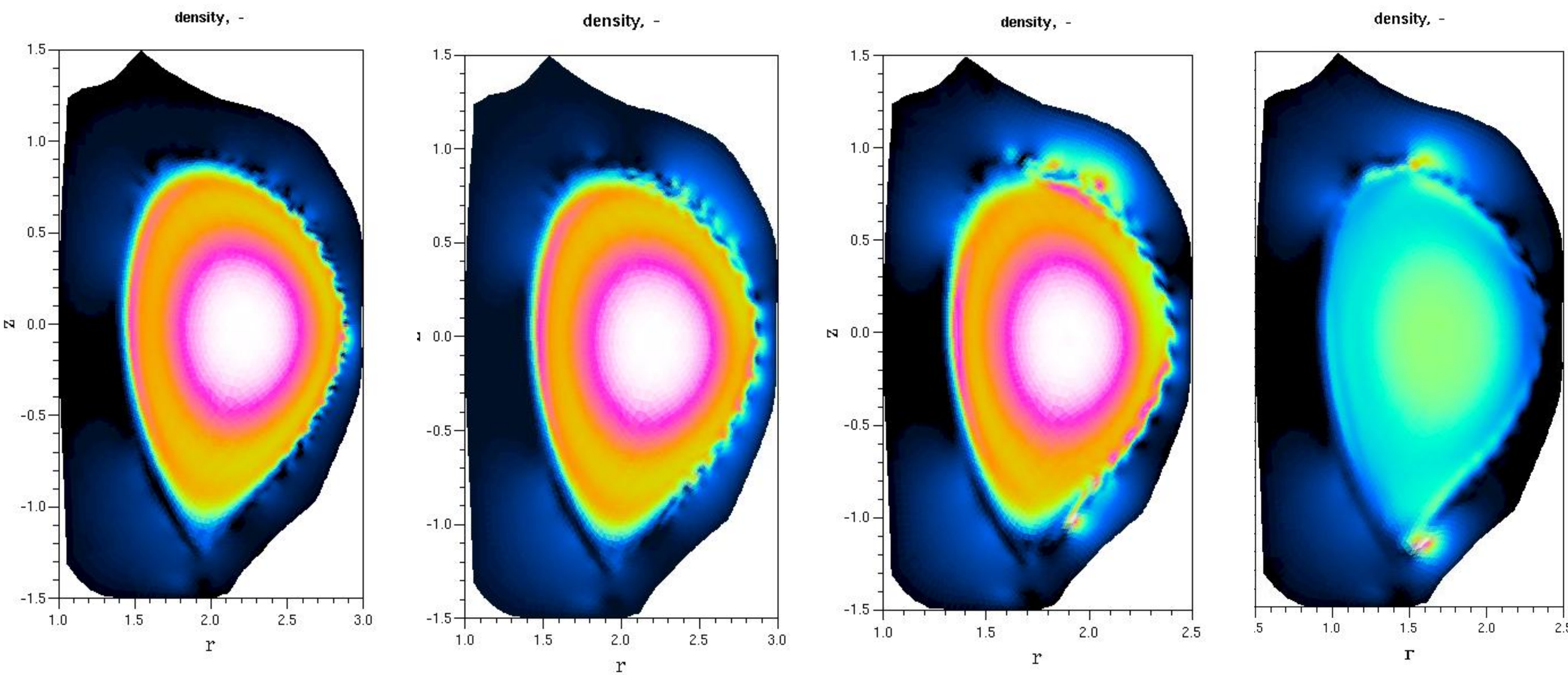


3^{rd} order (sub-triangles)



Higher resolution ELM expels less plasma radially, less far than earlier, lower resolution case

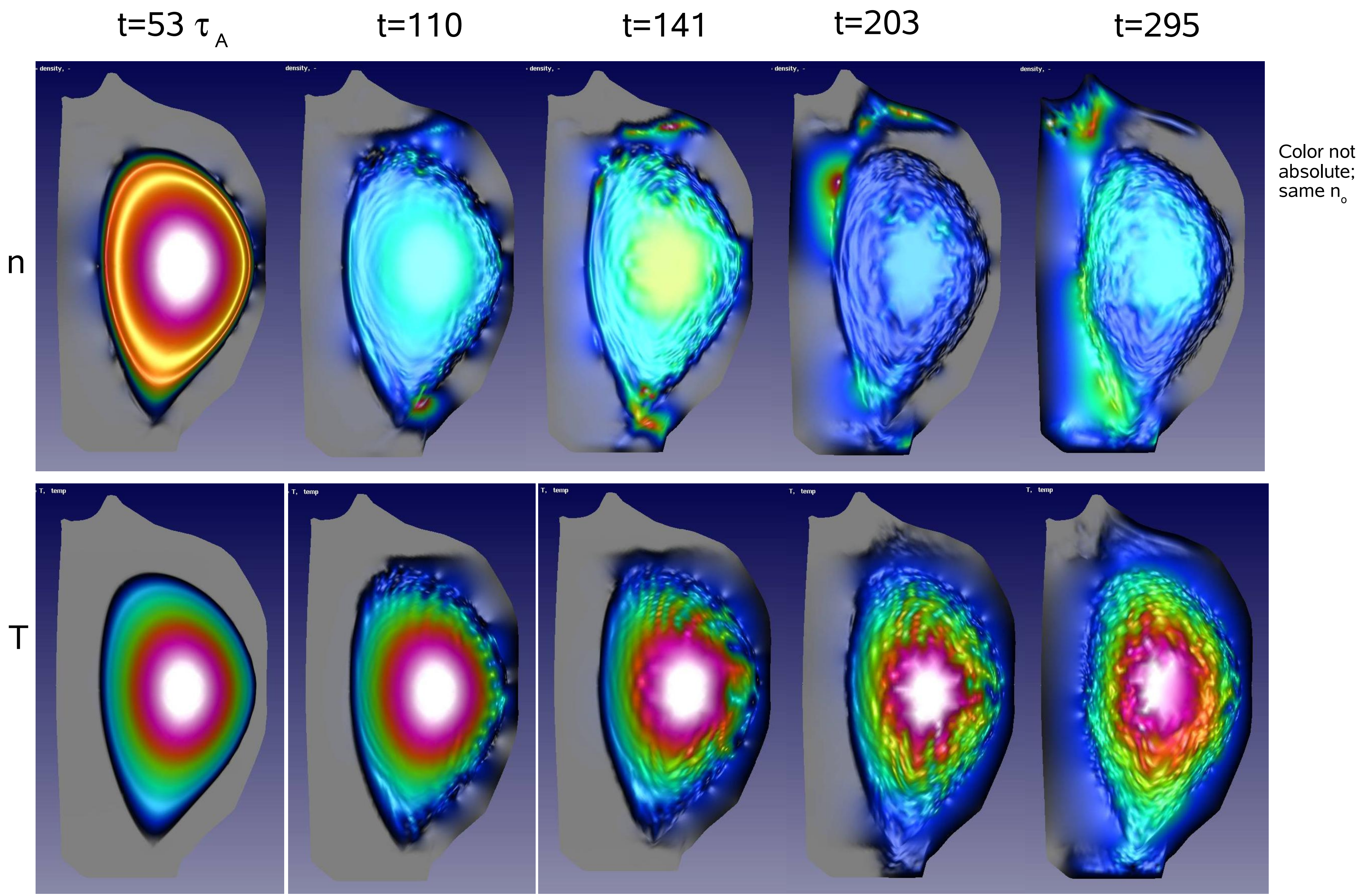
Plasma density shows a) early ballooning on midplane, b) poloidal spread up/down and growth near top, bottom, c) formation and d) accumulation outside near top/bottom. (HO3 $S=10^6$. Same n_o at all times.)



$t=58\ \tau_A$ $t=73\ \tau_A$ $t=96\ \tau_A$ $t=131\ \tau_A$

g113317

ELM at $S=10^7$, linear FEs: Density and temperature



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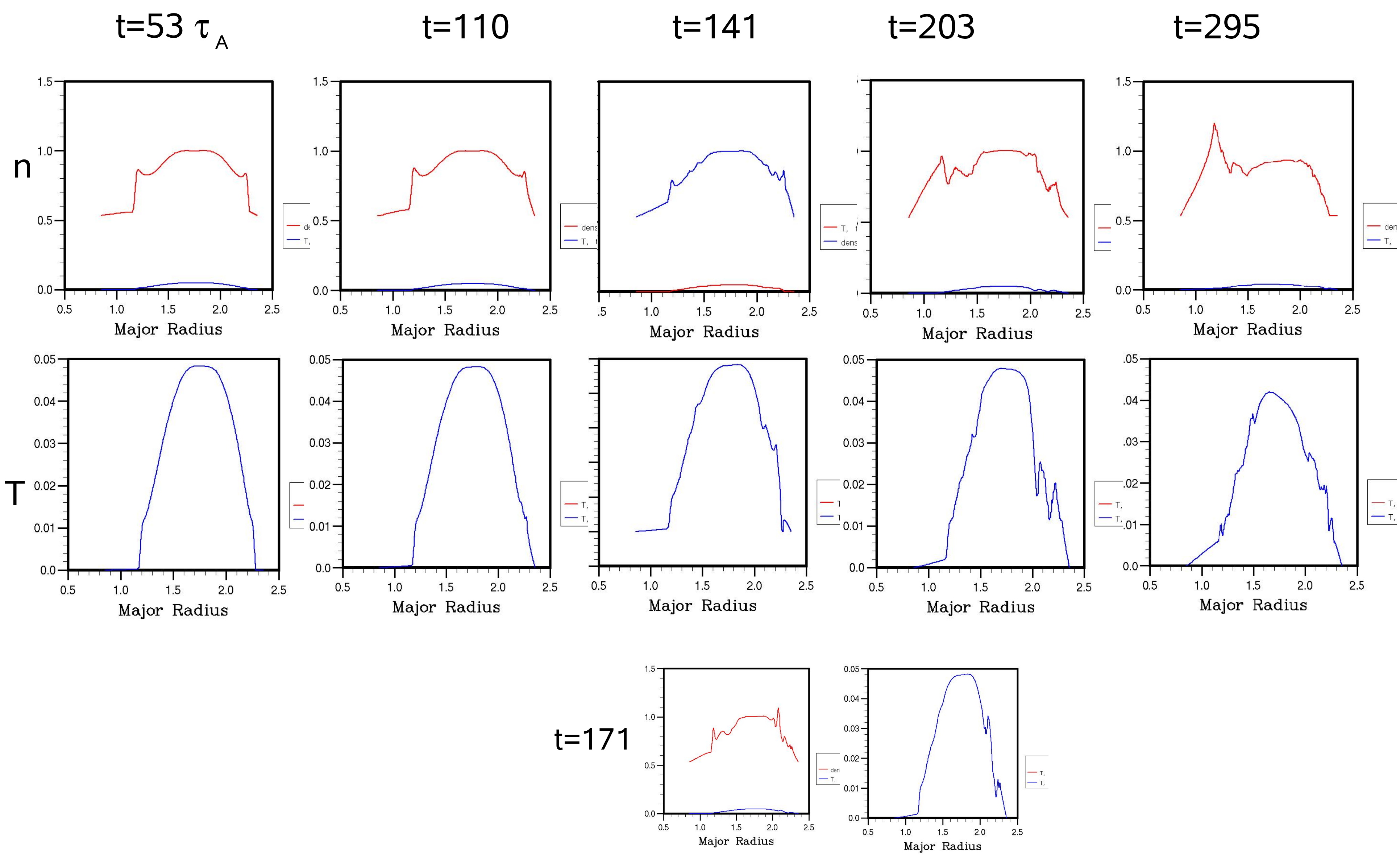
ELM at S=10^7, linearFE: Density andTemperature



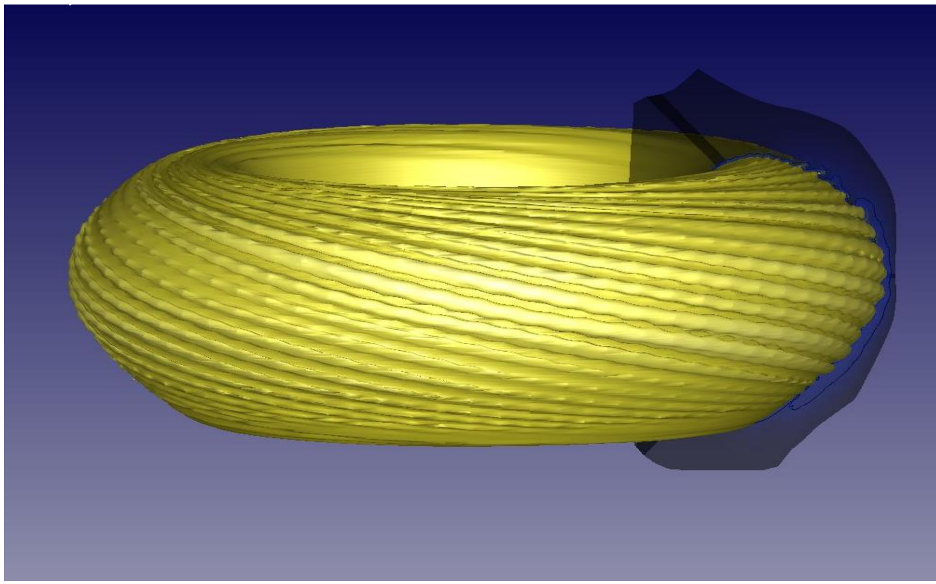
g113317

Multiple stages of an ELM Crash

- Ballooning/peeling instability, initially growing near outer midplane pushes plasma fingers radially outward beyond the LCFS, density holes pulled in.
- Density moves along field lines just outside/inside LCFS, away from midplane in both directions. Density accumulates at stagnation points near top, bottom of plasma, just outside LCFS. Plasma from outboard side reaches outer (and maybe inner) divertor on open field lines.
  - Density gradient in midplane pedestal decreases; midplane ballooning weakens
- Strong secondary ballooning-like instability develops near top/bottom of plasma; X-point field line geometry may limit the amplitude.
- Plasma spreads along (nearly contained, mostly toroidal) field lines to the inboard side at top/bottom, moves vertically just outside LCFS. Plasma into private flux region below X-pt.
  - Cold, low $n \approx 3$ localized density blobs on inboard side (MARFEs?)
- Plasma in open field line region diffuses along/across field lines; gradual healing towards original configuration.

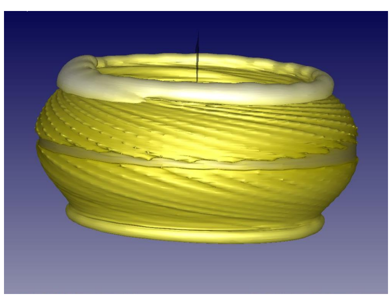
NL ELM perturbation has pseudo- m=1/n=1 shape.

* 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 a tokamak (DIII-D ELM $q_{95} \approx$ 3.5-3.7)

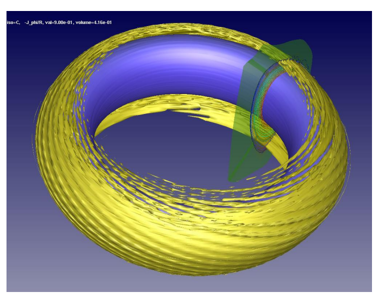


*Temperature, t=131 τ_A (HO3)
Side and top view, const T contours follow field lines.

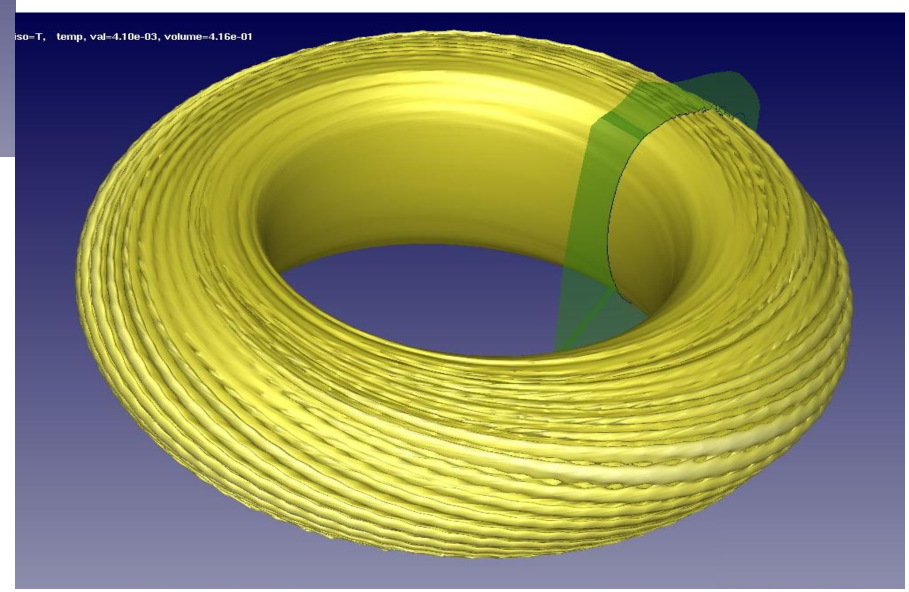
* Toroidal current similar; density also except near midplane



n

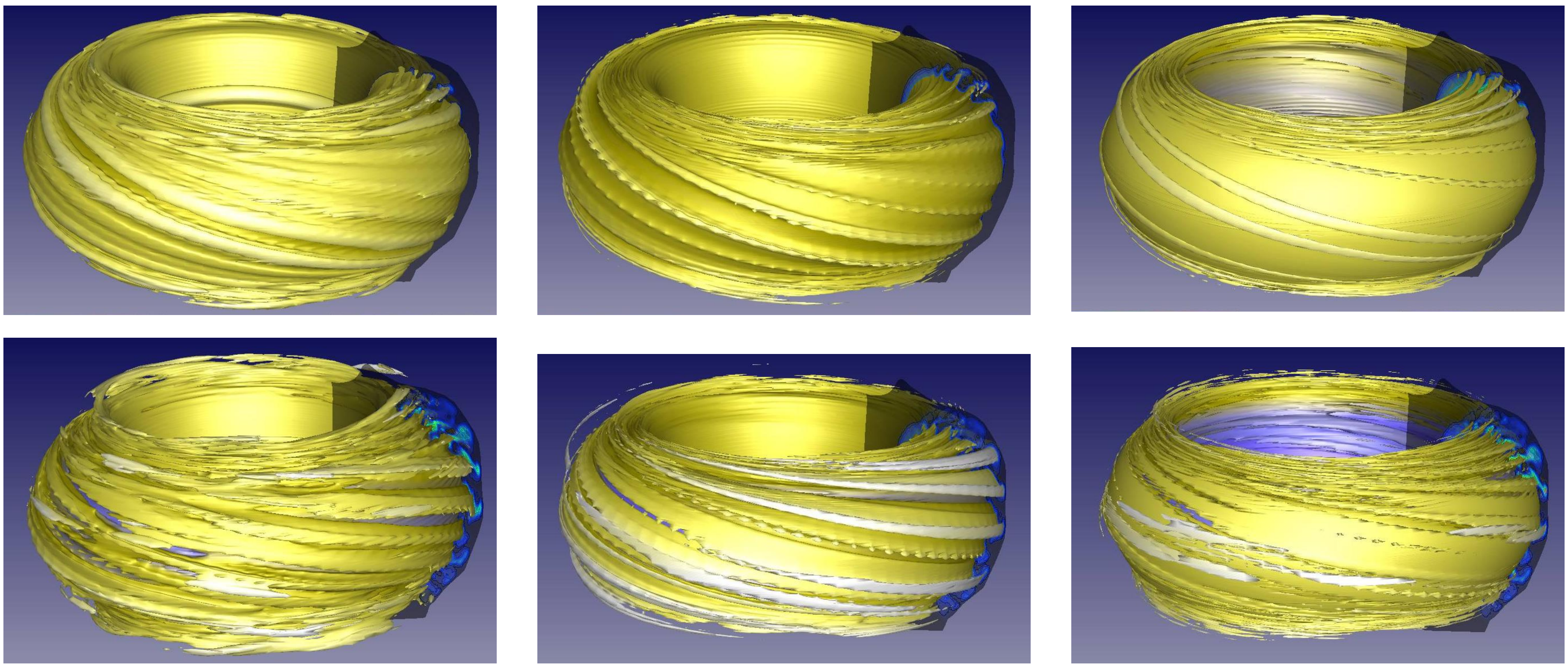


$-RJ_\phi$



Toroidal mode number decreases in time

n=1 envelope develops, but not single harmonic (shown early, later)



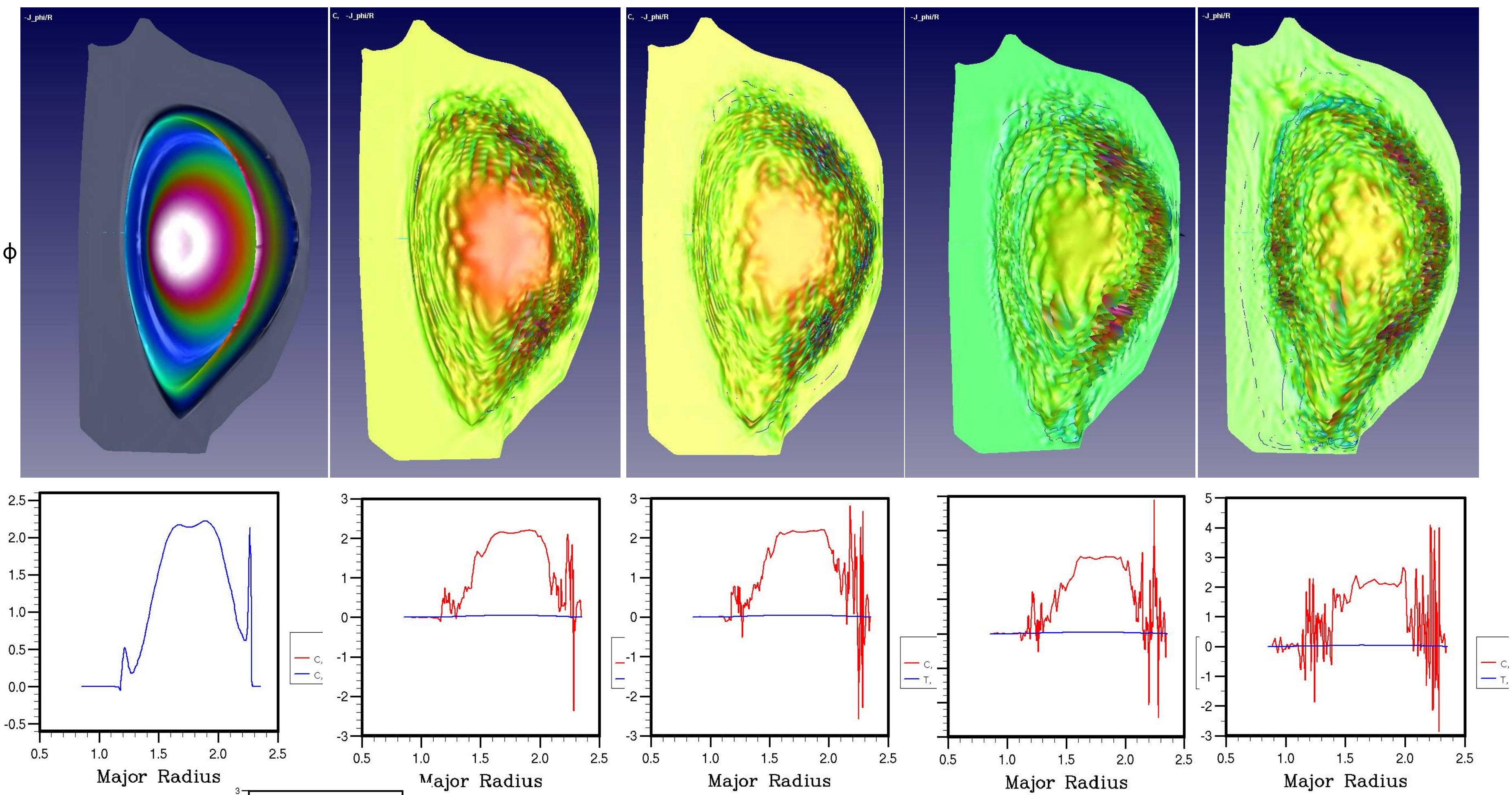
n $\quad$ T $\quad$ J_ϕ

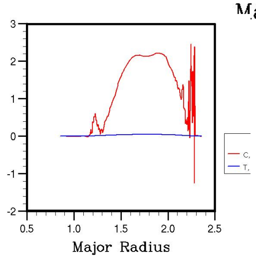
g119690, no RMP

Toroidal current density develops oscillations (S=10^7, linear FE)

t=53 τ_A t=141 t=171 t=203 t=295

$-RJ_\phi$

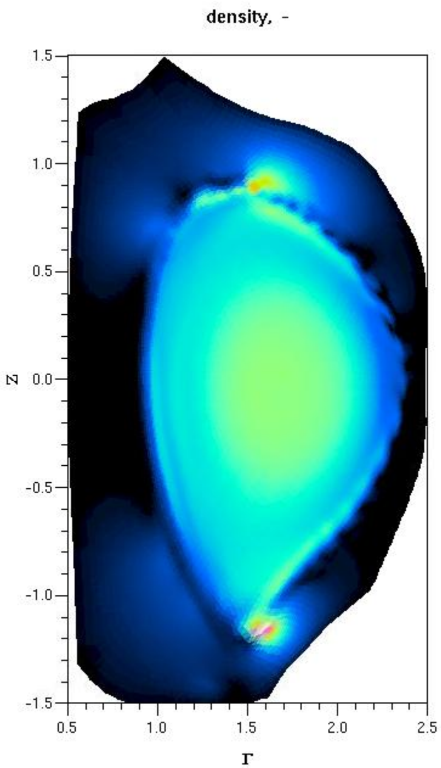




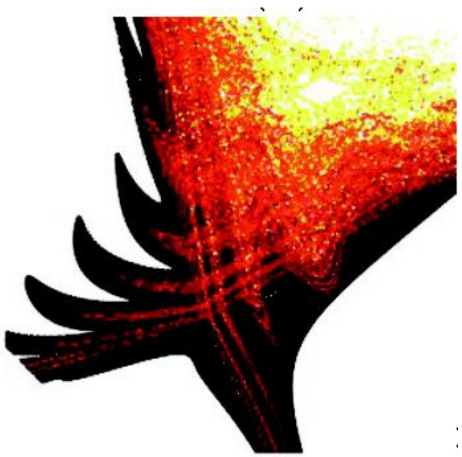
t=110

g113317

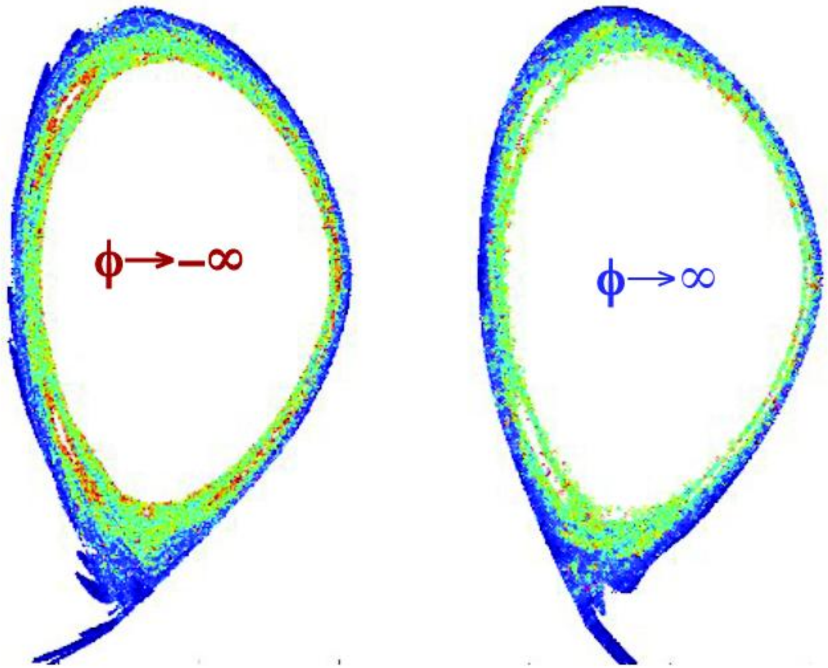
Plasma density accumulates axisymmetrically outside the nominal LCFS near top/bottom. Resembles the lower X-point DIII-D experimental field line reconstruction in 3D using TRIP3D (g126006; sim case g113317).



Simulation
$t=131\ \tau_A$



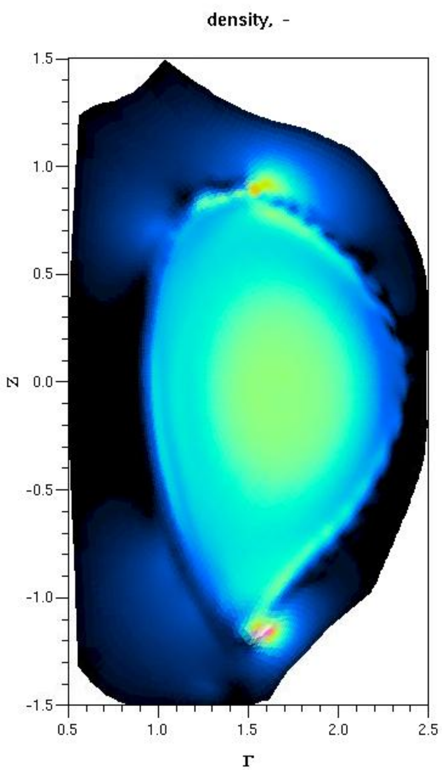
Field lines



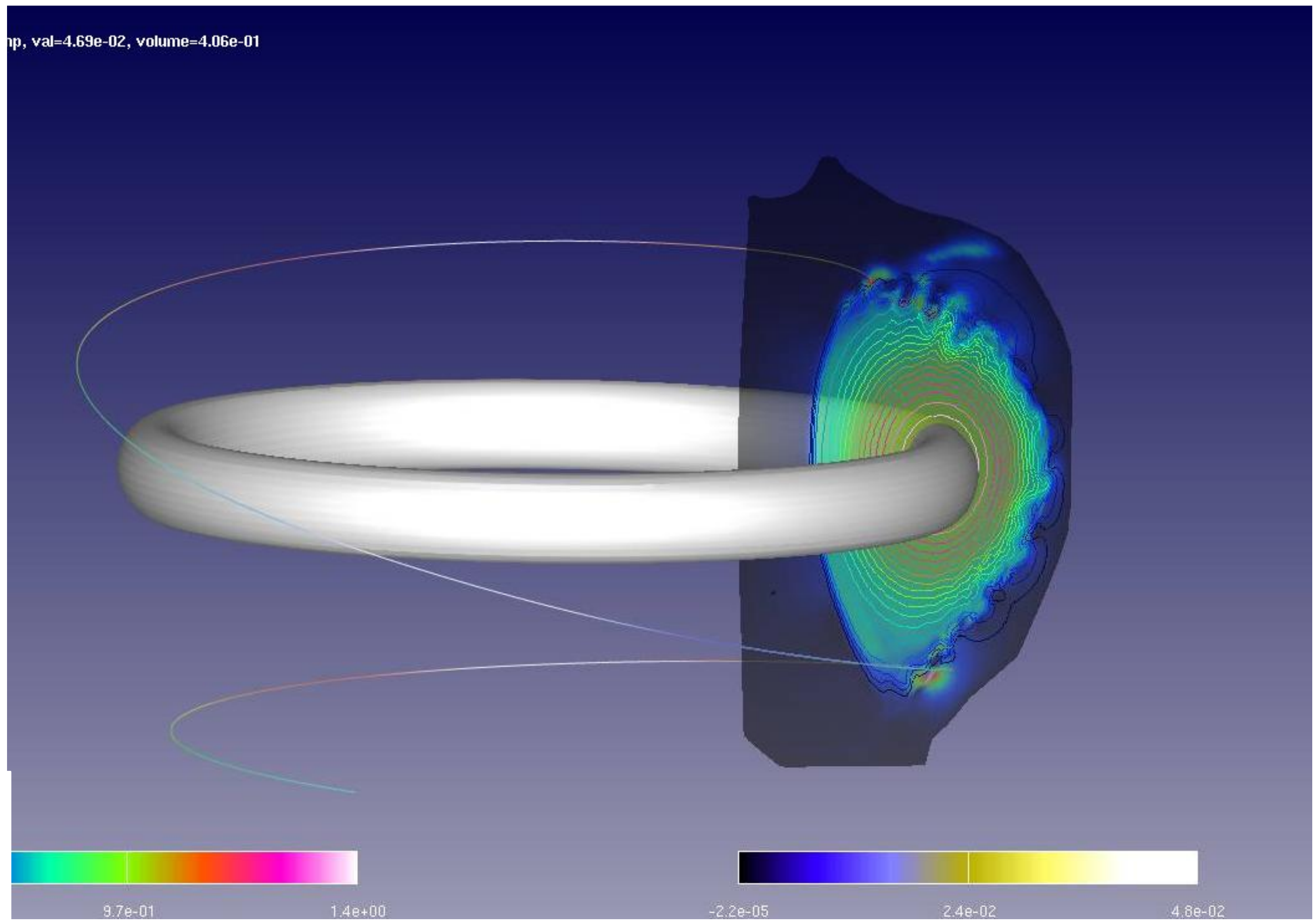
Tangle border

I. Joseph
APS07, EFW07

Field lines just outside LCFS connect upper and lower density regions in approx one toroidal circuit. Field lines at top, bottom mostly toroidal, but continue on to hit upper or lower wall/boundaries.



Sim
t=131 τ_A

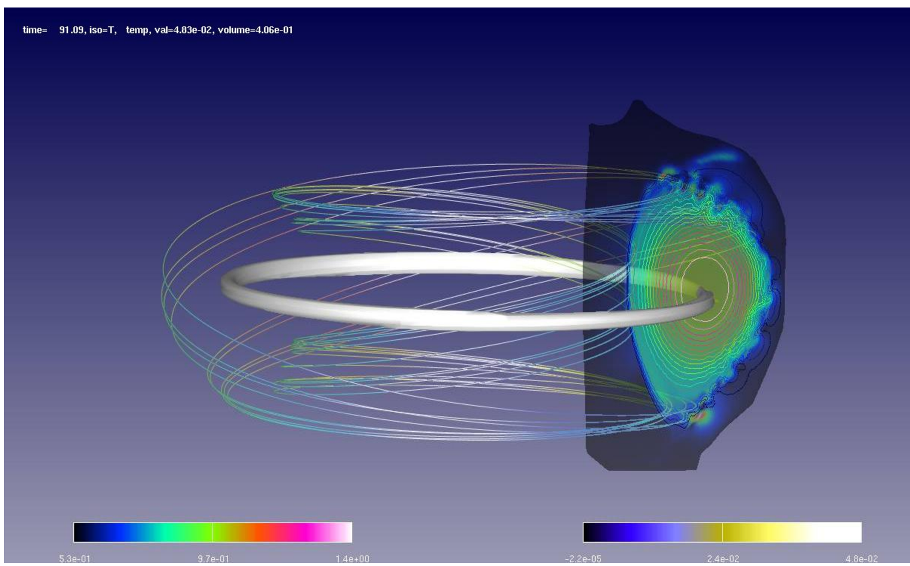


g113317

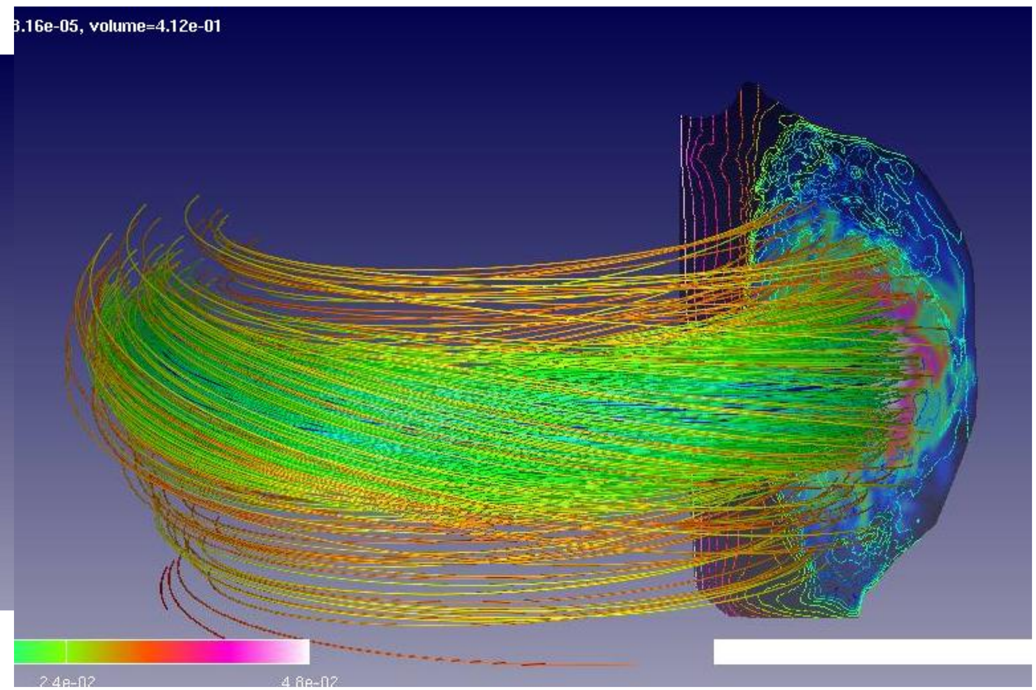
Density expelled by interchange-like instability?

ELM crash does not greatly change the overall magnetic field line structure outside LCFS (MHD, 2F). Interior field lines are perturbed, but remain relatively well-confined inside plasma.

* Near-LCFS region needs more careful study.
* Most field lines traced from plasma in +ϕ direction hit outer divertor.



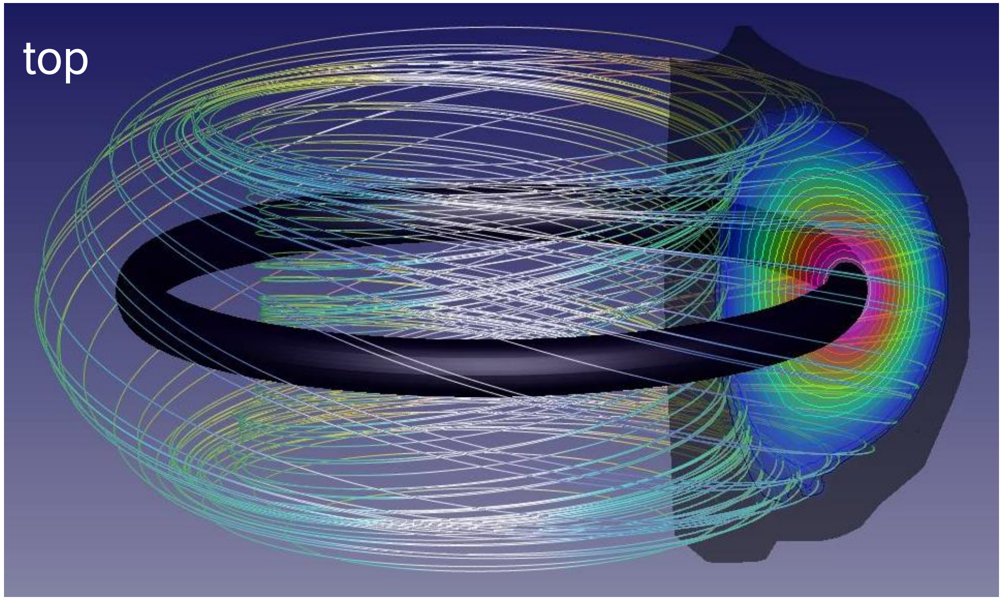
Just inside LCFS

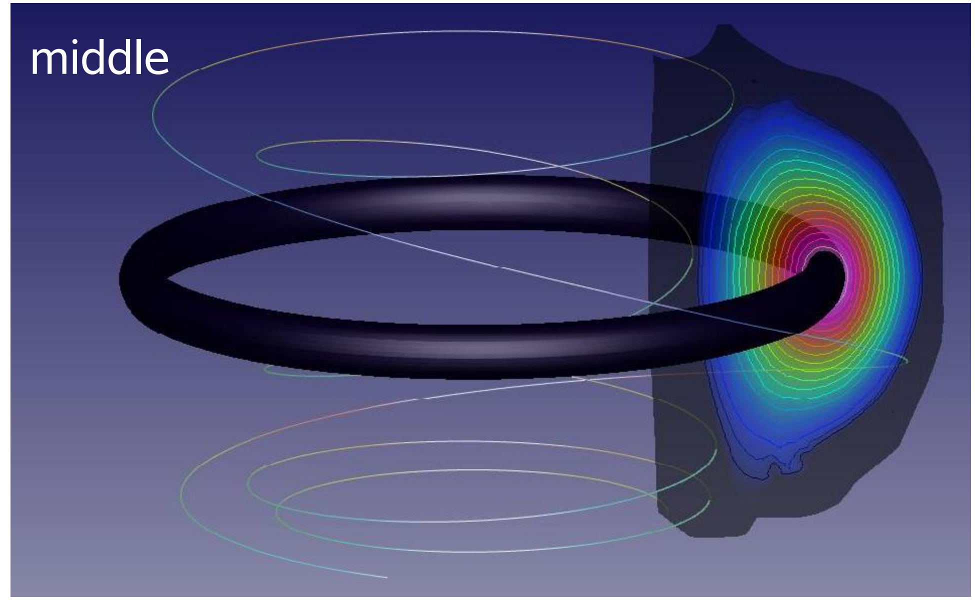


Multiple field lines, large ELM

g113317

Inner divertor

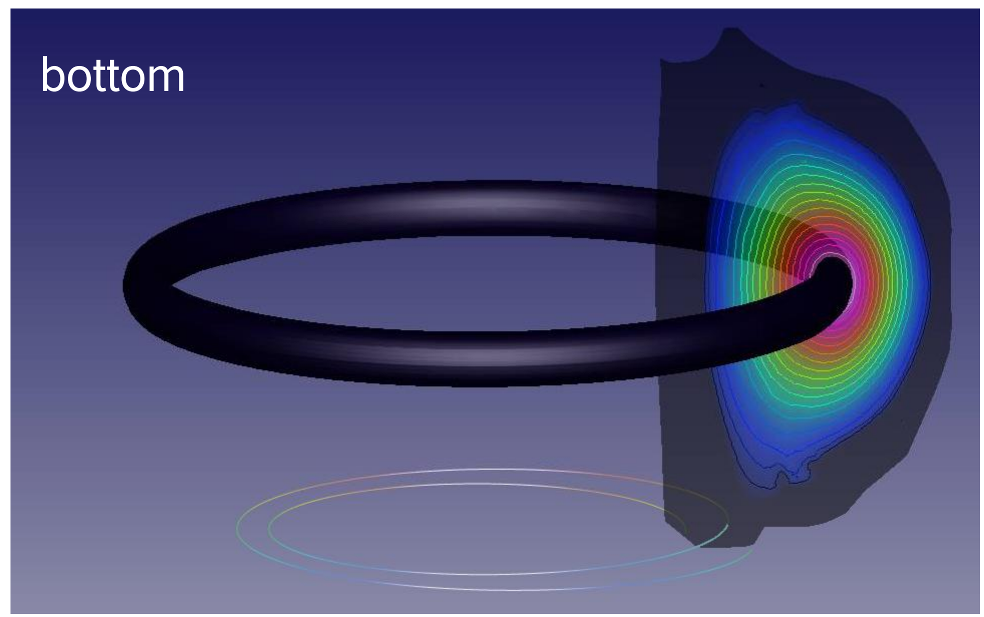




Field lines hitting inner divertor come directly from inboard side of plasma

* Three locations at divertor shown: top, middle, bottom of slanted plate

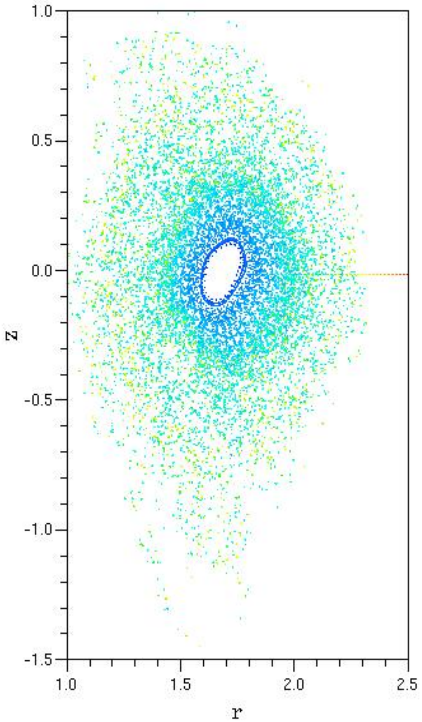
* -ϕ direction to inner divertor
* Closed flux region (bottom) or inbd side (middle) can connect to outer divertor in relatively short distance

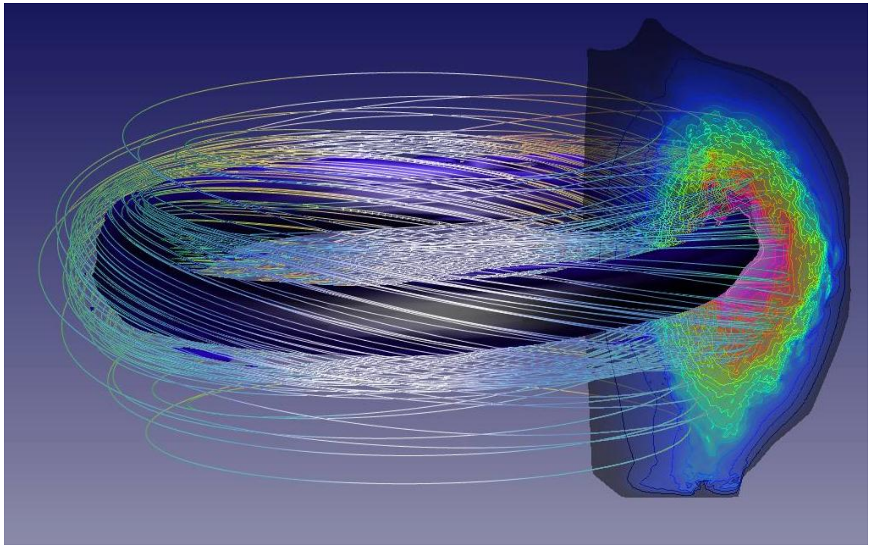


g126006 RMP

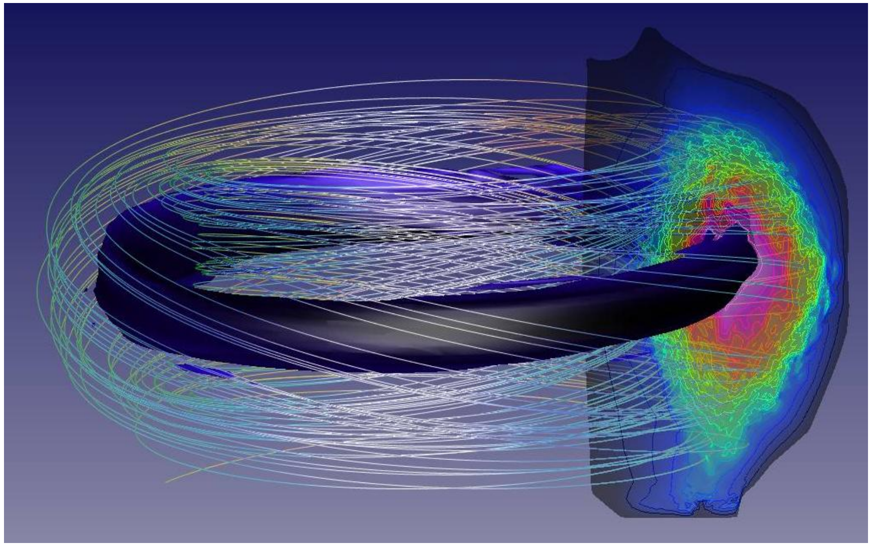
Magnetic field appears stochastic, but ...

- Despite puncture plot, much of plasma is fairly well confined (t=295)
- Loss from X-pt regions





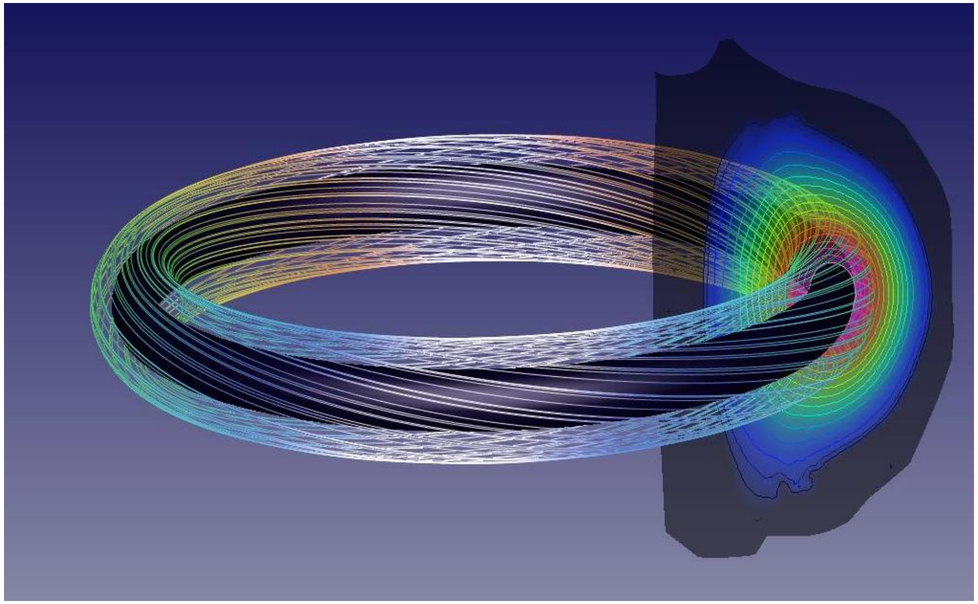
Start: outer midpl

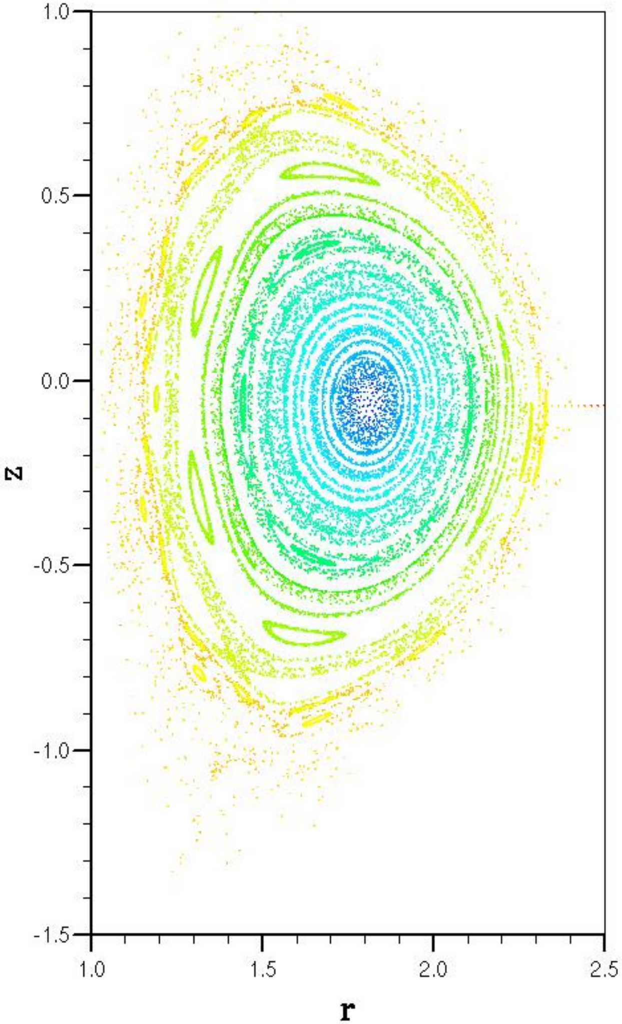


Near X-pt

g113317 (no RMP)

RMP: Interior plasma has good flux surfaces





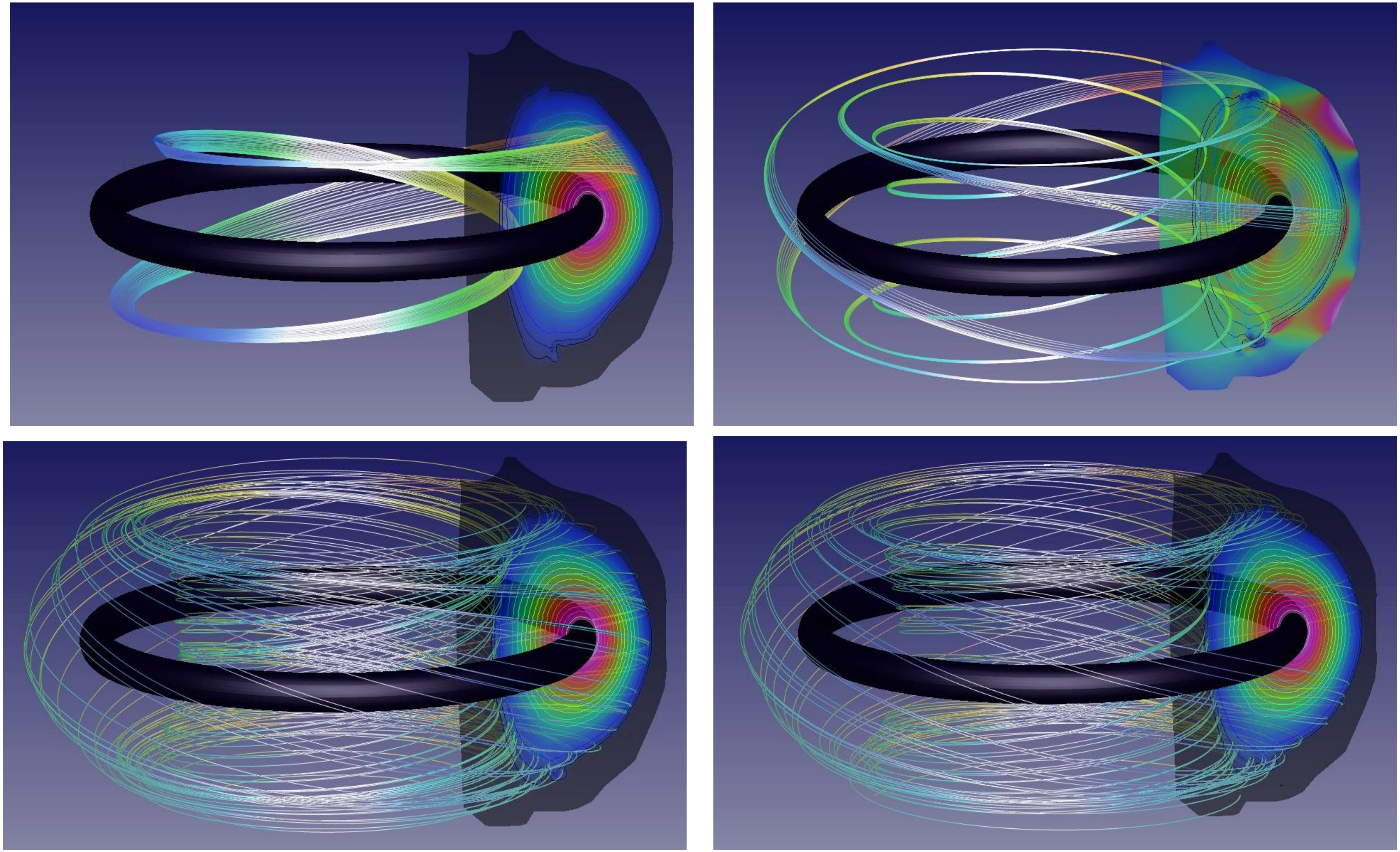
Vacuum RMP (toroidal n=3) has only small effect deep inside plasma

Outer plasma is perturbed. (Puncture plot at ϕ=0).

Early time t=10.6 τ_A; RMP evolves in time!

g126006

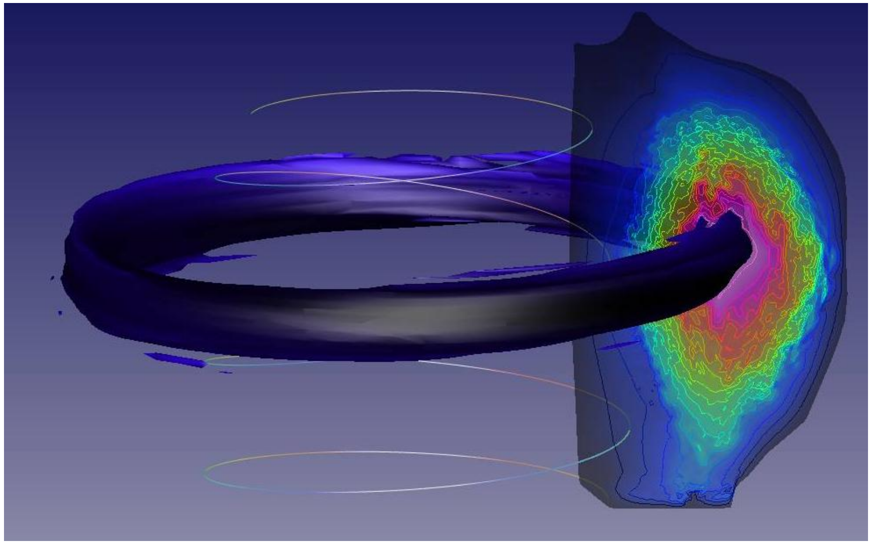
Field lines with vacuum RMP



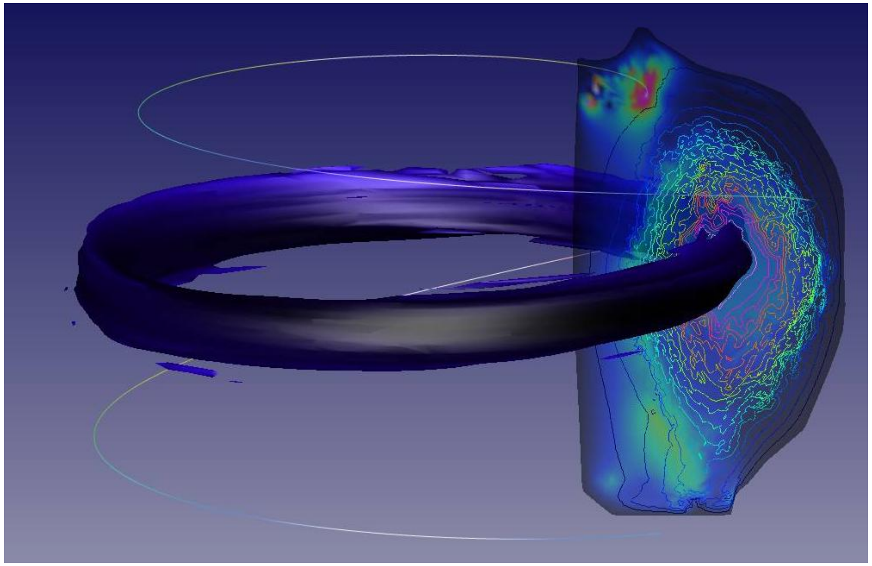
g126006 with n=3 RMP

g113317 has different shape, field than g126006

- JET-similar discharge, ELMS; no RMP
- X-point at larger R
- Inner divertor all connects to inbd side, mostly to the region outside plasma LCFS

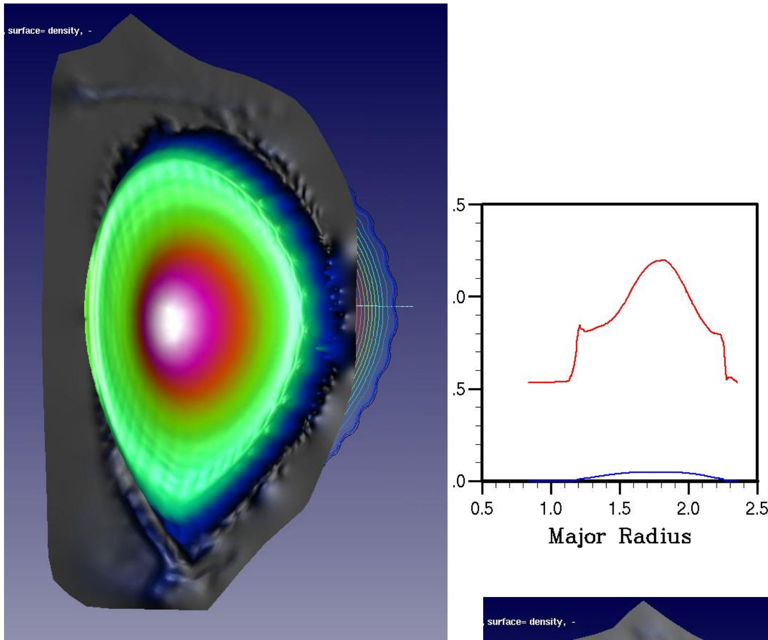


Long time top density spot connects to outer divertor

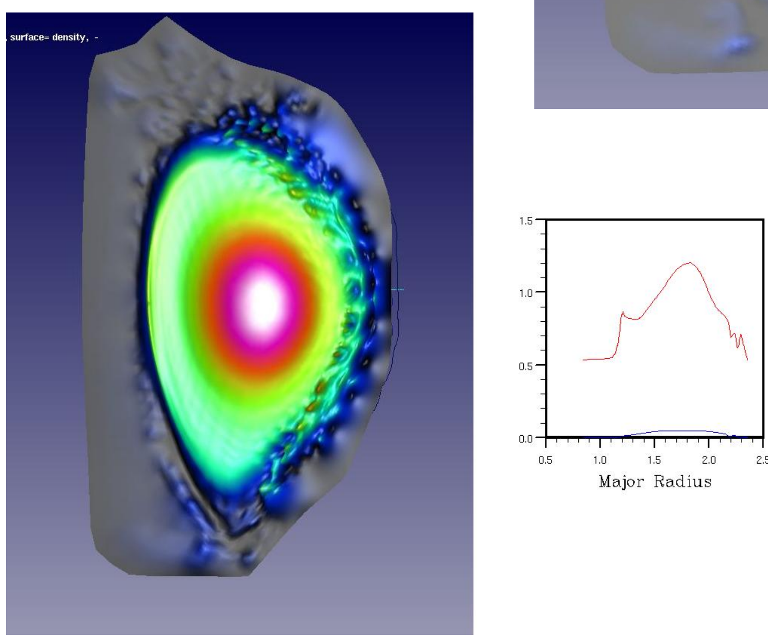


Toroidally rotating plasma has stronger ballooning: Density

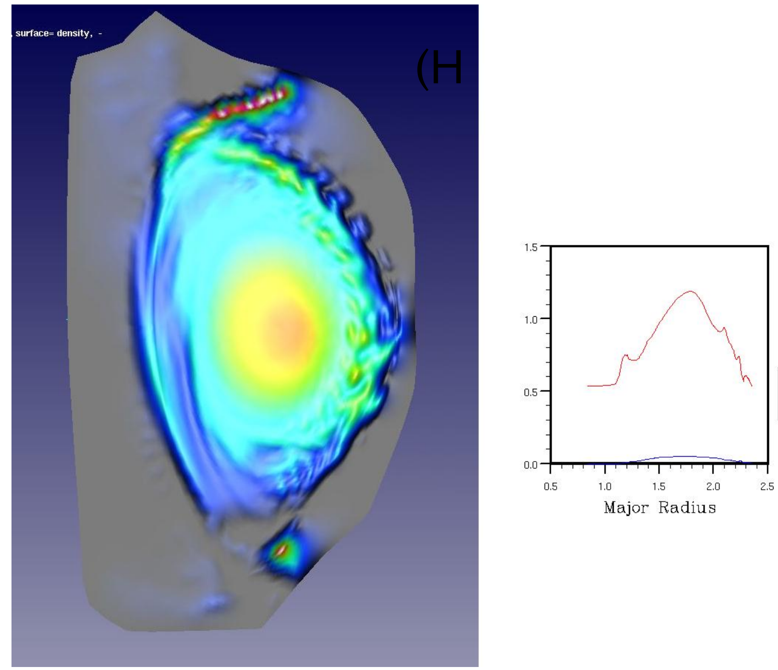
(HO3, no RMP)



t=36.6 τ_A



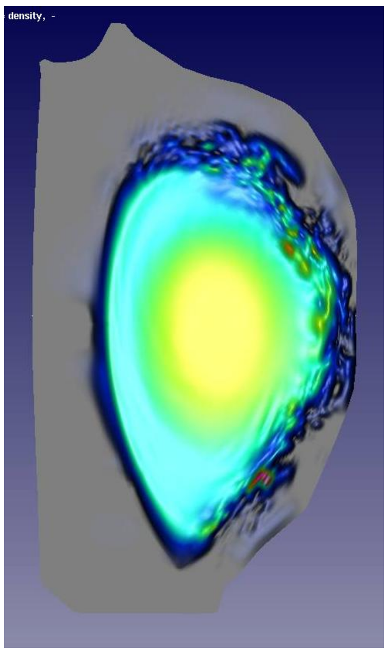
t=58 τ_A

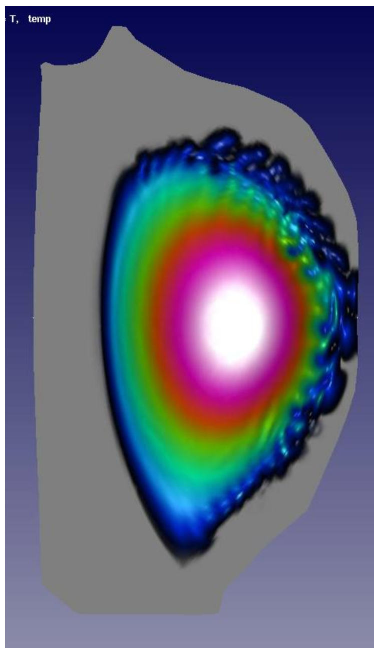


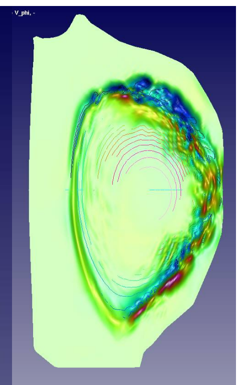
t=88 τ_A

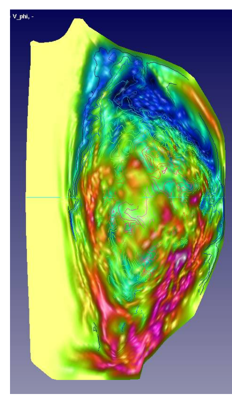
Two-fluid ELMs

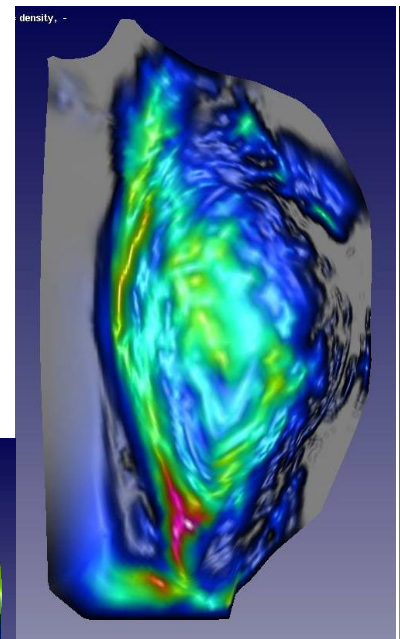
*Drift model
*NL ELM ballooning perturbation is more mixed than MHD.
*Density loss from top, bottom of plasma seems larger than MHD.
  (Due to drifts $B_{\phi} x \nabla_{Z} p$ in R-direction onto open field lines?)
*Accelerated NL growth due to $\nabla_{\|} p_e$ (??)   (linear FE, $S = 10^6$, H=0.02)

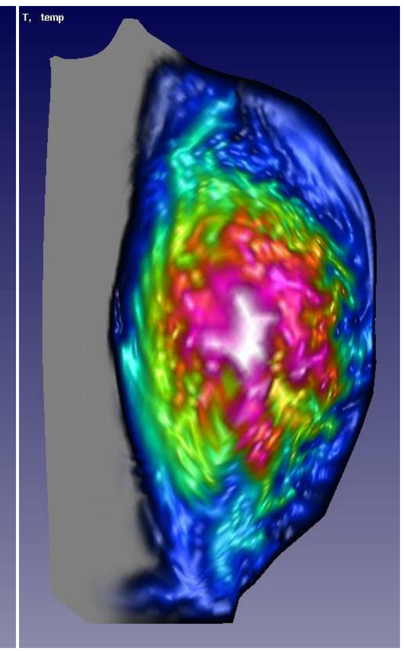










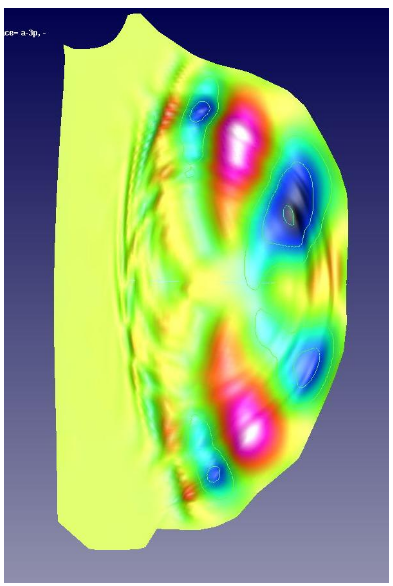


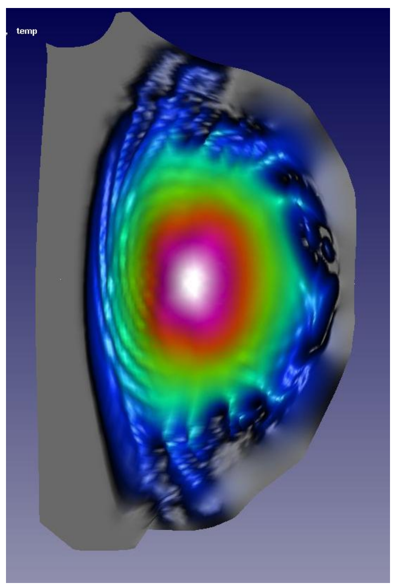
n T v_ϕ n T

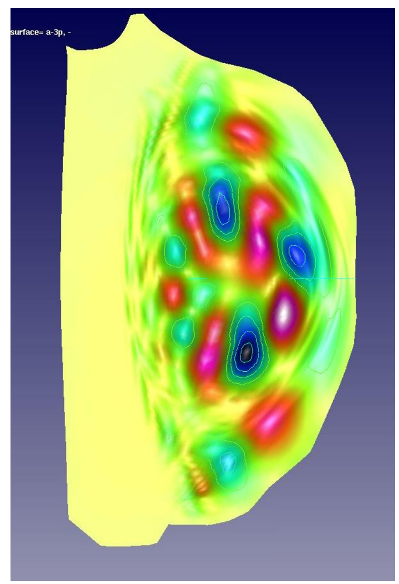
$t = 70\tau_A$ t=164

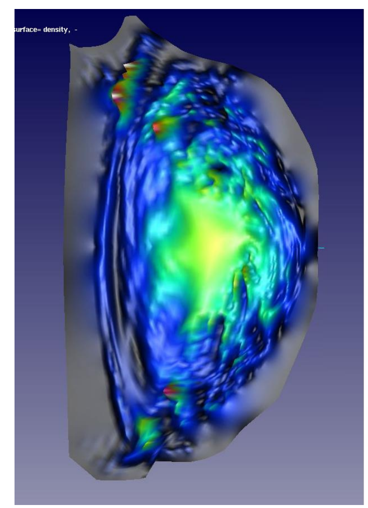
RMP can penetrate deeply into plasma if toroidal rotation $v_{\phi a}$ at plasma edge is too small.

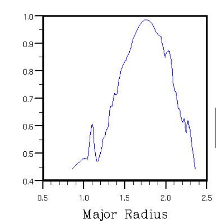
* Toroidal rotation with peak v_ϕ=0.1 v_A, but $v_\phi \rightarrow 0$ at LCFS.
* Poloidal flux ψ_3 (out of phase n=3 harmonic) rapidly develops inside plasma due to a resistive instability with $\gamma \sim S^{1/2}$ (Strauss, IAEA FEC 2008).
* Density more perturbed than temperature. (g126006, linear FE,S=10^6)









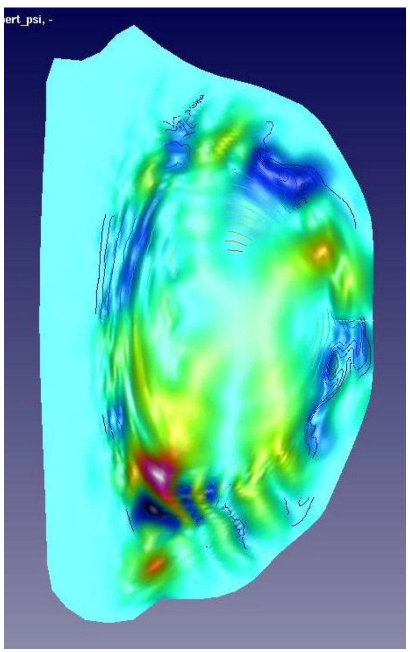


ψ_3 t =42 τ_A T ψ_3 t=63 τ_A n

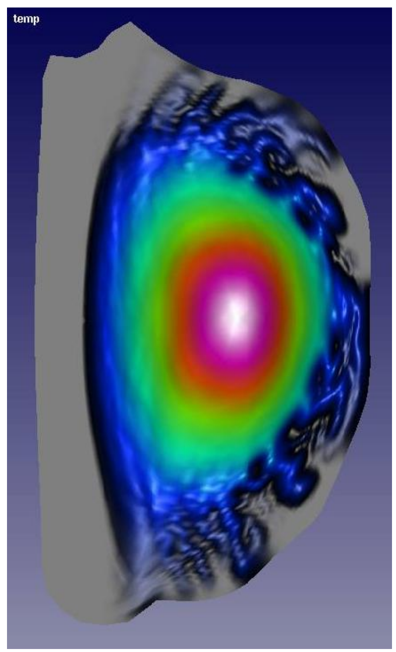
Finite v_ϕ at plasma edge slows RMP penetration.

* Toroidal rotation with peak v_ϕ=0.07v_A, finite $v_{\phi a} \approx$ 0.1$v_{\phi 0}$ at LCFS.
* RMP field penetrates less, slower; Temperature, density in plasma interior less affected. Izzo (IAEA FEC 2008) found similar result.
* Two-fluid has faster, stronger NL RMP penetration than MHD, with more density lost to top, bottom. But, not for very steep pedestal?

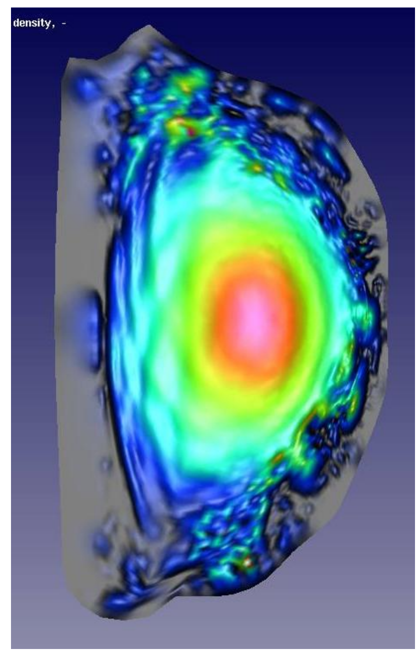
=> Two-fluid may be important.



ψ_3

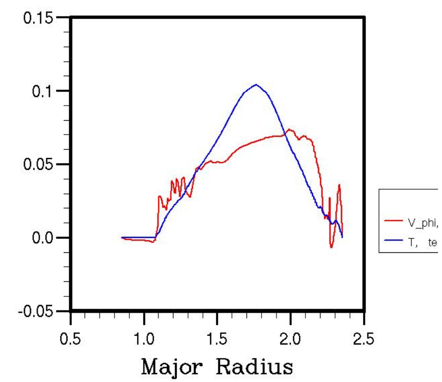


T



n

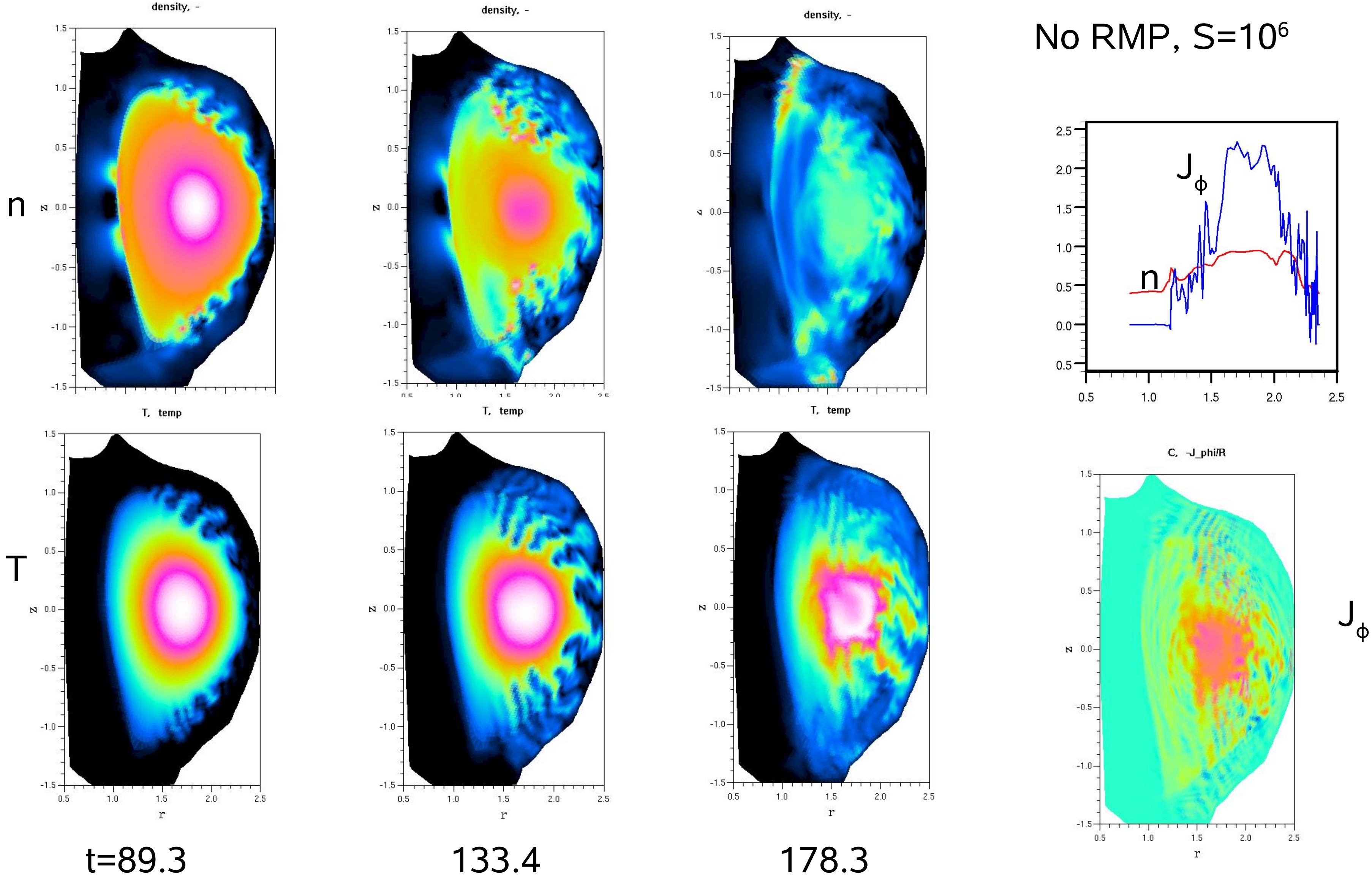
t=84.5 τ_A



v_ϕ red
T blue

g126006

DIII-D case g119690 with very steep edge pedestal: Initial slow 'leaking' of density followed by big, rapid ballooning-type ELM crash (shown)



Summary

- Extended MHD simulations at higher resolution carried out
  - Major upgrade to M3D code uses higher order finite elements; faster computers allow higher resolution simulations
  - More realistic parameters - lower resistivity,viscosity; allows realistic two-fluid strength, diamagnetic frequencies
- Simulations of three different Type I ELMs show multi-stage crash
  - Magnetic field structure important
  - Lack of reconnection suggests density expelled by interchange
- Initial studies of two-fluid model, toroidal rotation, RMP
  - Potential importance of two-fluid NL effects on ELM crash and on RMP interaction
- Question: How much is MHD, how much kinetic?