Higher Resolution ELM and RMP Results

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Topics

- Higher resolution in M3D – higher order finite elements
  - 2nd and 3rd order triangular, with reordered 2D poloidal plane grid
- New result: Multiple stage ELM crash, spatial and temporal
  - Importance of magnetic field line configuration
- Toroidal rotation and RMP (see also H. Strauss talk)
- Two-fluid ELMs – first studies
- Viz – AVS/Express at NERSC

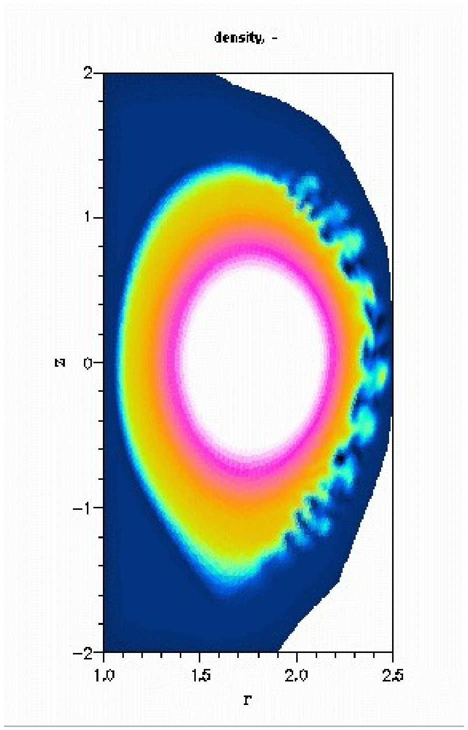
M3D code with higher order finite elements

- Over the summer, the M3D initial value code was improved to handle higher order finite elements (previously, linear elements)
  - 2nd and 3rd order, regular and lumped-Cohen triangular elements
  - Structure allows plug-in of other higher order elements
  - For ELM input equilibria so far, working on VMEC/other
- ELM NL simulations (MHD): For same number of grid nodes,
  - 2nd order regular (HO2): 2.2x slower than linear per τ_A
  - 3rd order regular: 4.5x slower
- 3rd order regular is good compromise between speed, smoothness – higher order may be better, but linear FE's ideal for fast scoping.
- More grid points in poloidal plane also allows higher toroidal resolution
  - Keep full toroidal spectrum, instead of low-n toroidal periodicity

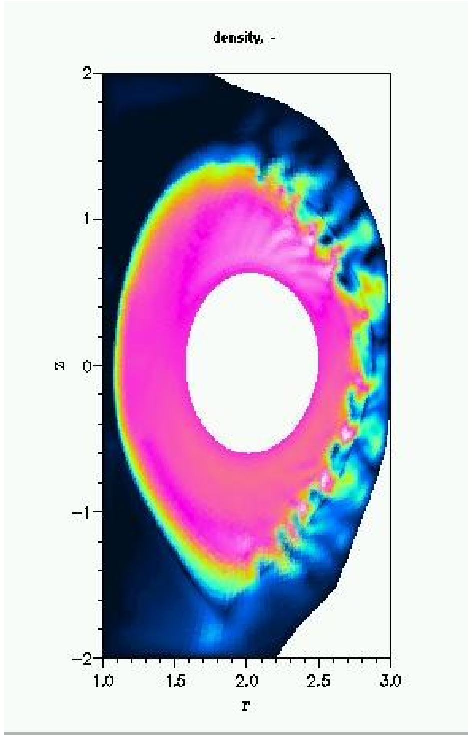
Older results: ELM crash

- Older results (2006-7) support a "classical" ballooning mode picture.
  - N=3 toroidally periodic (modes n=0,±3,6,9, etc). Initial pert n=9.
  - Linear FE, 8600 vertices in poloidal plane, packed; 32 pol planes
  - $S=10^6$, $\mu = 10^{-5}$ at top of pressure pedestal
  - Axisymmetric equilibrium, stationary; plasma annulus
  - Based on DIII-D experimental EFIT with pedestal bootstrap current
- Ballooning-type NL instability spread 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
  - NL stabilization mechanism is reduction of density gradient over the plasma edge region, reaching well inside original pedestal. Temperature gradient less reduced (Strauss, IAEA 2006)
  - At long times, perturbation reduces to a few dominant field lines.

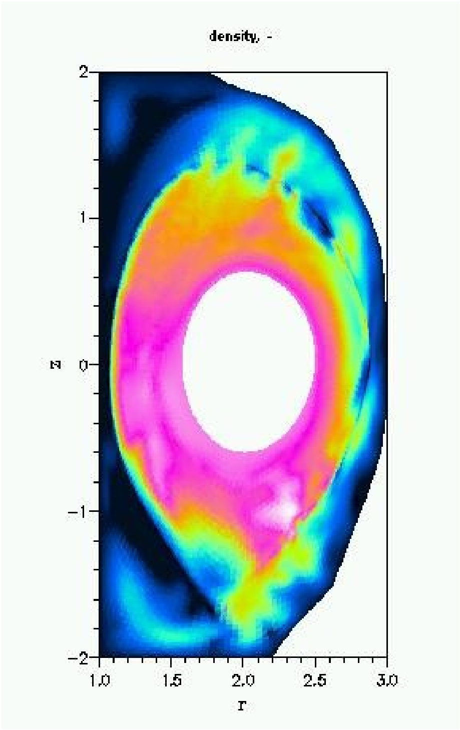
MHD ELM evolution (2007):
Plasma density shows a) fast ballooning, b) mixing/dispersal, c) long-time healing towards original contours (DIII-D g113317)



t=77 τ A

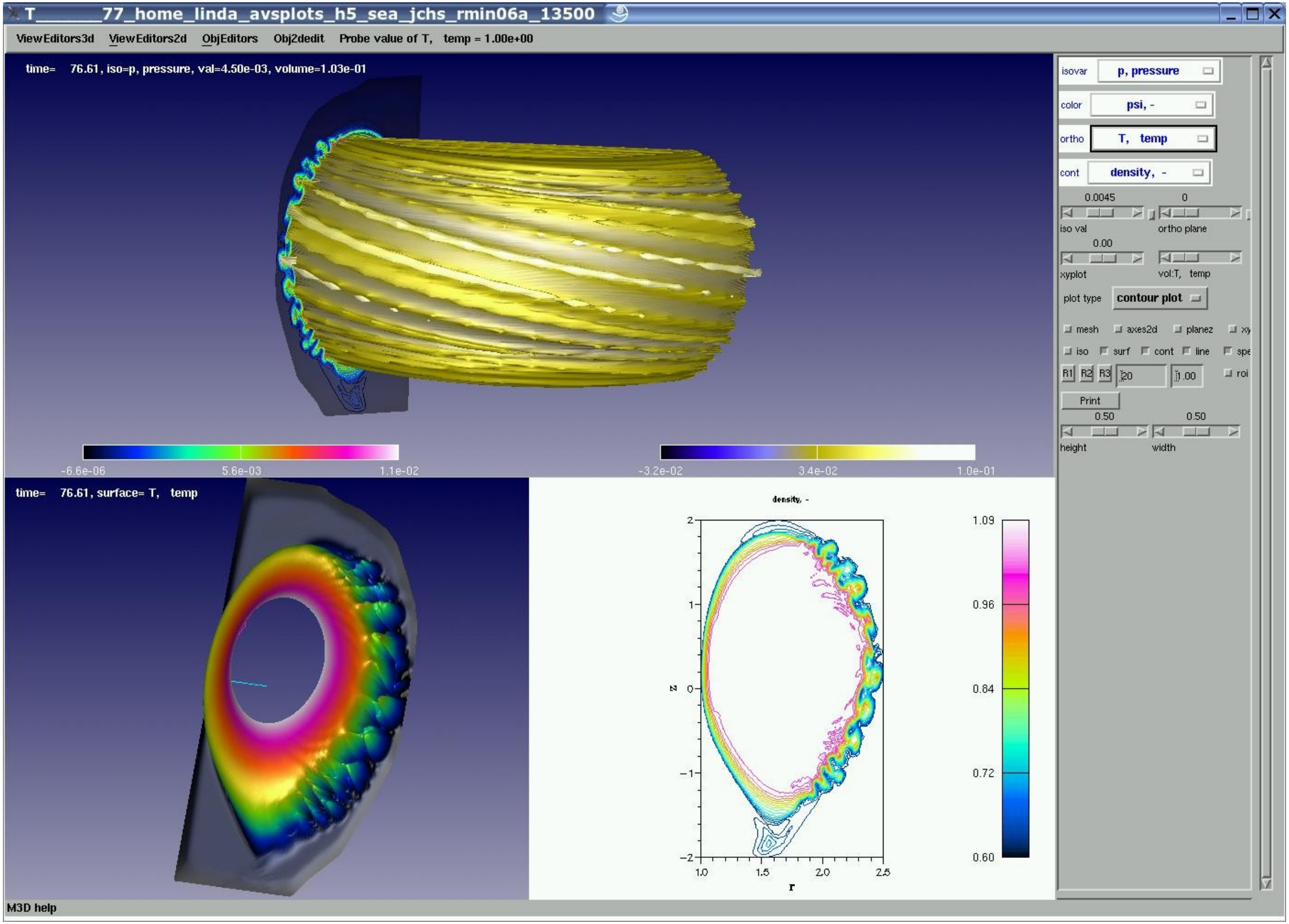


t=99 τ A

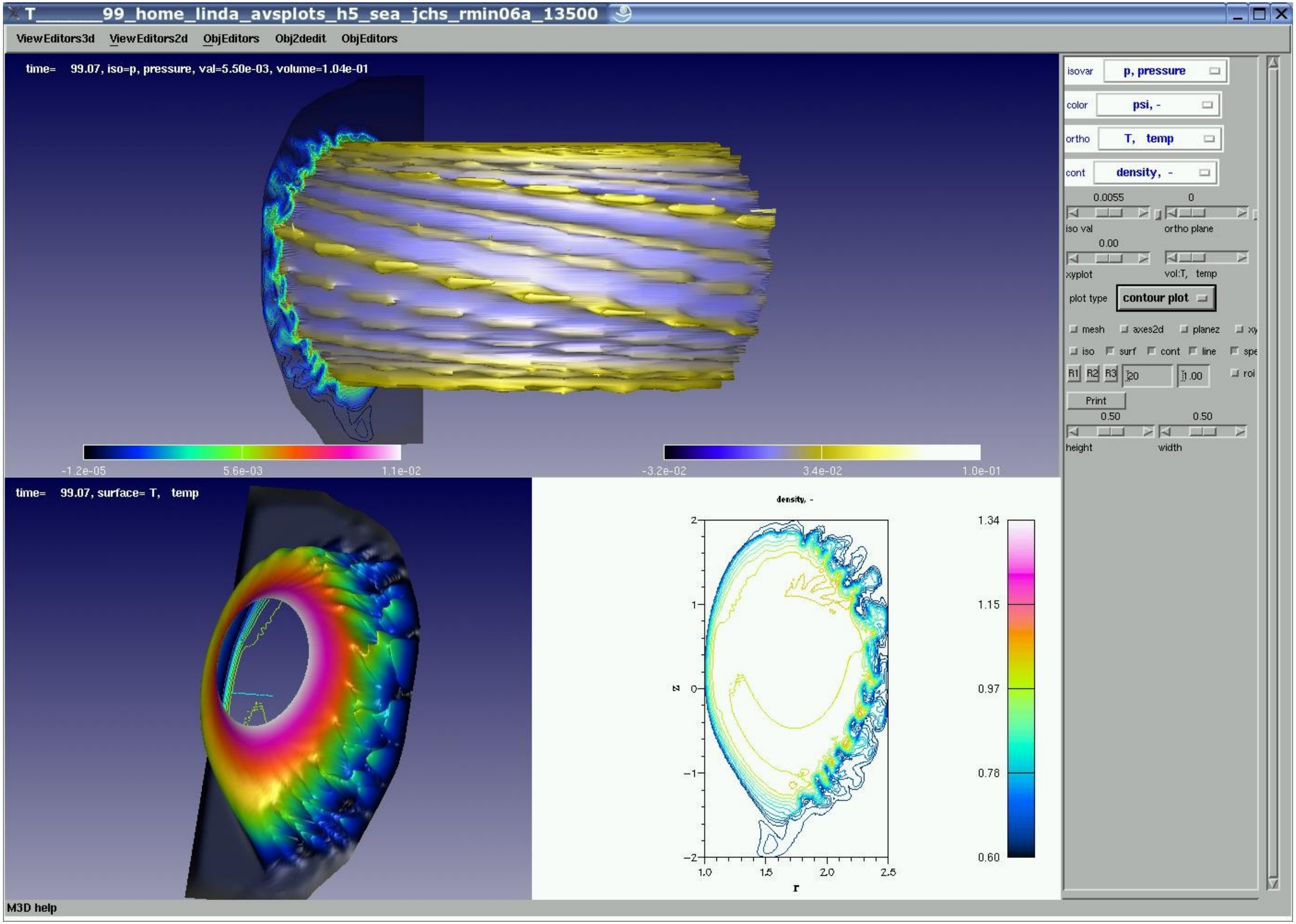


t=492 τ A

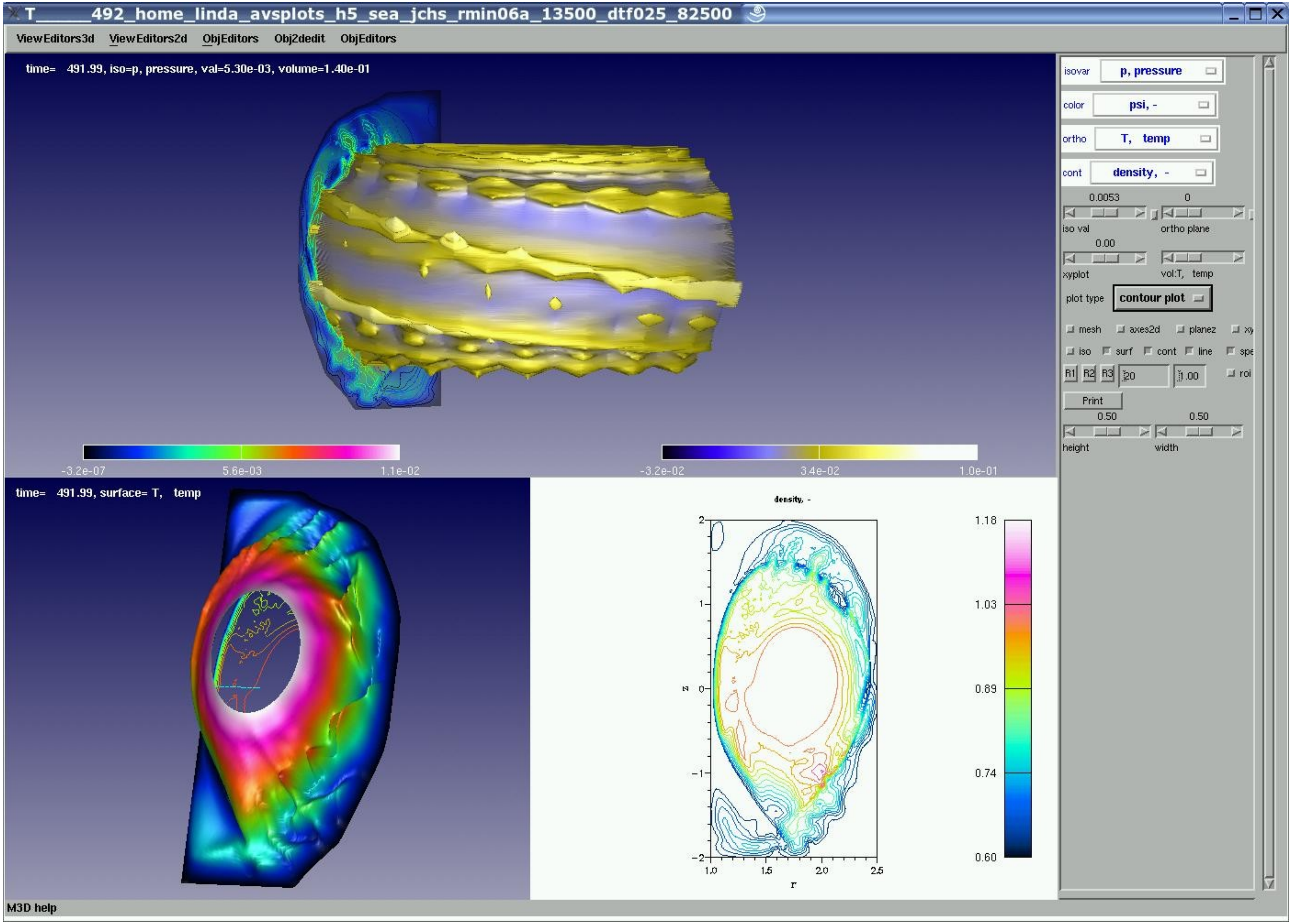
3D shape of ELM also evolves. MHD and 2F similar in first two stages.
t=77. Ballooning perturbation (p,n,T) initially follows magnetic field lines.



t=99. Plasma hits wall. Perturbation is stronger on certain magnetic field lines.



t=492. Long time saturation - healing to near original configuration. Perturbation at plasma edge develops on dominant field lines.

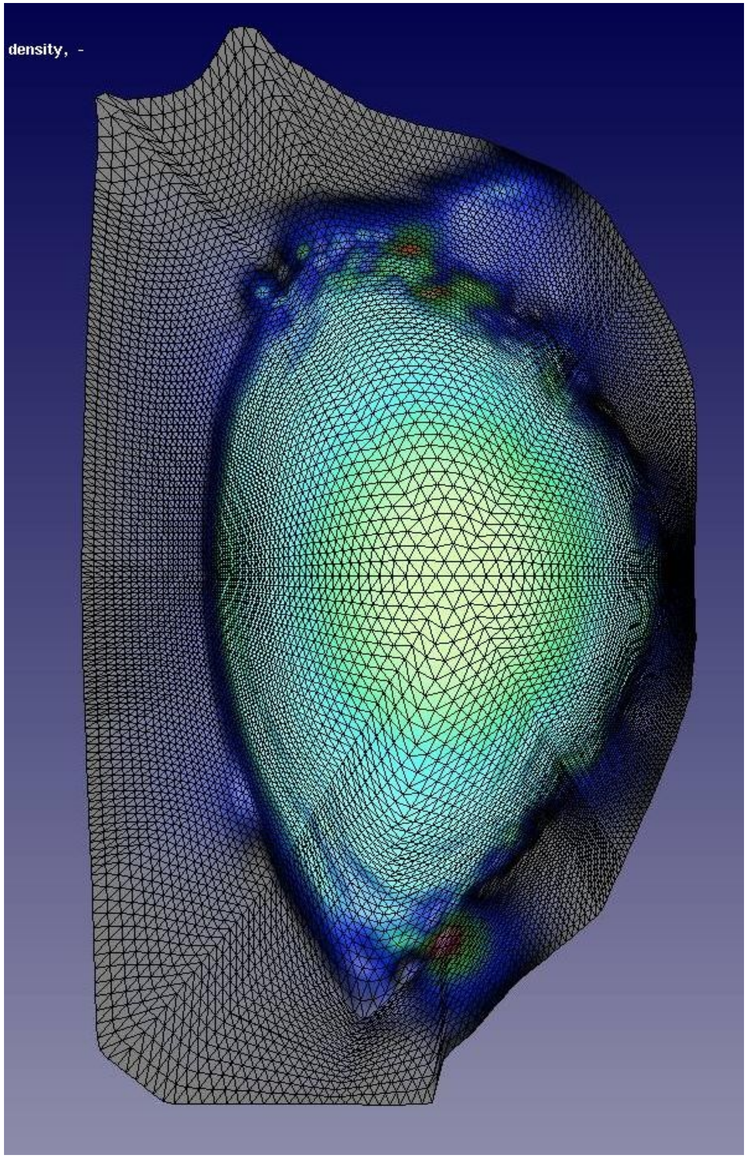


New results

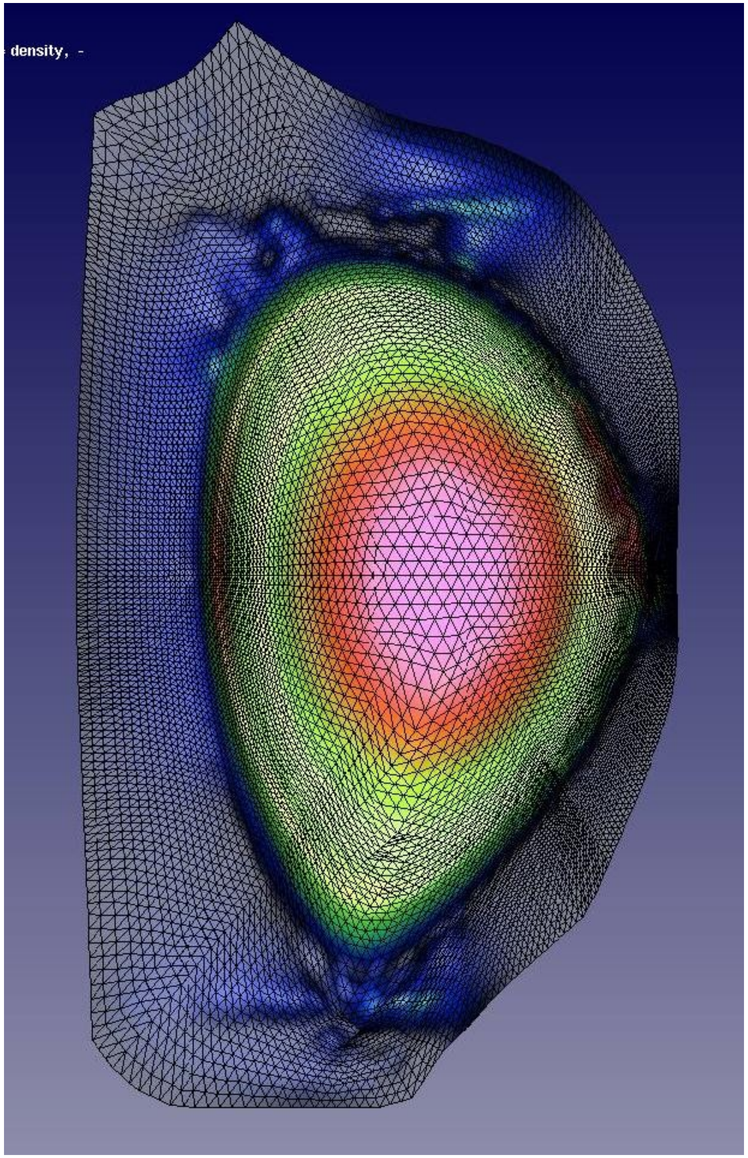
- Higher resolution
  - Finer grid, 10981 vertices/nodes in pol plane vs 7650-8600
  - No toroidal periodicity, 72+ planes or 22+ toroidal harmonics FFT
  - Lower resistivity: $S=10^6$, $\mu= 10^{-5}$ at top of pressure pedestal, up to $S=10^7$, $\mu= 10^{-6}$ with same $S_{VAC}=10^3$.
  - Bigger computers (Cray XT-4 NERSC, ORNL) *regularly* available late 2007 → linear FE runs at higher resolution
- Different NL evolution → multiple stage ELM crash.
  - Initial ballooning-type infinitesimal perturbation over outboard region (as before).
  - Less density moves less far, radially outward onto open field lines. Flow along field lines toward top, bottom of plasma. At longer time, density accumulates at top, bottom (no divertor, pumping!)
  - NL stabilization mechanism is still reduction in pedestal density gradient. Localized region near the midplane is more important.

Finite element mesh: 10981 nodes

Linear FE

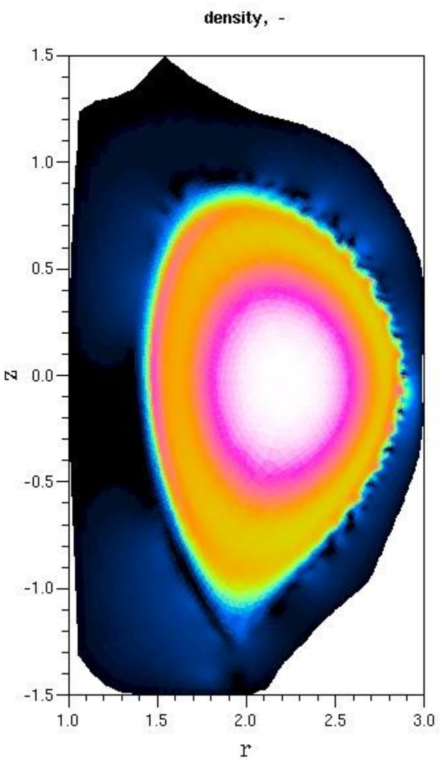


3rd order (sub-triangles)

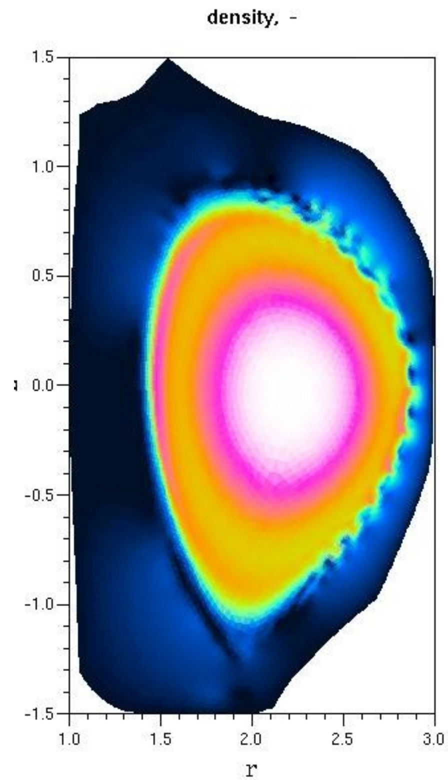


HO3 ELM expels less plasma radially, less far, than linear FE.

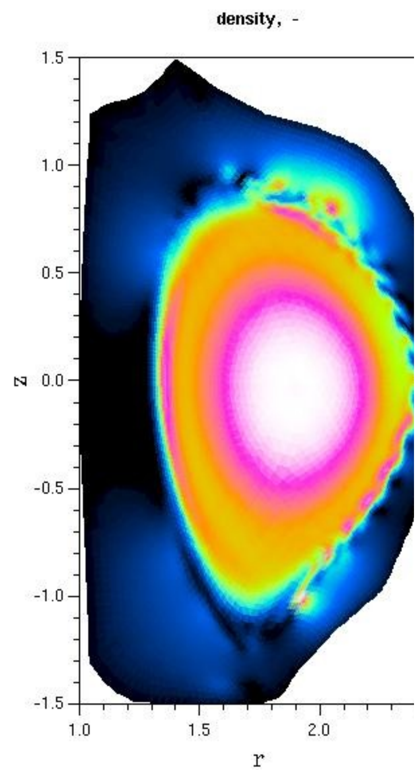
Plasma density shows a) outboard ballooning on midplane, b) poloidal spread up/down, c) formation and d) growth of outside peaks near top/bottom (Same central density in all cases).



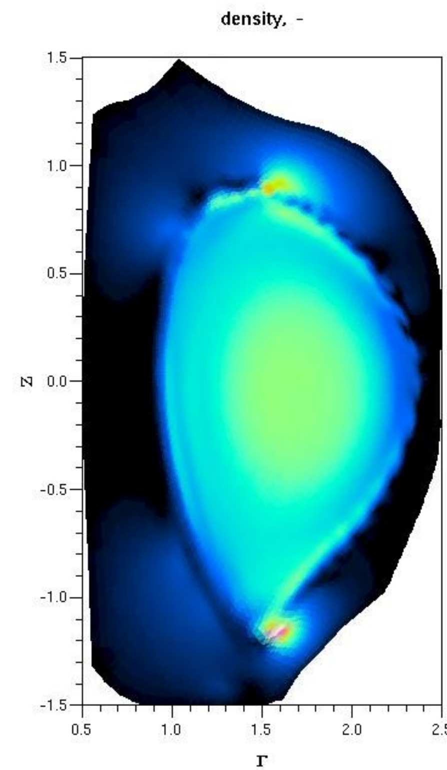
t=58 τ_A



t=73 τ_A

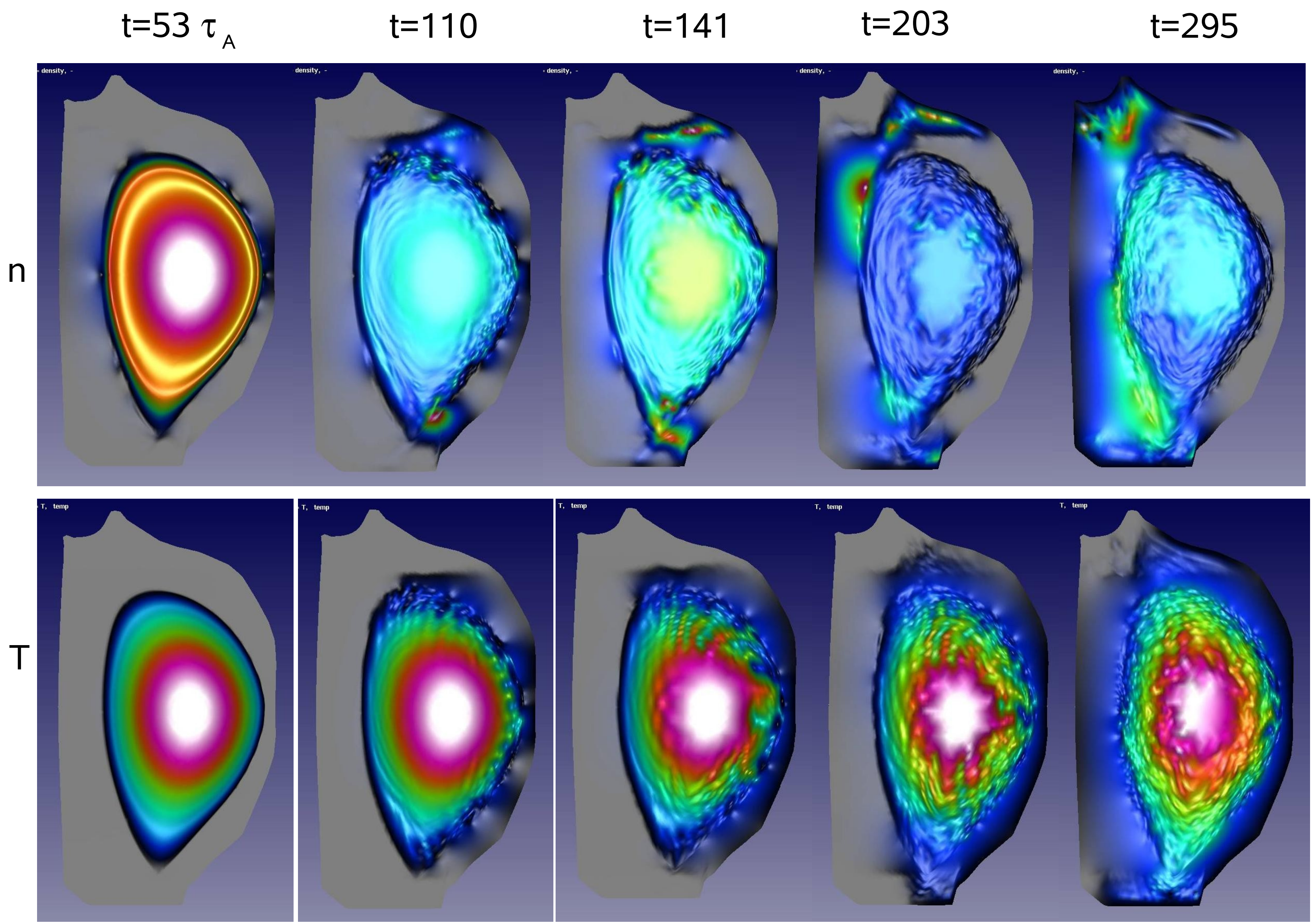


t=96 τ_A

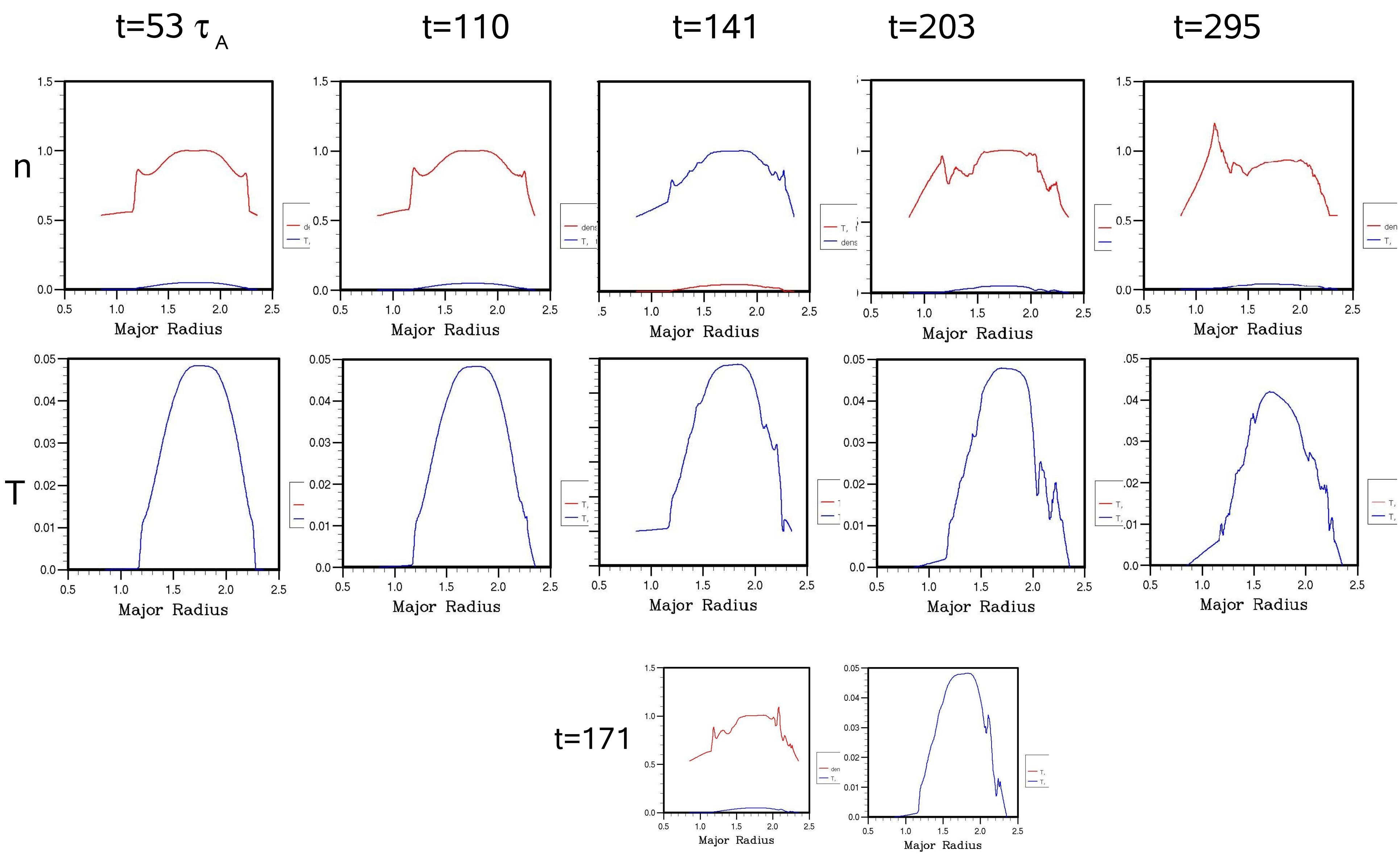


t=131 τ_A

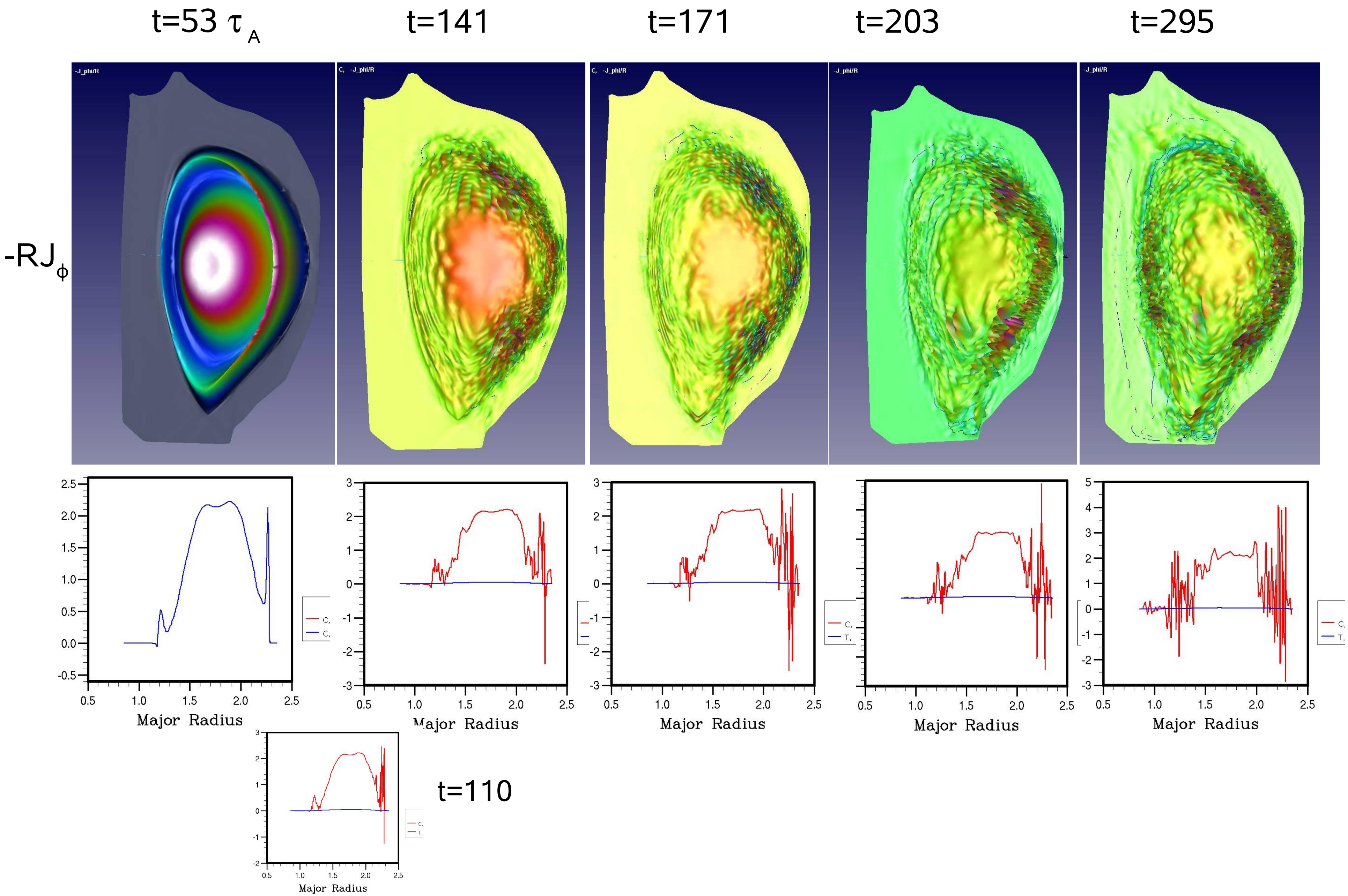
ELM at S=10^7, linear FE: Density and temperature



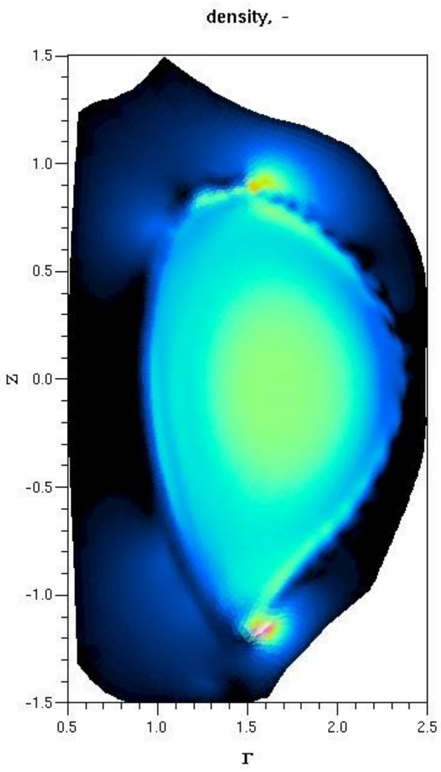
ELM at S=10^7, linearFE: Density andTemperature



ELM at S=10^7, linear FE: Toroidal current density

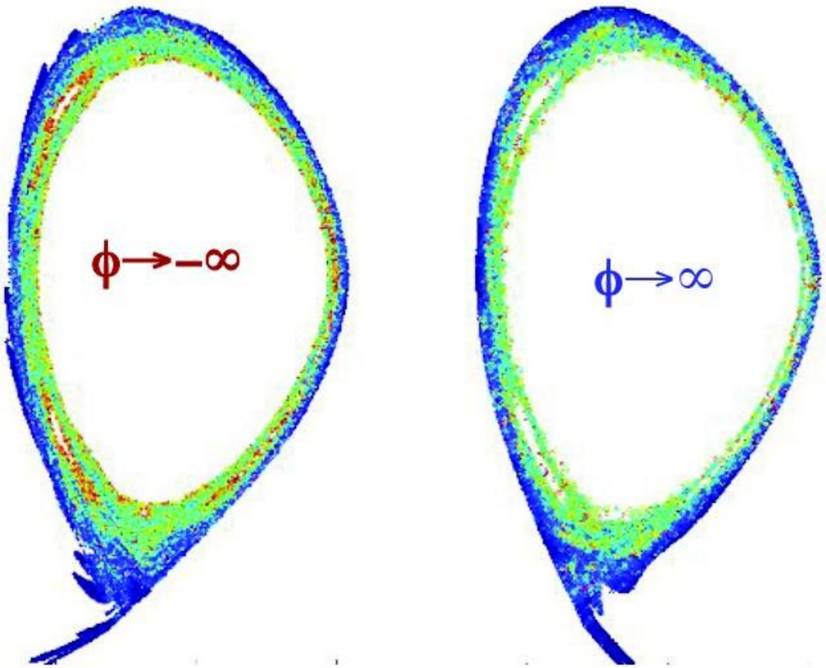


Plasma density develops an axisymmetric 'knob' outside the nominal LCFS near the X-point and near top. Lower one resembles the DIII-D experimental field line reconstruction in 3D using TRIP3D (case g126006).



Simulation
t=131 τ_A

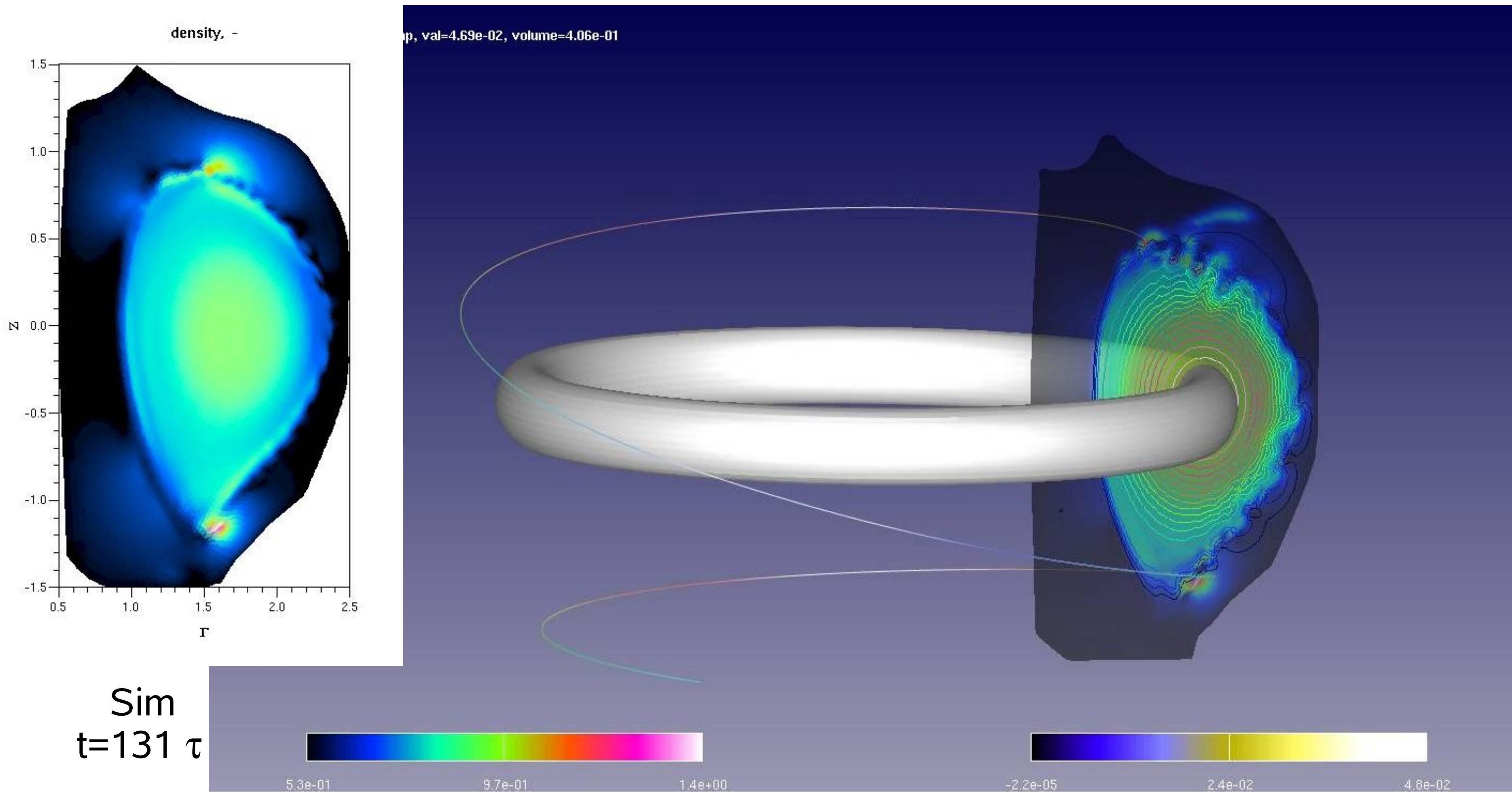
Field lines



Tangle border

I. Joseph
APS07, EFW07

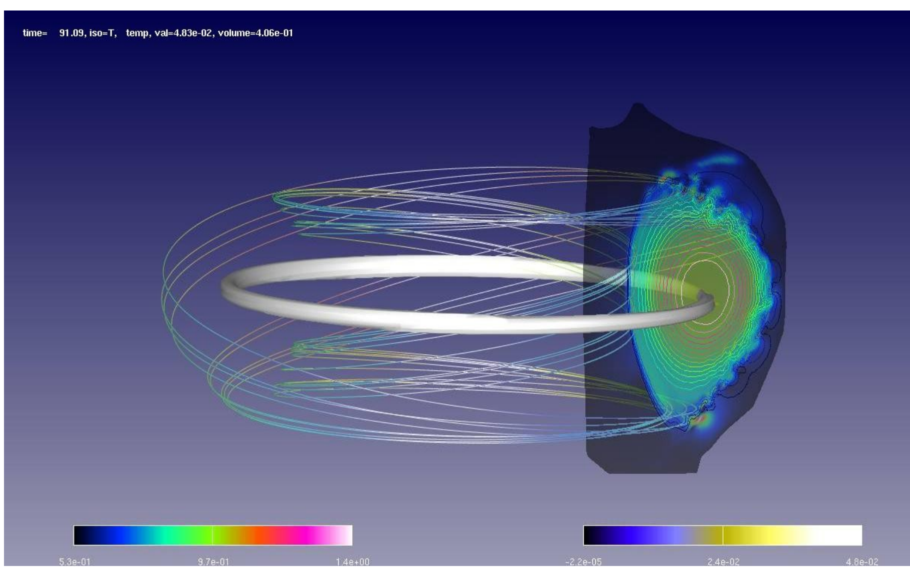
Simulation suggests that upper density accumulation is also real.
Magnetic field lines connect the upper and lower density accumulation points, but structure is complicated .
Field line starting just outside LCFS. (DIII-D g113317, similar magnetic structure)



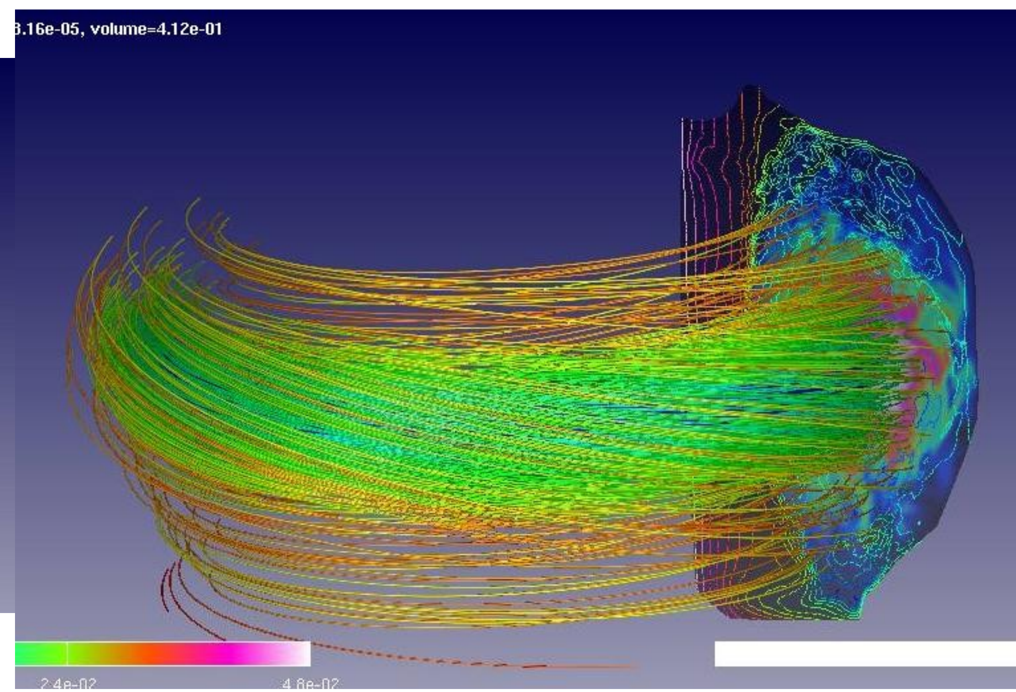
Sim
t=131 τ

ELM crash does not greatly change the overall magnetic field line structure, except maybe near LCFS (MHD, two-fluid).

*Just outside LCFS on outboard side, field lines connect to the bottom of domain within approximately one toroidal circuit, even from top.
*(Near the outboard wall, they hit the wall within a very short distance.)
*Just inside the LCFS, field lines also wrap from top to bottom around outboard side in approx one toroidal circuit. May wrap multiple times at top, bottom.
* Near-LCFS region needs more careful study.



Just inside LCFS

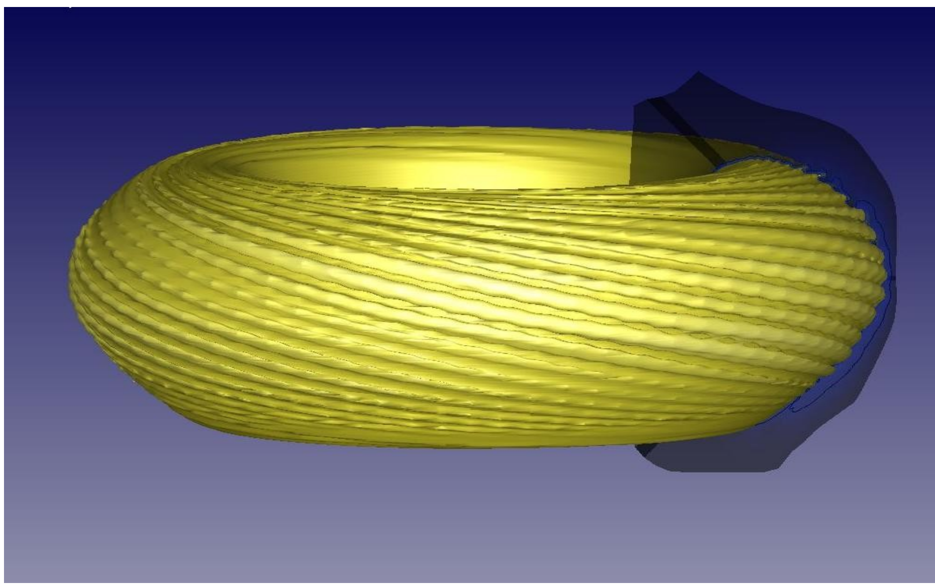


Multiple field lines, large ELM

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 field lines.

*Characteristic field line geometry in a tokamak (DIII-D ELM $q_{95} \approx 3.5\text{-}3.7$)

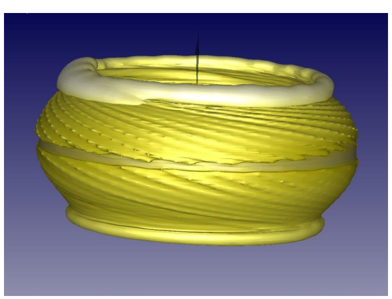


*Temperature, t=131 τ_A (HO3)

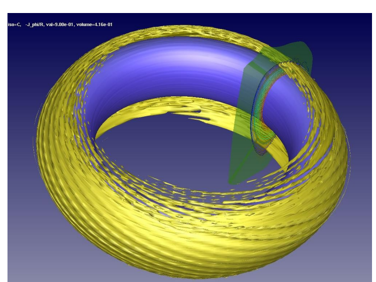
Side and top view, const T contours.

Perturbation ≈ follows field lines.

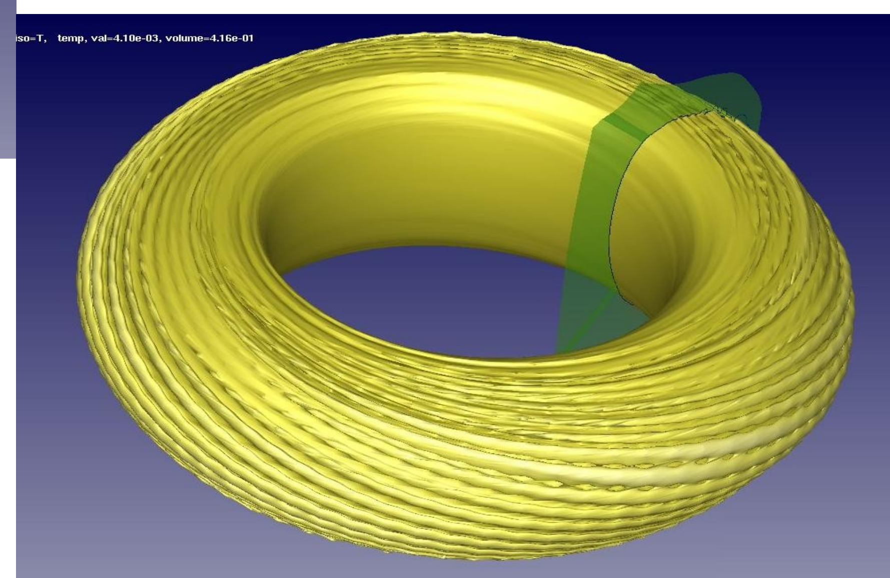
* Toroidal current similar, density also except near midplane



n



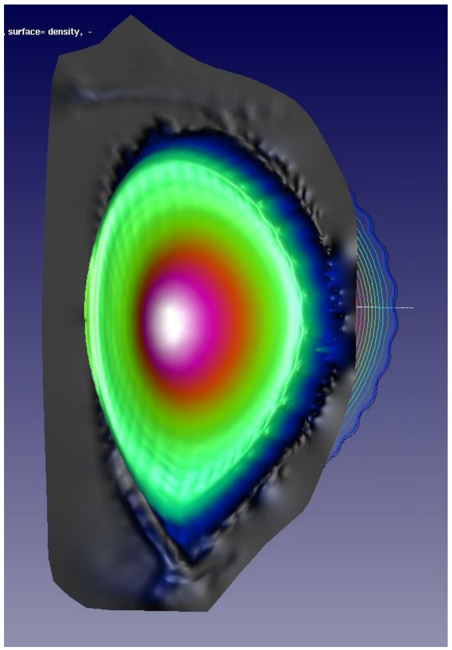
$-RJ_\phi$

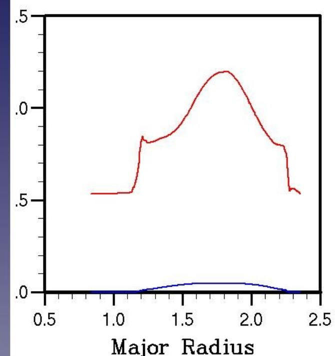


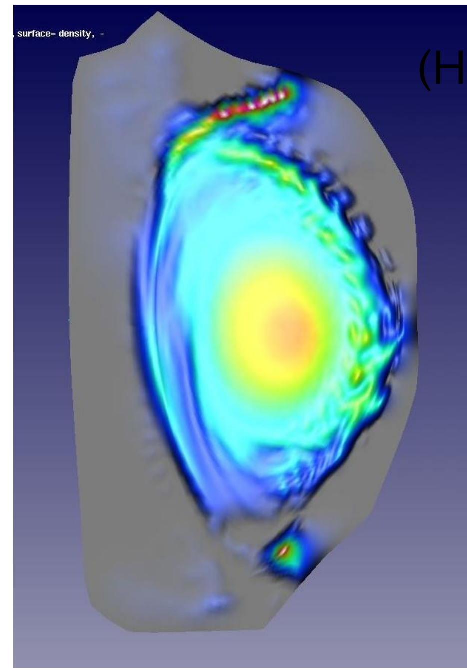
Toroidally rotating plasma has stronger ballooning: Density

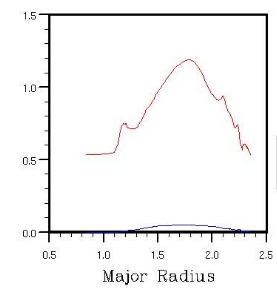
HO3, no
RMP)

(H



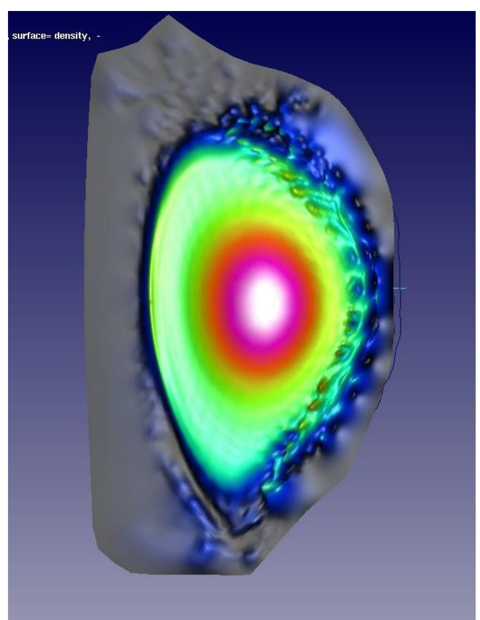


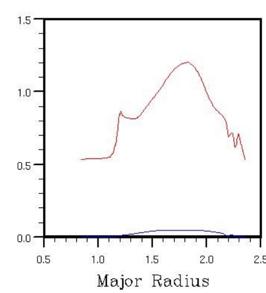




t=36.6 τ_A

t=88 τ_A

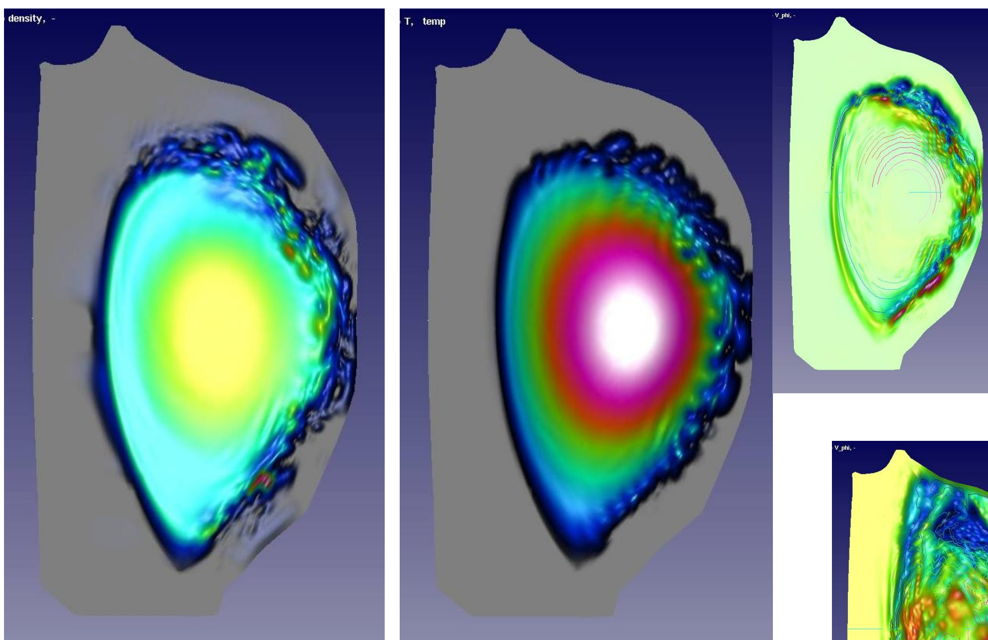


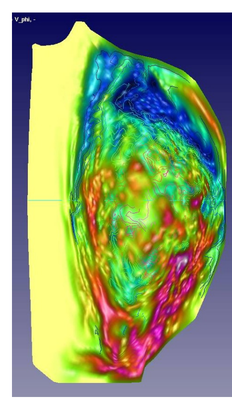


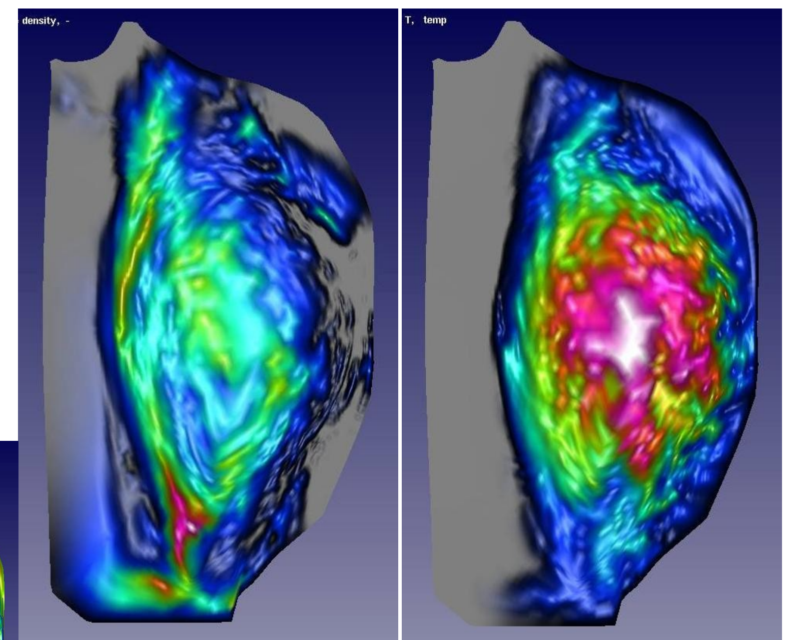
t=58 τ_A

Two-fluid ELMs

*Two-fluid retested against linear ideal MHD fishbone benchmark.
*Initial ELM studies: Perturbation is more mixed than MHD
*Nonlinear accelerated growth due to parallel gradient of p_e?
(linear FE, $S = 10^6$, H=0.02)





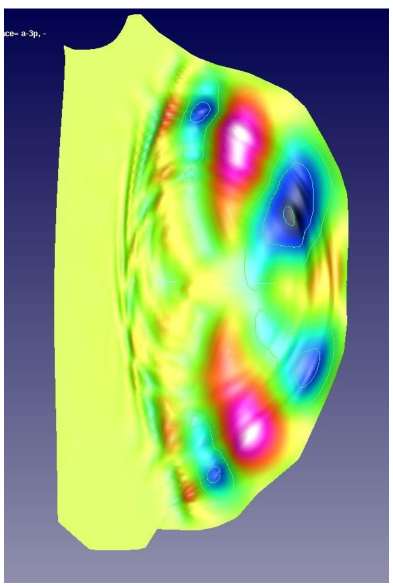


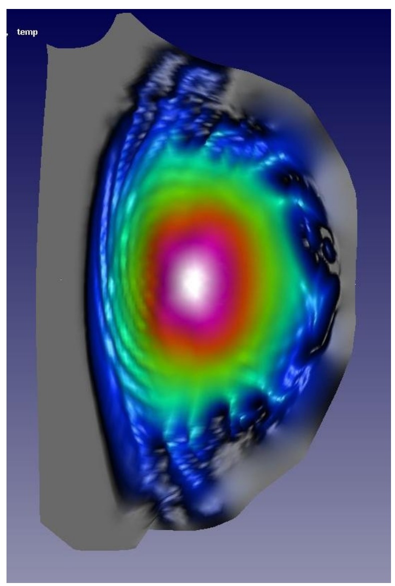
n T v_ϕ n T

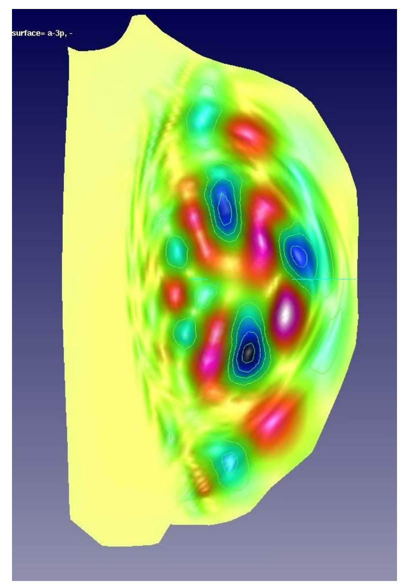
$t = 70\tau_A$ t=164

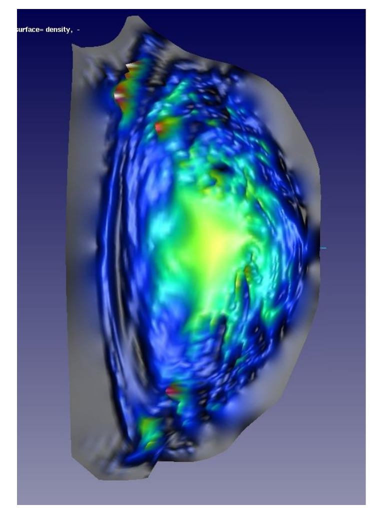
RMP with toroidal rotation can penetrate deeply into plasma if edge v_ϕ is too small.

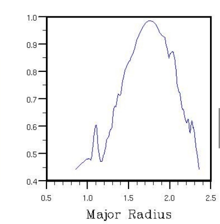
* Toroidal rotation with peak v_ϕ=0.1 v_A, but $v_\phi \rightarrow 0$ at LCFS
* Poloidal flux ψ_3 (out of phase n=3 harmonic) rapidly develops, moves in
* Density more perturbed than temperature. (g126006, linear FE,S=10^6)









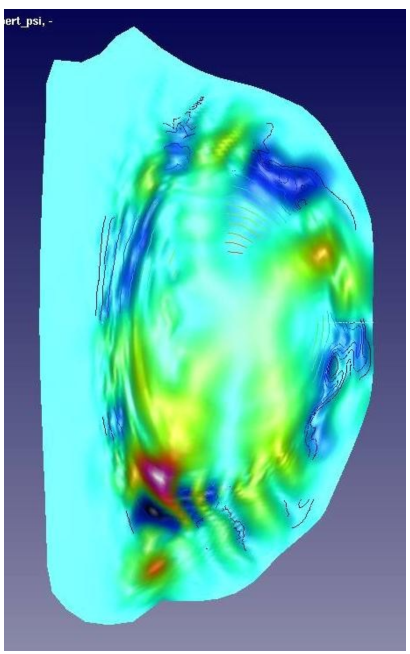


ψ_3 T ψ_3 n

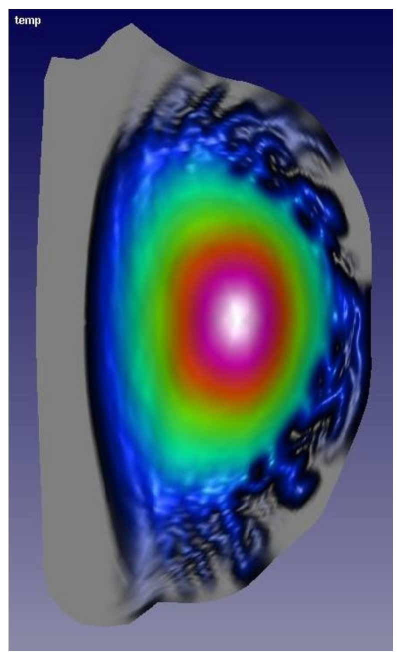
t =42 τ_A t=63 τ_A

RMP penetration with finite edge v_ϕ is more limited.

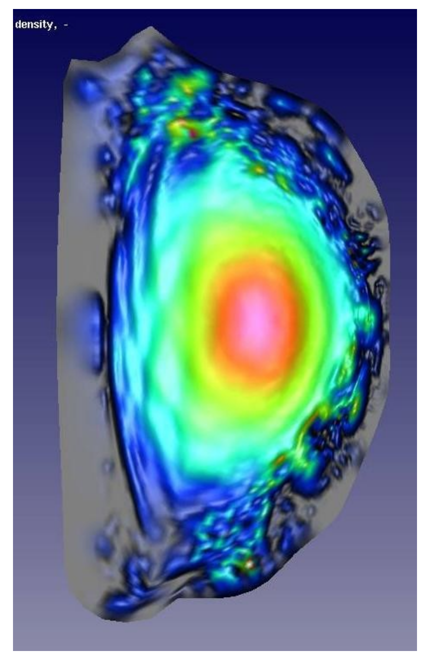
* Toroidal rotation with peak v_ϕ=0.07v_A, finite $v_\phi \approx$ 0.1$v_{\phi 0}$ at LCFS.
* RMP field penetrates less.
* Temperature, density in plasma interior less affected. n=3 pert.
  Some density lost to outside LCFS, especially at top, bottom.



ψ_3

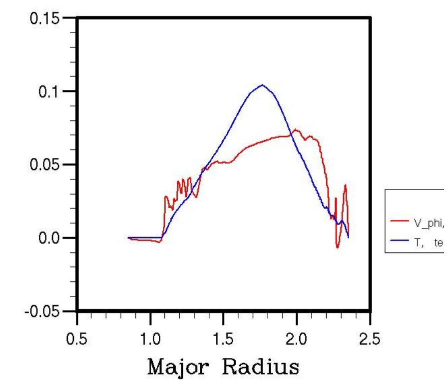


T



n

t=84.5 τ_A



v_ϕ red
T blue

Other accomplishments

- Graduate student studying expulsion of toroidal angular momentum by ELM; preliminary results at APS-DPP, M. Landreman, poster GP6.00093
  - Older version of code, ported to BigBen (Cray XT-3, Pittsburgh Supercomputer Center) in May 2008.
- AVS/Express visualization at NERSC (davinci), based on IDAVE by S. Klasky. Public version now available in module (used here!)
  - Web HOWTO: **http://vis.lbl.gov/~jacobsen/express** (Janet Jacobsen, NERSC viz group). Should work with NIMROD script.
  - New fast interactive X-term package NX makes this usable over a remote internet connection

Summary

- Higher order finite elements in M3D - 2nd and 3rd order; code structure generalizes to high order
  - Improved resolution allows more realistic parameters : lower resistivity,viscosity, thus realistic two-fluid strength.
- Higher resolution MHD simulations of ELM crash show a detailed spatial and temporal structure
  - Many features appear to agree with experimental observations
  - Magnetic field structure important!
- Initial two-fluid ELM studies
- Viz setup using AVS/Express at NERSC
- Lots of work still needed!
  - More manpower
  - Also, a good debugger for Cray XT-4. Many thanks to NERSC consultants for their help!