Progress on "flux pumping", ELMs, disruptions, and VDEs

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Presented at

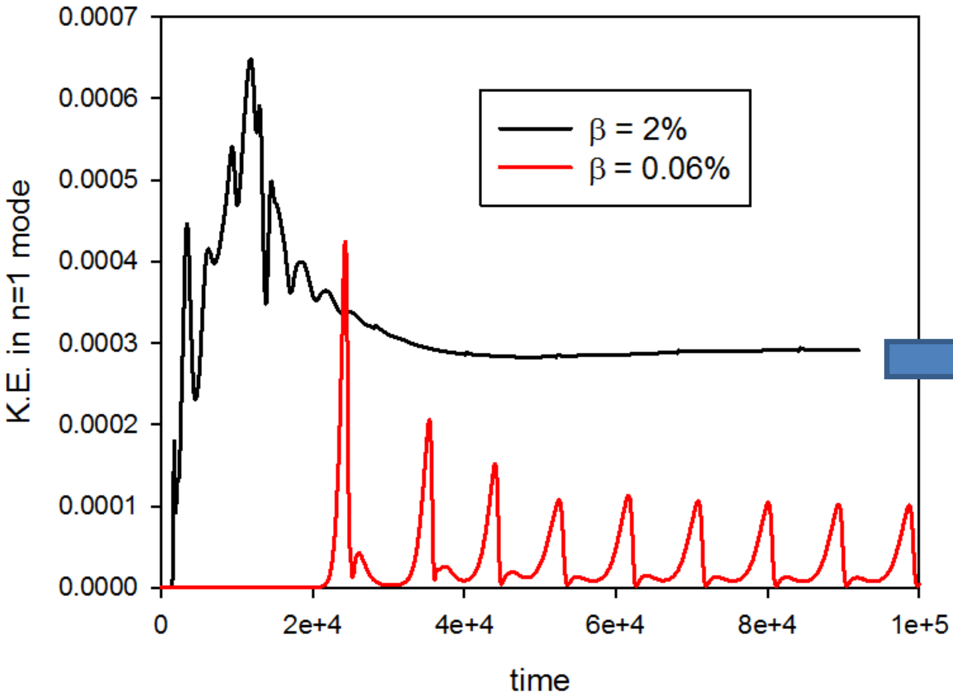
CEMM Meeting

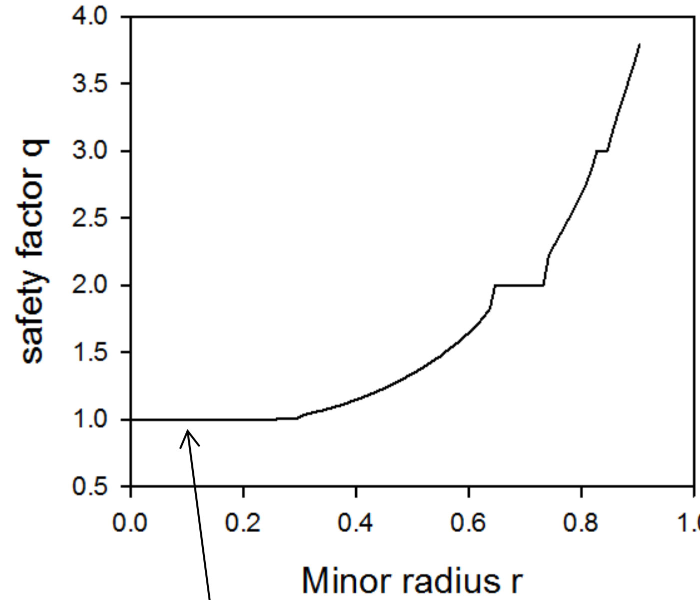
Institution	PI	Workscope
GA	Lao/Lyons	RMP and Kinetic MHD in M3D-C1
GA	Lao/Izzo	Mitigation of disrupting MHD active Plasma
FTCI	Glasser	Resistive DCON, verification, disruption prediction
MIT-PSFC	Ramos	Linear kinetic MHD formulation for M3D-C1
MIT-LNS	Sugiyama	ELM studies with M3D-C1 and benchmarking
HRS Fusion	Strauss	Disruption studies for forces and benchmarking
PPPL	Jardin	Sawteeth, hybrid-discharges, disruptions, RMPs, ELMS
SCOREC RPI	Shephard	Mesh and solver improvements for M3D-C1
Tech-X	Kruger	EHO, giant sawteeth, NTM, code performance
Utah State	Held	RSAE benchmark, NTM, giant sawteeth
U. Wisc.(EP)	Sovinec	Sheath bcs for VDEs, GS collab., ELM topics

Flux Pumping*

*Invited talk, Tuesday 11:00am
Jardin, Ferraro, Krebs, PRL (Nov 2015)

$\beta \equiv \mu_0 p/B^2$ =2% behavior much different from low β





Large region in center with q = 1

- At low-β, plasma kinetic energy (and T_{e0} and q_0) undergo periodic oscillations where current peaks, reconnection occurs and process repeats (sawteeth)

- At 2% β, plasma goes into a stationary state with large helical flow patterns and ultra-low magnetic shear with q=1 in center

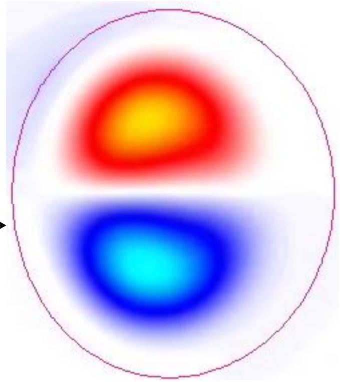
$$q = \frac{\#\ \text{of toroidal transits}}{\#\ \text{of poloidal transits}}$$

Ultra-flat q profile drives interchange instability

Plotted is U on one toroidal plane (φ=0) from a 3D simulation where:

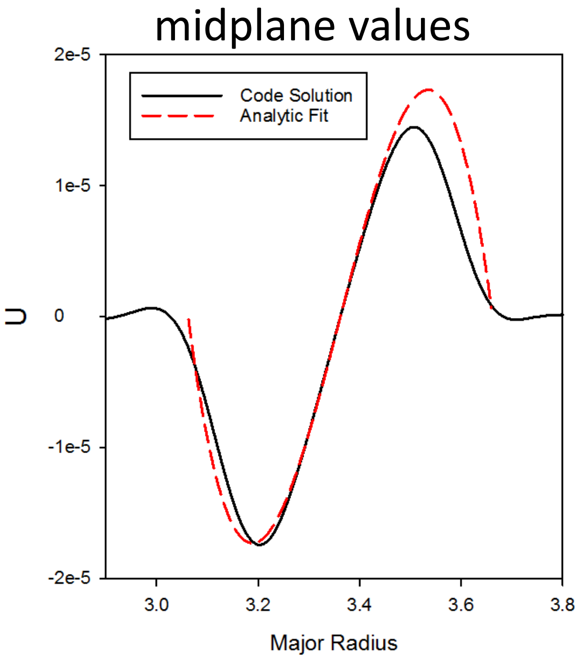
$$\mathbf{V}_{1,1} = R^2 \nabla U \times \nabla \varphi$$

q =1.01 →



Compare with the unstable eigenfunction found in [1]

$$U(r,\theta,\varphi) = U_0 r[1-(r/r_1)^2]\sin(\theta-\varphi)$$



Shape of stationary nonlinear code velocity stream function agrees well with linear eigenfunction.

Flow produces electric potential:

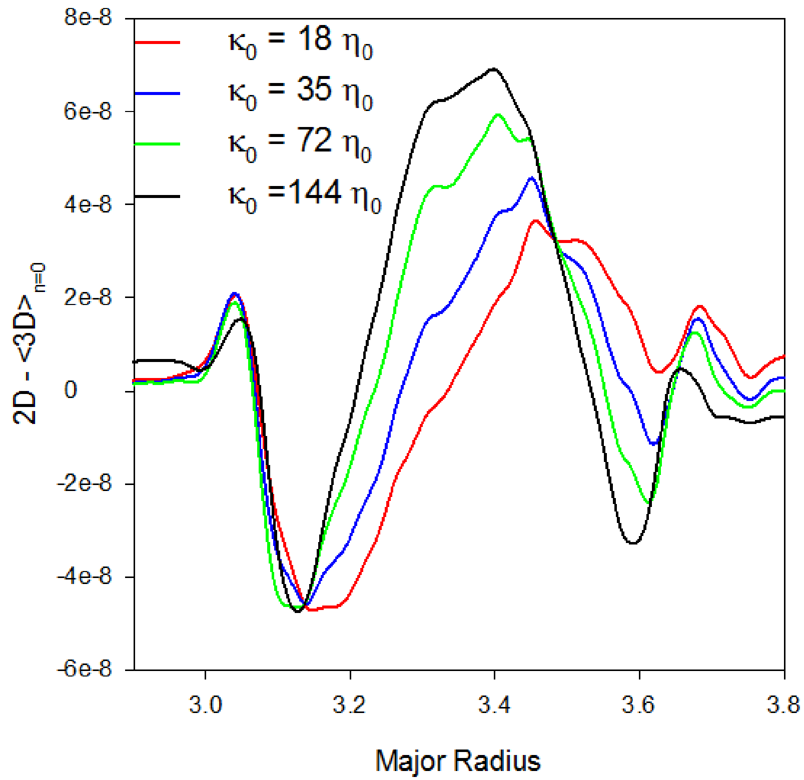
$$\nabla \Phi \simeq \mathbf{V} \times \mathbf{B} \simeq F \nabla U$$

$$F \equiv RB_T$$

[1] Hastie and Hender, NF **28** (1988) p. 585 "Toroidal internal kink stability in tokamaks with ultra flat q profiles"

$B_{1,1} \bullet \nabla \Phi_{1,1}$ produces dynamo voltage that sustains configuration

$$\left(\mathbf{B} \bullet \nabla \Phi\right)_{3D\_n=0} - \left(\mathbf{B} \bullet \nabla \Phi\right)_{2D}$$



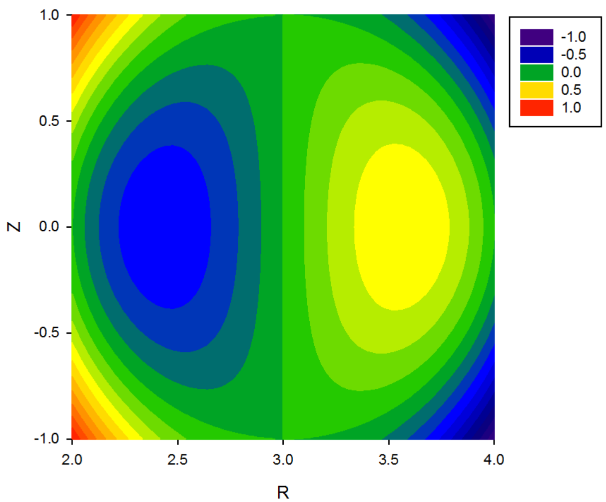
This is caused by the perturbed n=1 magnetic field acting on the perturbed n=1 potential, driven by the interchange mode

How can $\mathbf{B}\cdot\nabla\Phi$ have a non-zero toroidal average in a volume?

Now suppose $\tilde{\mathbf{B}}$ is a small (1,1) field component resonant with Φ:

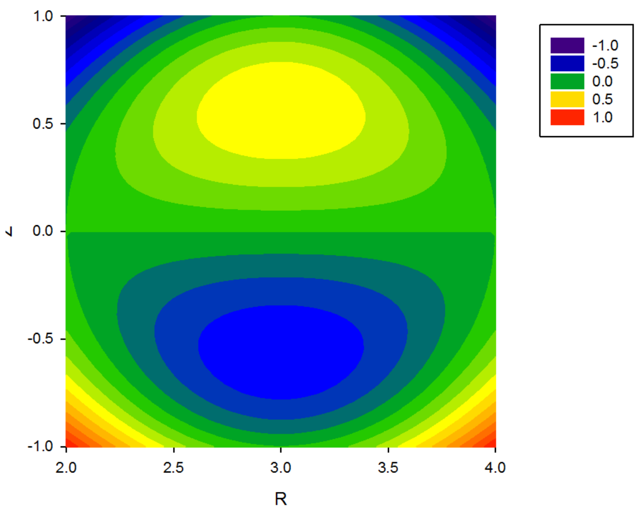
$$\mathbf{B} = \mathbf{B}^0 + \hat{\varphi}\times\nabla\psi_{1,1} \qquad \psi_{1,1} = \varepsilon r\left(1-r^2\right)\sin\left(\theta-\varphi\right)$$

Potential Φ



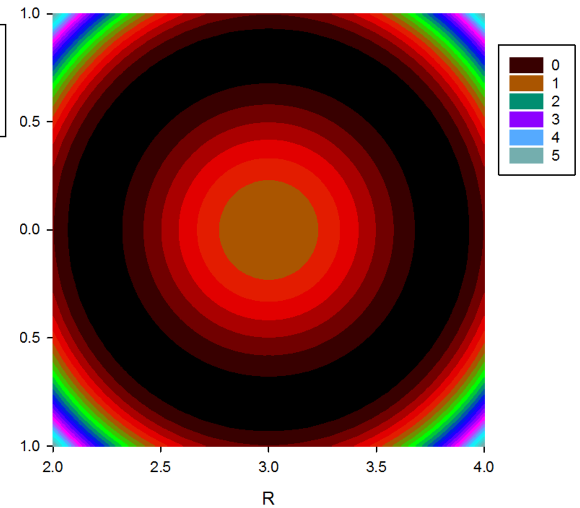
$$\Phi = \Phi_0 r\left(1-r^2\right)\cos\left(\theta-\varphi\right)$$

Perturbed field $\psi_{1,1}$



$$\psi_{1,1} = \varepsilon r\left(1-r^2\right)\sin\left(\theta-\varphi\right)$$

$\left\langle \tilde{\mathbf{B}}\cdot\nabla\Phi \right\rangle$



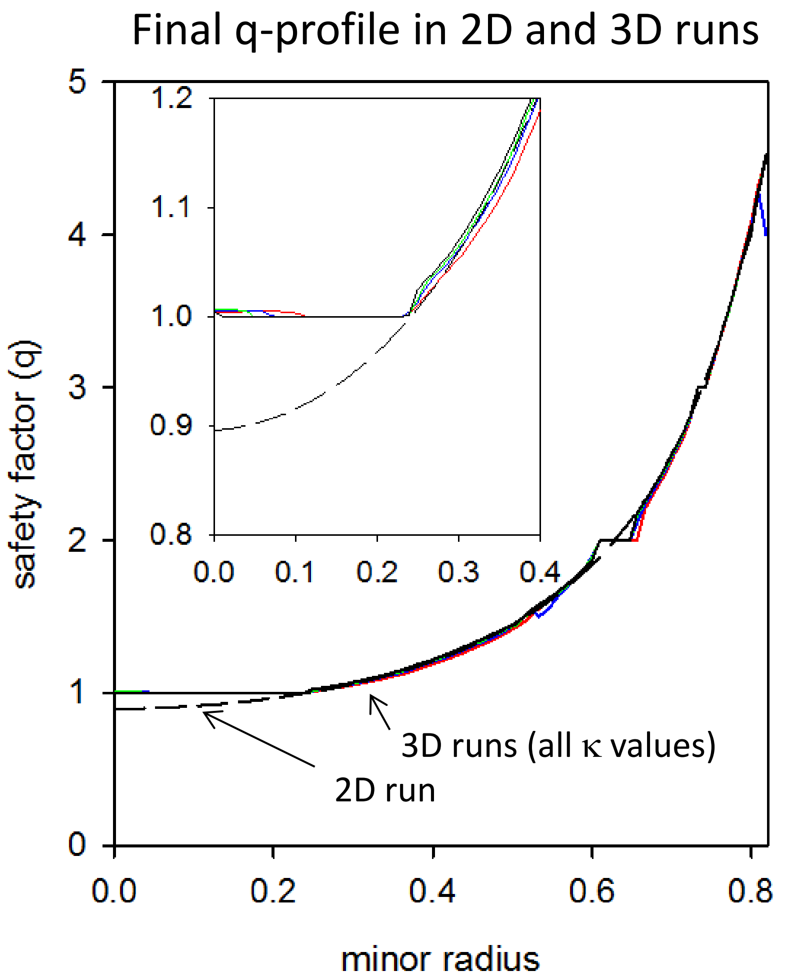
$$\left\langle \mathbf{B}\cdot\nabla\Phi \right\rangle = \varepsilon\Phi_0 \left\langle \begin{matrix} \left(1-3r^2\right)\left(1-r^2\right) \\ \times\left(\cos^2\left(\theta-\varphi\right)+\sin^2\left(\theta-\varphi\right)\right) \end{matrix} \right\rangle$$

$$= \varepsilon\Phi_0 \left\langle \left(1-3r^2\right)\left(1-r^2\right) \right\rangle$$

positive definite for r sufficiently small!

Resonant field perturbation produces an effective voltage along perturbed field!

No longer constrained to $\eta\langle \mathbf{J}\bullet\mathbf{B}\rangle = \text{const}$, central regions in all 3D runs approach minimum energy Taylor State with q=1



The nonlinear drive that keeps the current from peaking gets stronger as q→1 from above

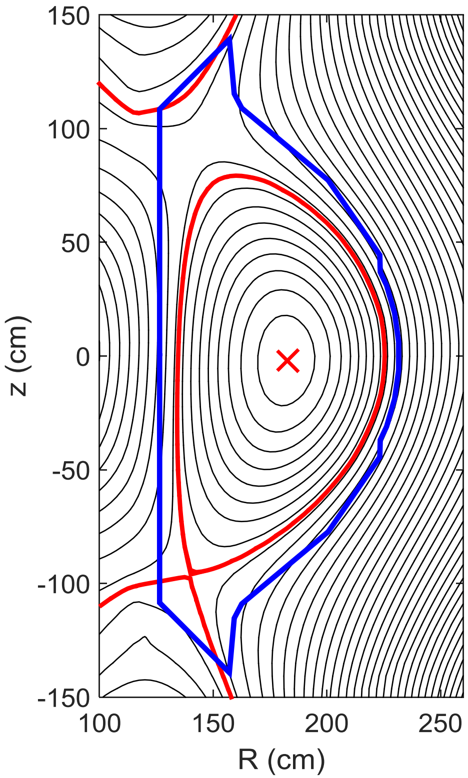
This feedback mechanism results in an ultra-flat q-profile in center with $q_0 = 1 + \varepsilon$ (where $\varepsilon \ll 1$)

ELMs

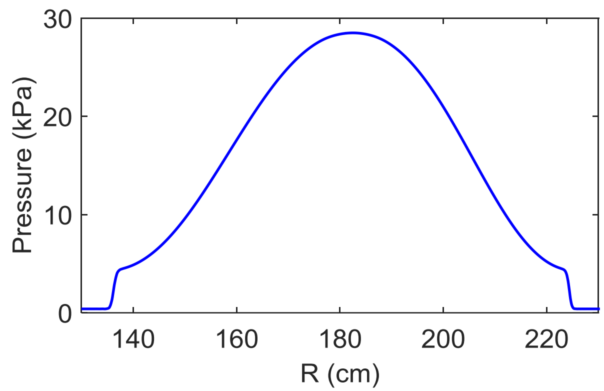
Plasma equilibrium used in simulations

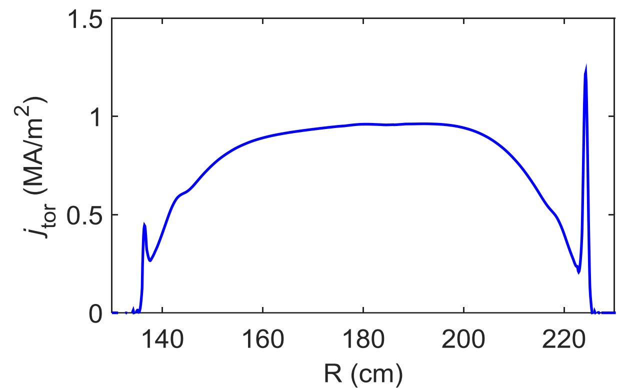
At ***t* ~ 4.36** s of KSTAR discharge **#7328**

- Magnetic geometry (EFIT + TEQ)

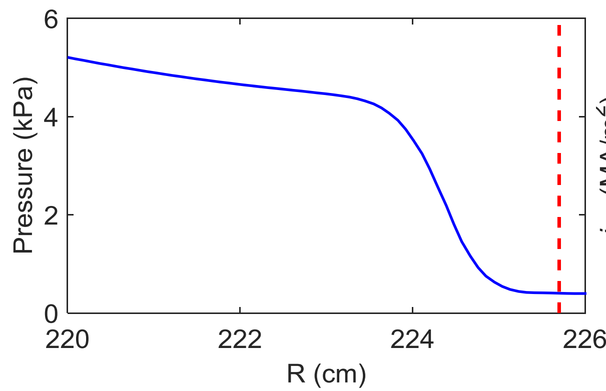


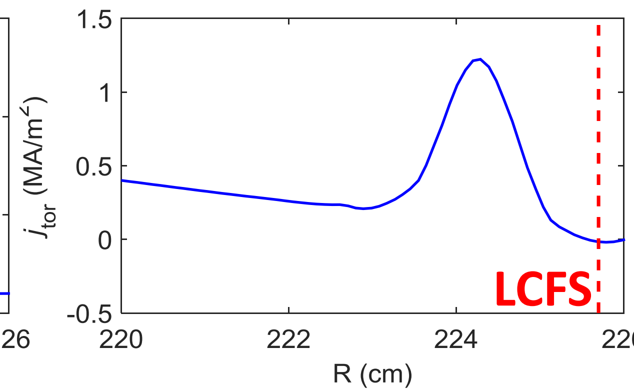
- Equilibrium profiles across mid-plane

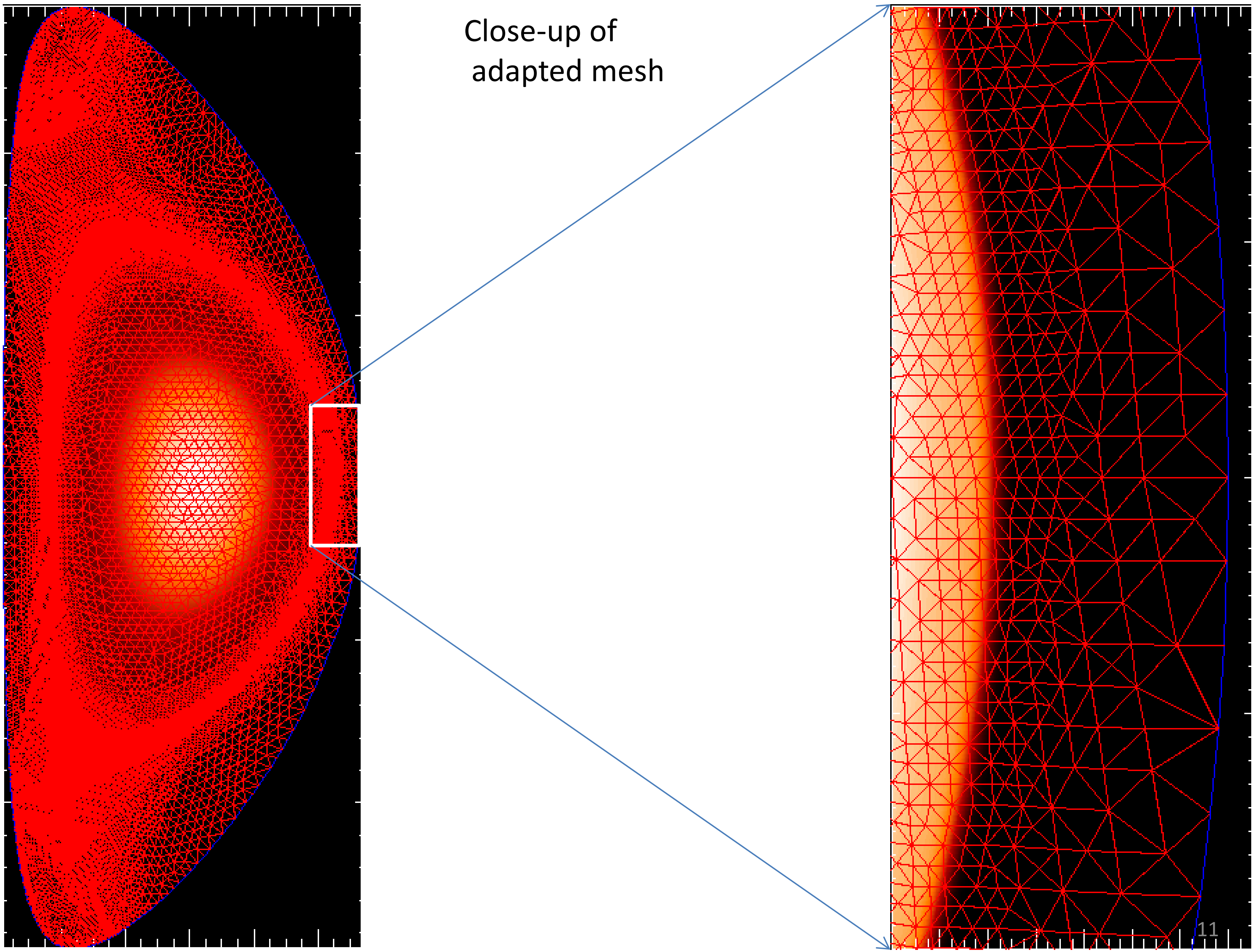




- Profiles on LFS mid-plane

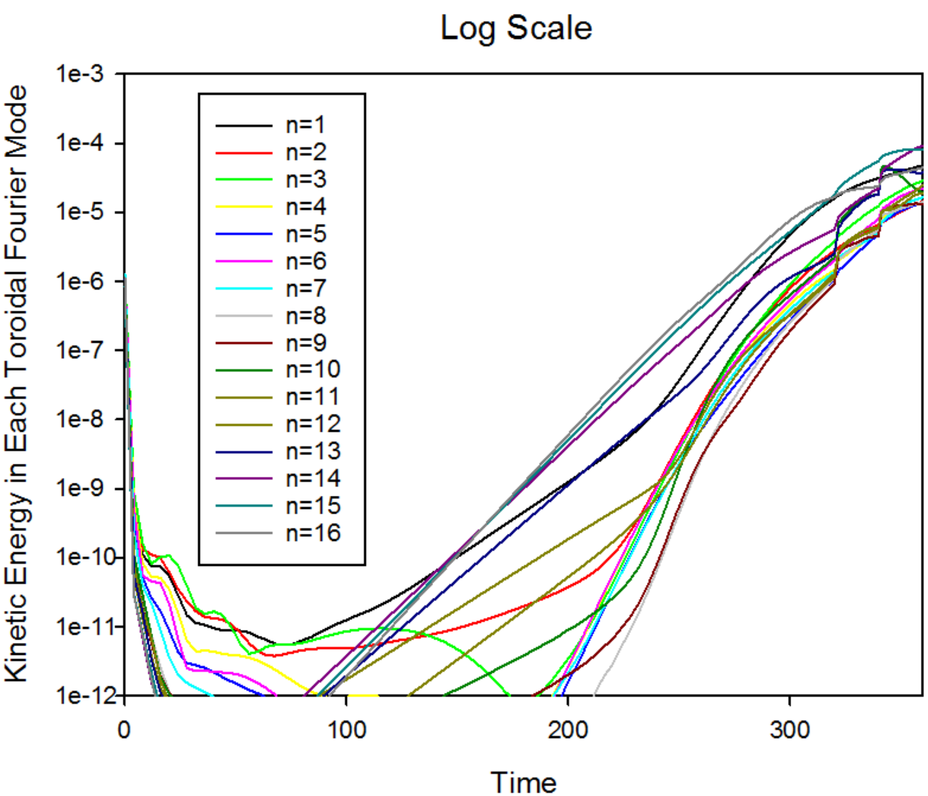


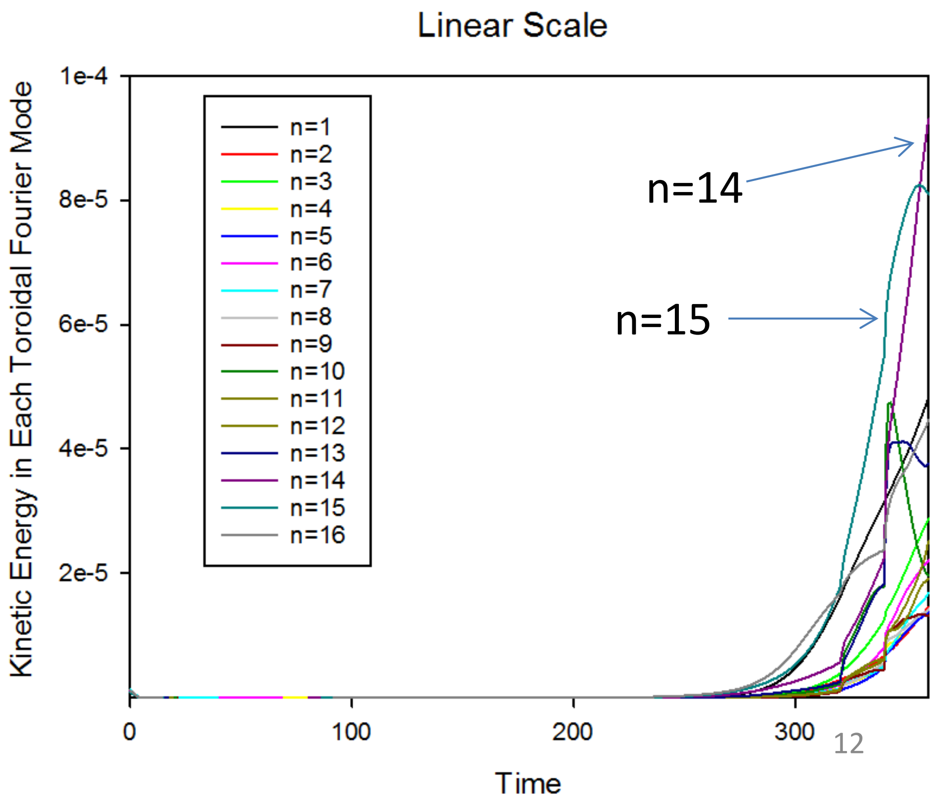


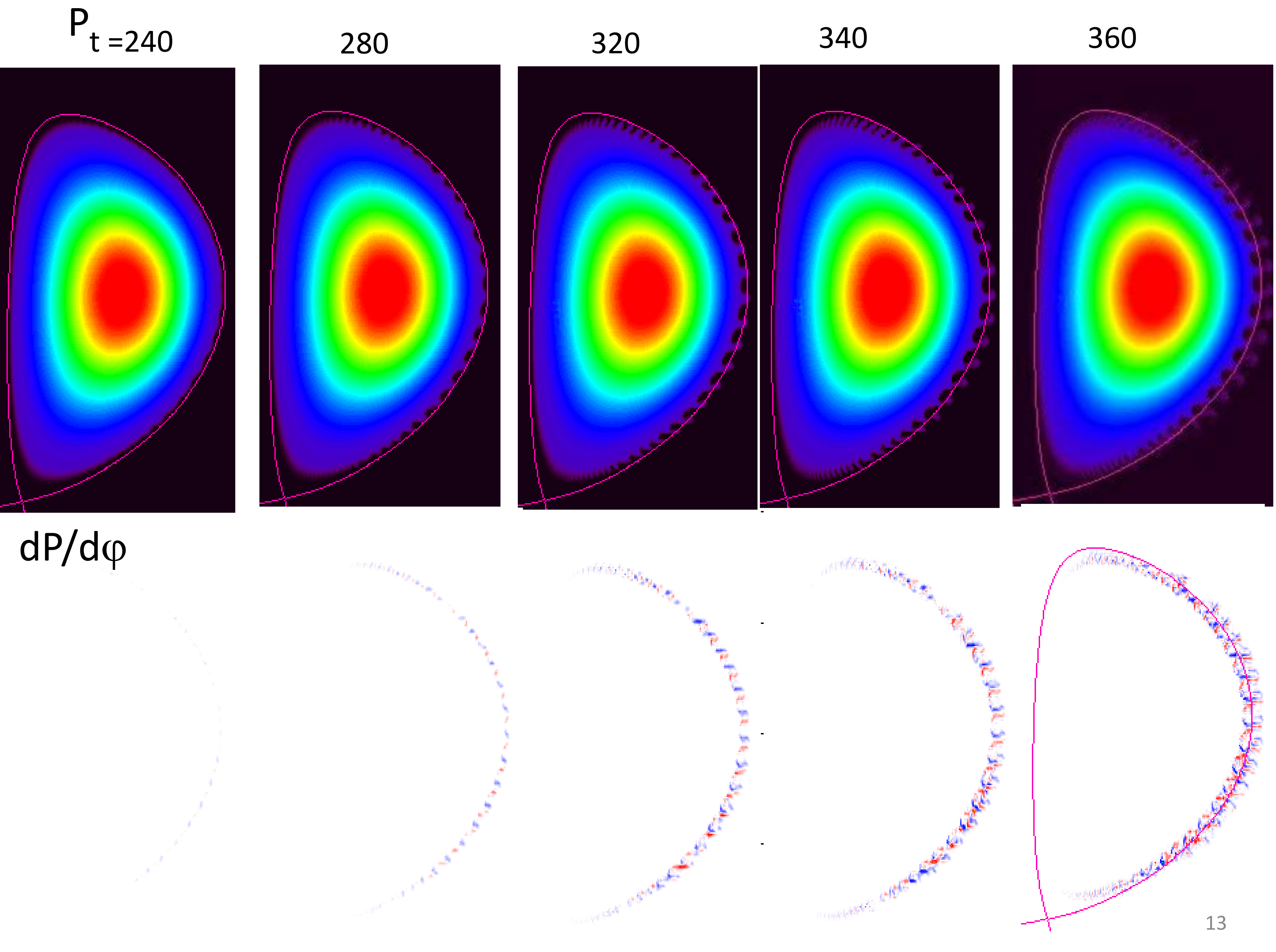

Close-up of
adapted mesh

Kinetic energy in different toroidal harmonics vs time:

Nonlinear 84 plane run on Hopper:





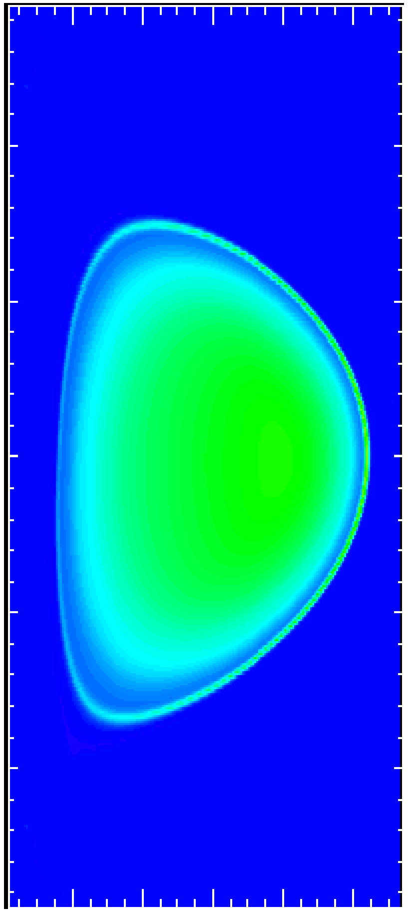


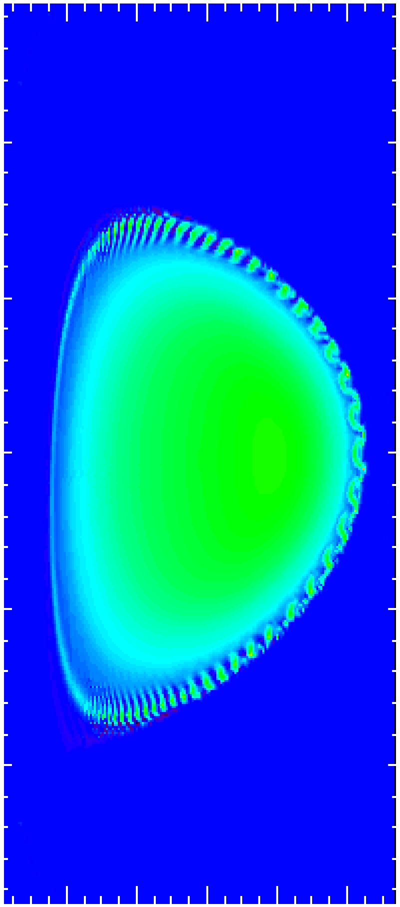
$P_{t=240}$
280
320
340
360
$dP/d\varphi$

Current Density $\Delta^*\psi$

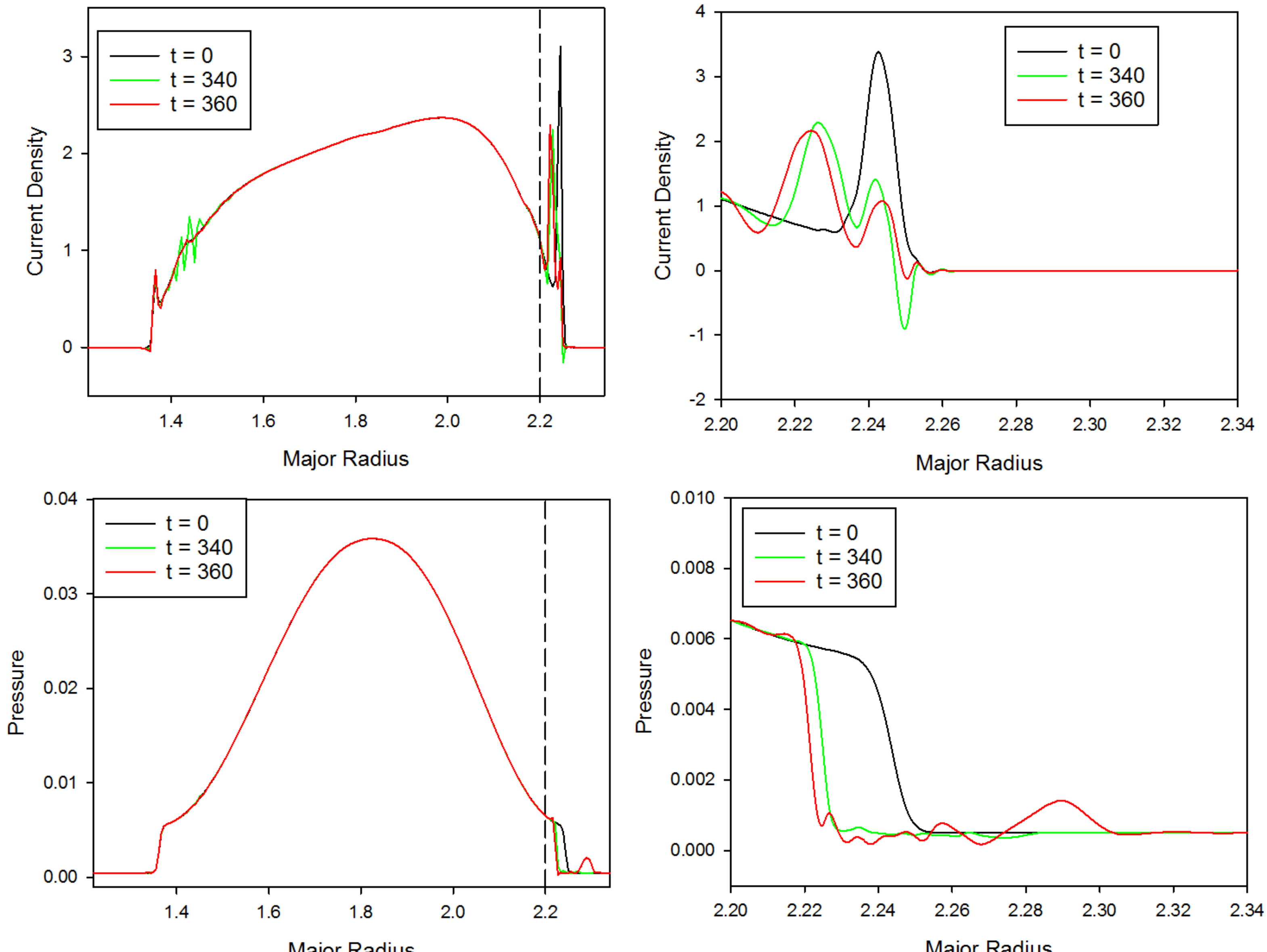
t = 0

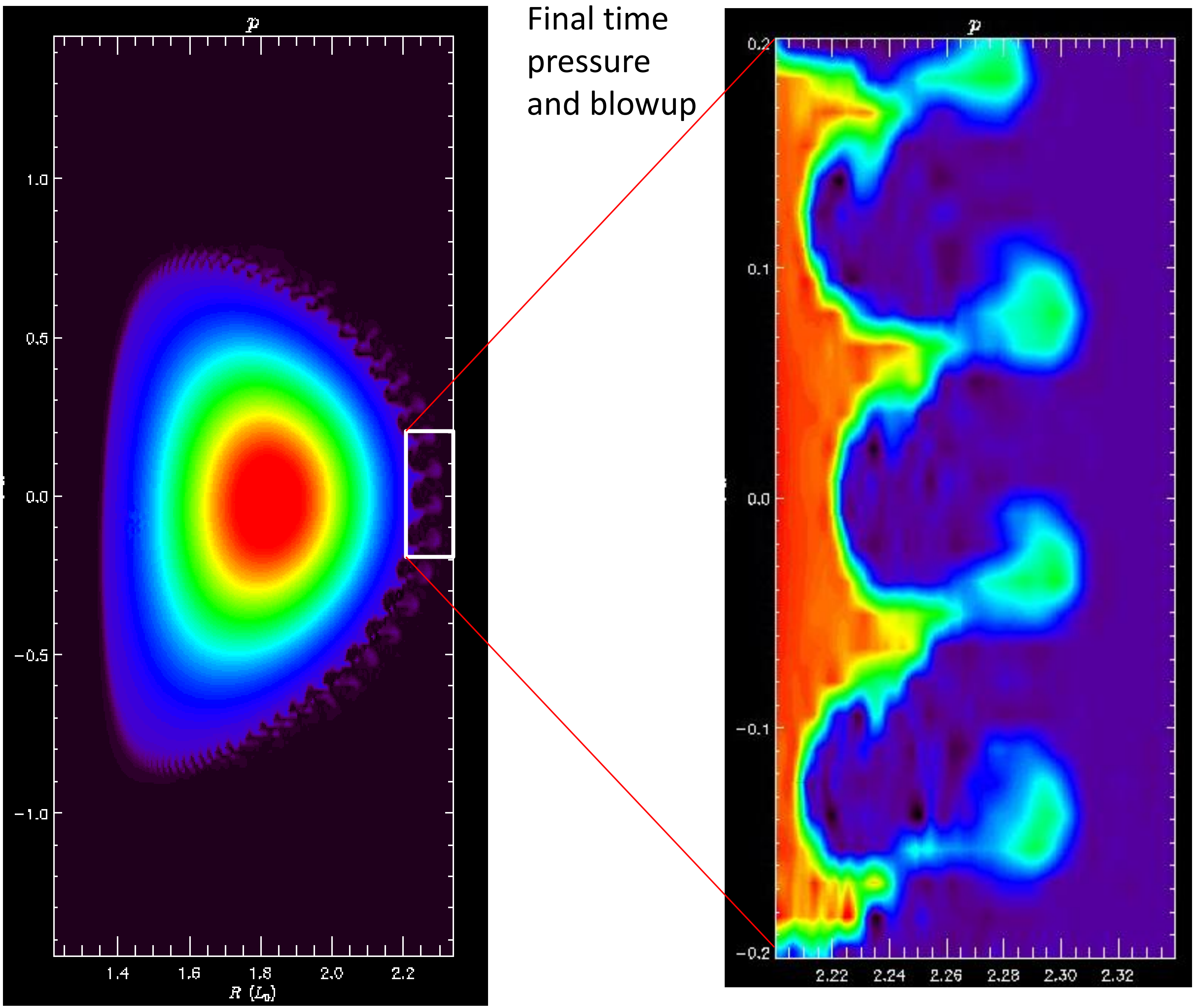
t = 360



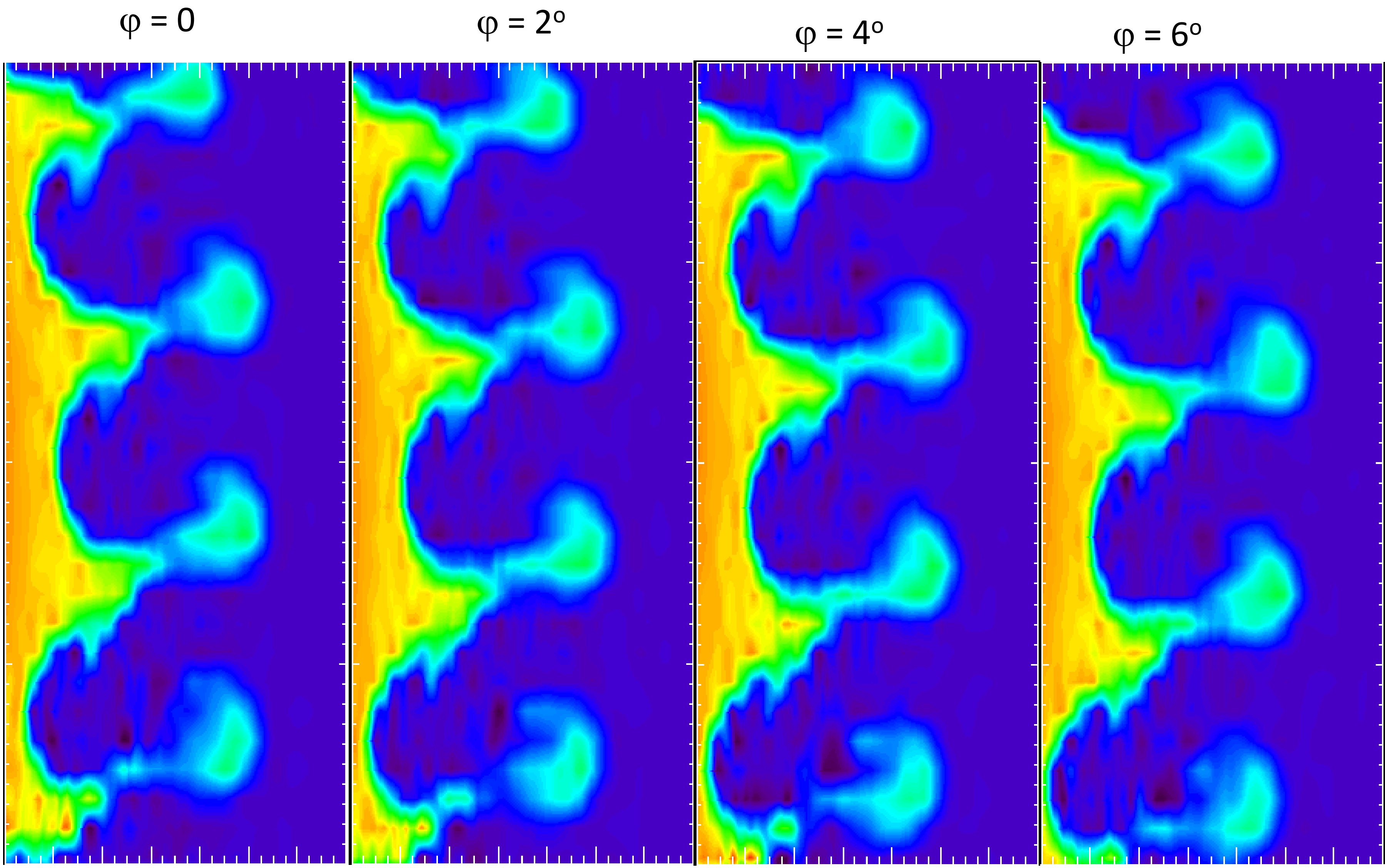


Superposition of mid-plane profiles of current and pressure shows that instability eats away at edge and doesn't affect central region.



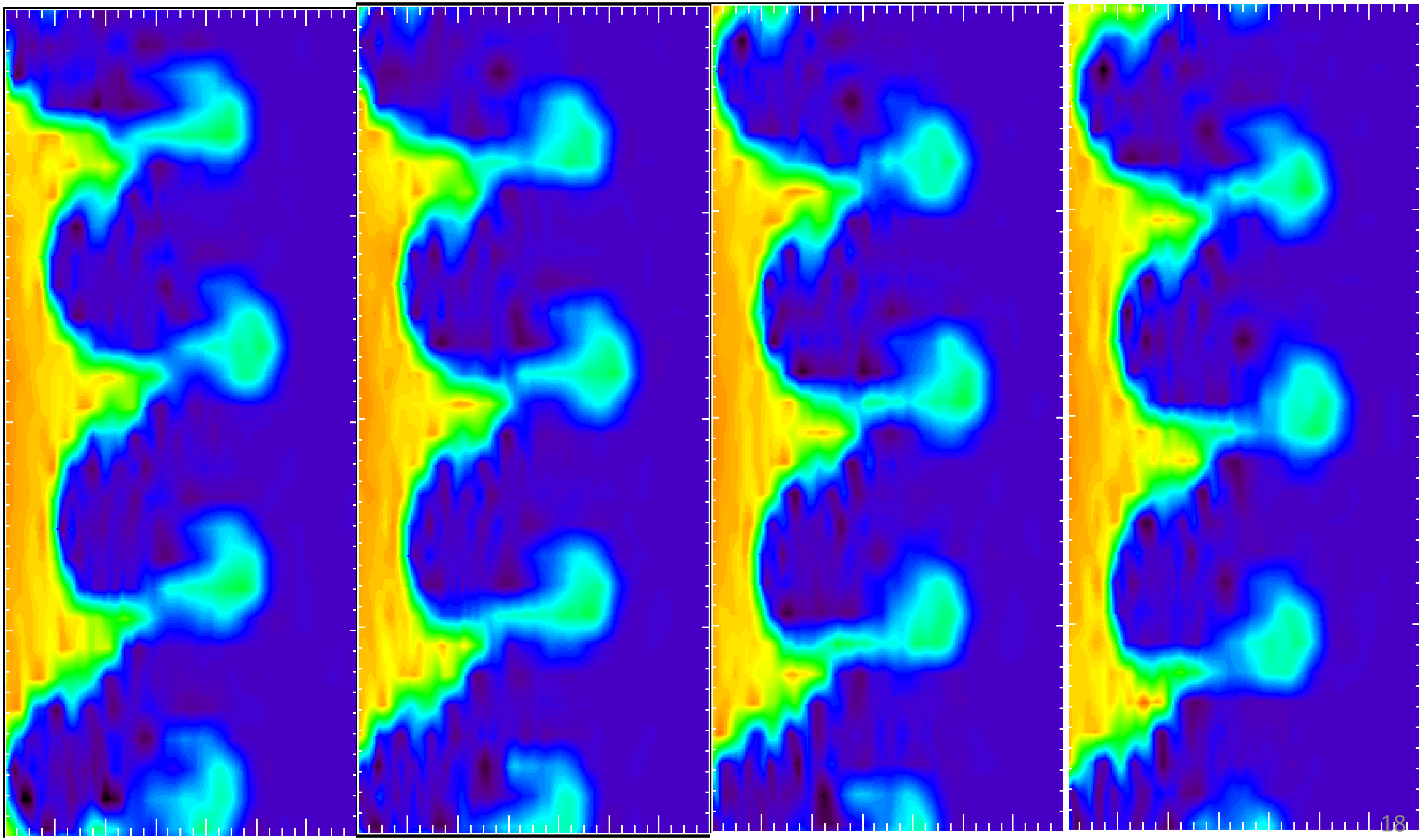

p
1.0
0.5
0.0
−0.5
−1.0
1.4
1.6
1.8
2.0
2.2
R (L0)
Final time
pressure
and blowup
p
0.2
0.1
0.0
−0.1
−0.2
2.22
2.24
2.26
2.28
2.30
2.32

Pressure contours at every 2° (toroidal angle) shows there are no grid-point to grid-point oscillations (grids are at every 360/84 = 4.28 degrees)



2^o (toroidal angle) scan continued

$\varphi = 8^o$ $\varphi = 10^o$ $\varphi = 12^o$ $\varphi = 14^o$



Linear growth rates

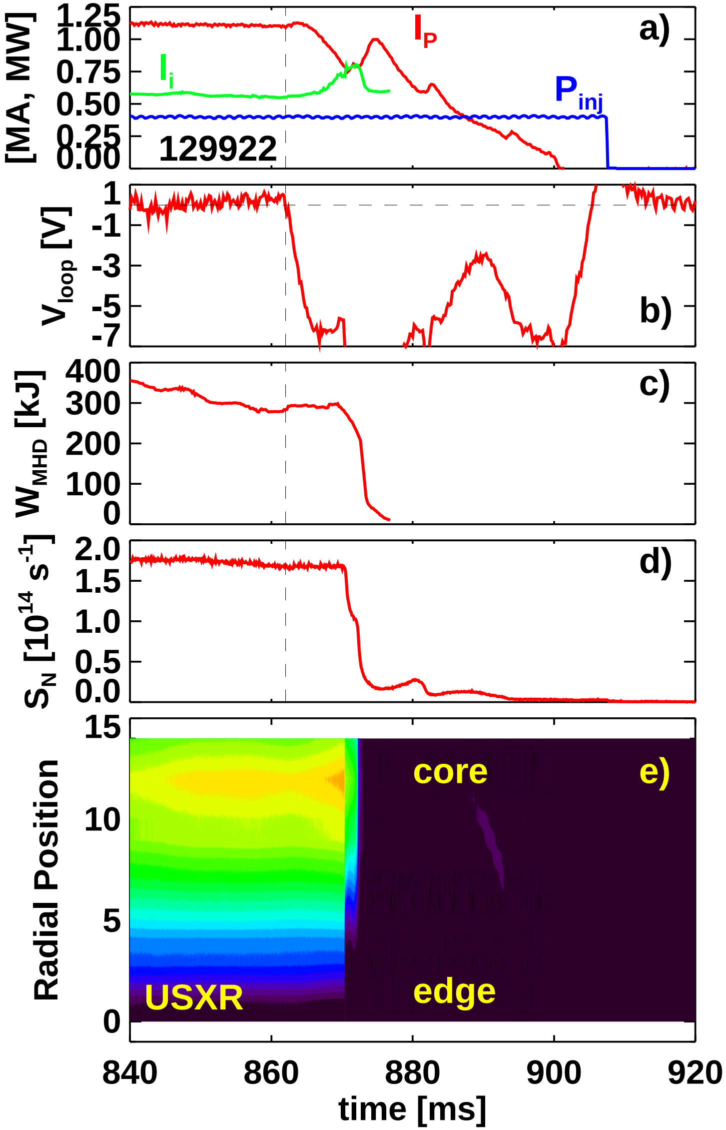
Thermal conductivity is very stabilizing! (ntor=8)

$\kappa_{\perp}$	$\kappa_{\|\|}$	γ
0	0	.050
0	1	.032
1. E-7	1	.031
1. E-6	1	.020
1. E-5	1	Stable!

Disruption caused by current rampdown

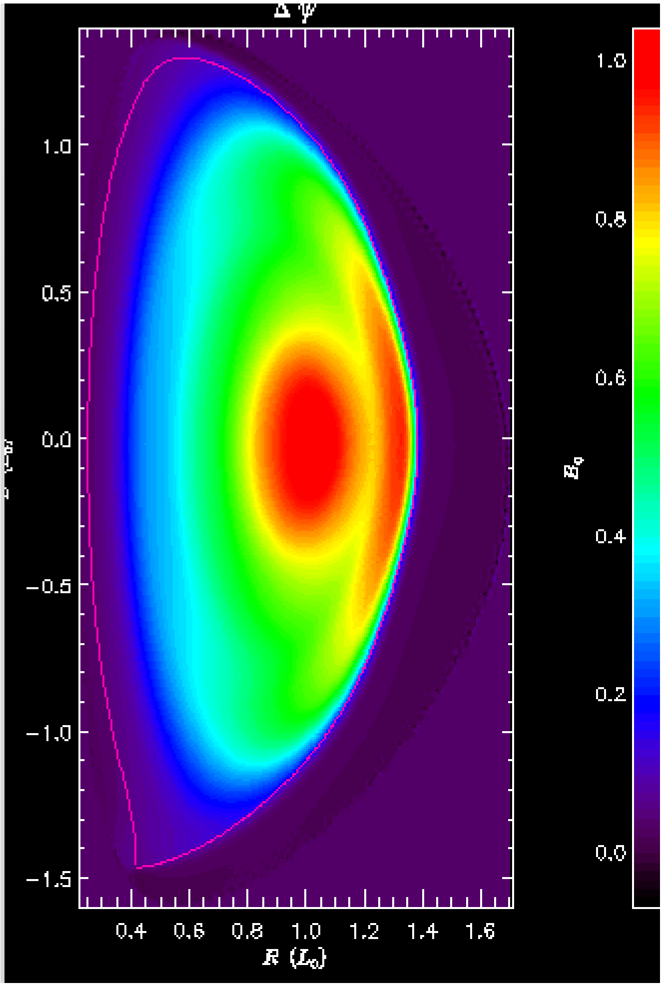
Unique Class of Major Disruptions Identified in NSTX

- Recipe:
  - Generate a stable low(er) q95 discharge.
  - Run it to the current limit of the OH coil.
  - Ramp the OH coil back to zero, applying a negative loop voltage, while leaving the heating on.
  - Watch l_i increase, then disruption occurs.
- Mechanism responsible for 21 for the 22 highest W_{MHD} disruptions in NSTX.
- Specific example in the general area of how unstable current profiles lead to catastrophic instability

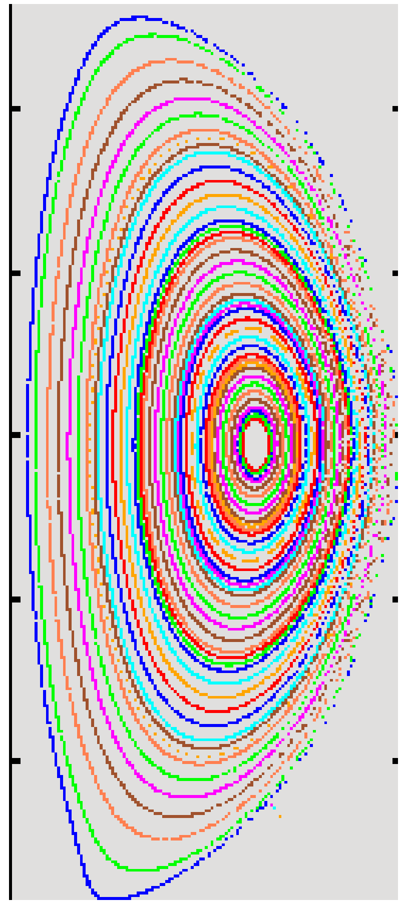


[S. Gerhardt, Nov. 2013]

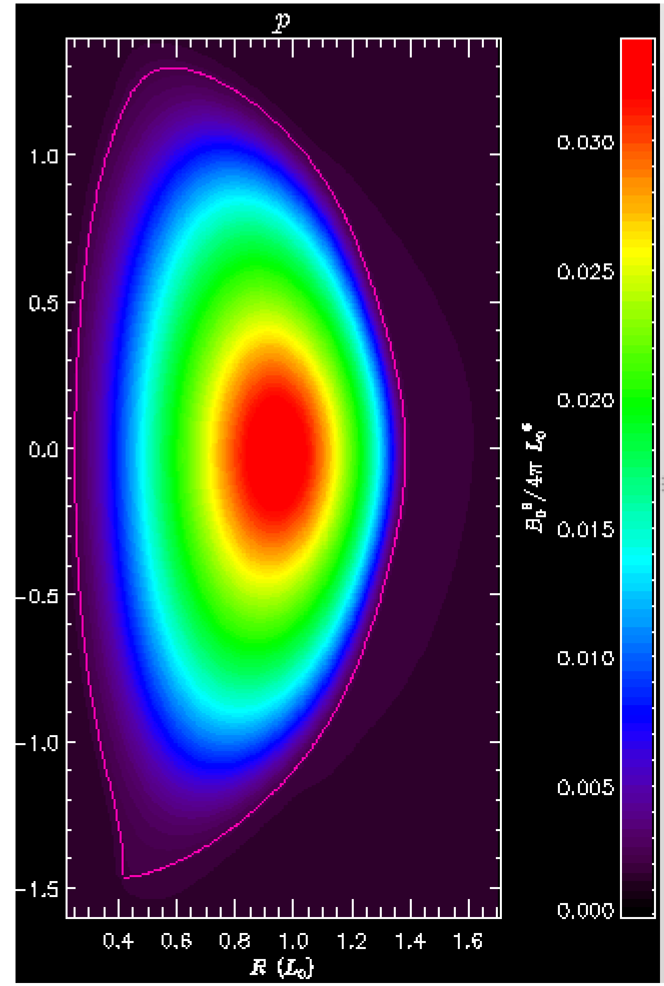
R J_φ



Poincare



Pressure



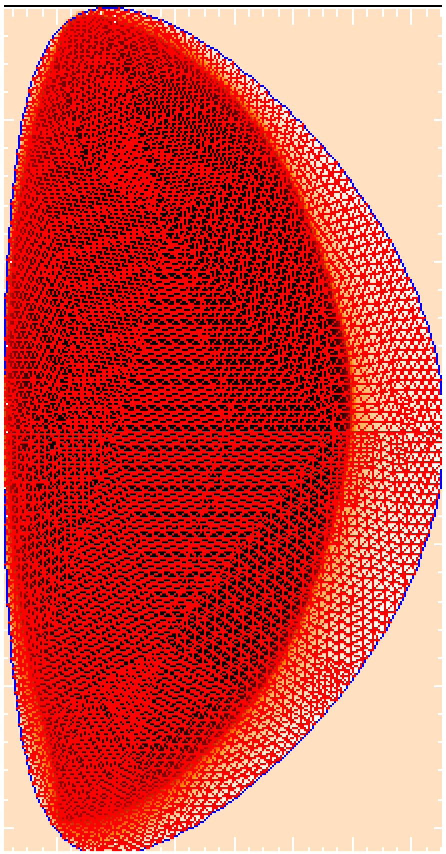
shot 129922
Time 860 ms

I_P ~ 1.1 MA
q_0 ~ 1.22
β ~ 6 %

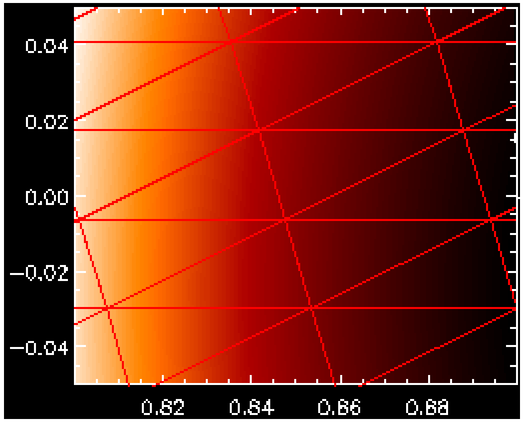
Te(0) = 1.14 keV
V_L = 0.36 Volts
χ = 1 m^2/sec

Numerical Parameters:

Entire domain



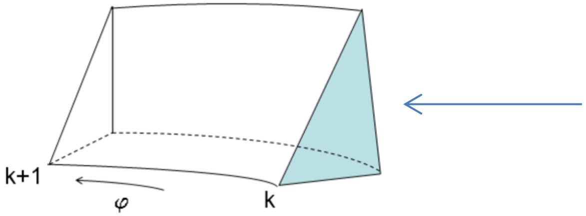
10 cm x 10 cm patch



$S = 10^7$ (in center)

2D triangle size: 2 – 4 cm

32 and 64 toroidal planes



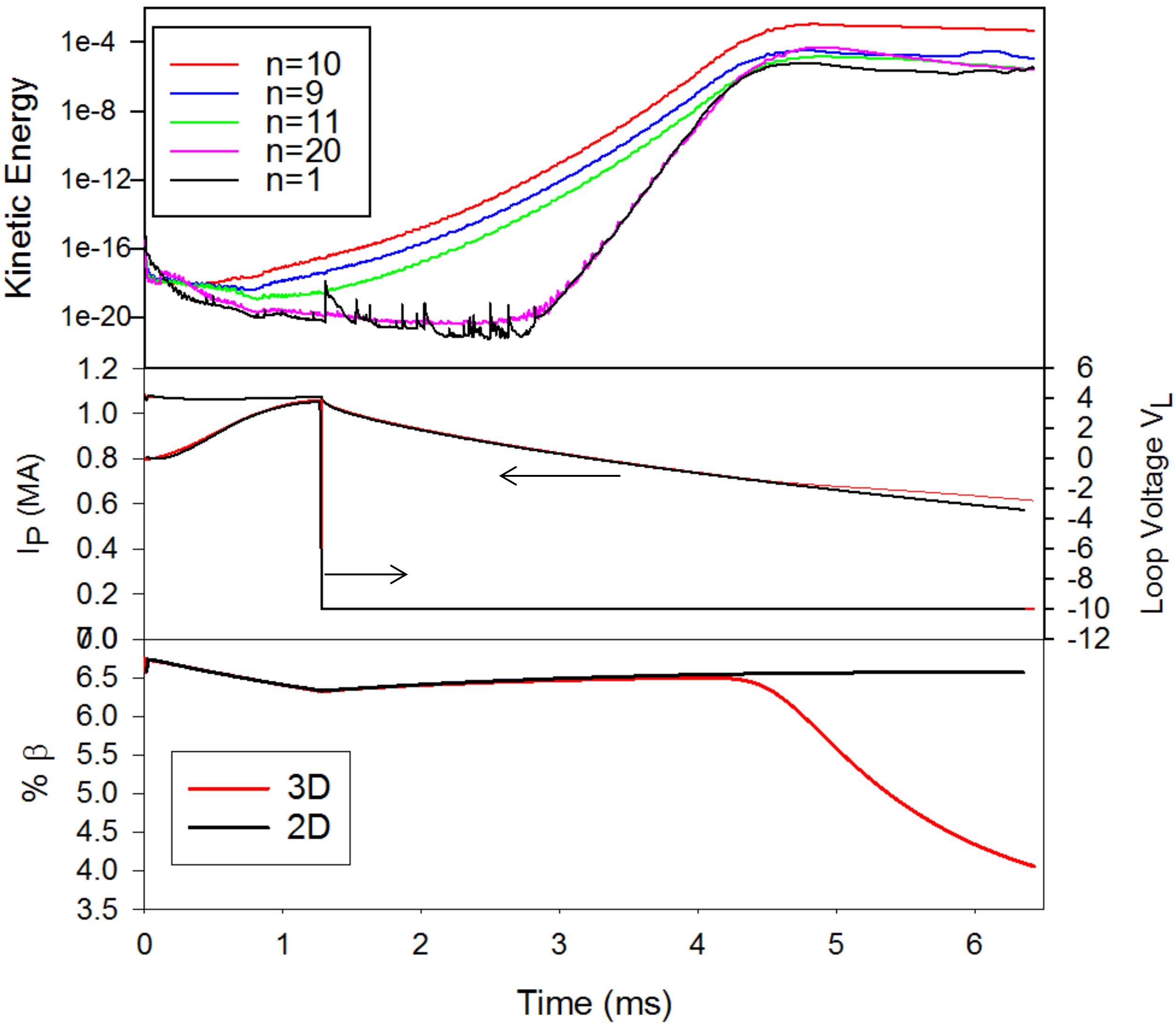
Triangular prism finite elements

Within each element, each scalar field is represented as a polynomial in (R,φ,Z) with 72 terms. All first derivatives are continuous.

This is a challenging problem because:

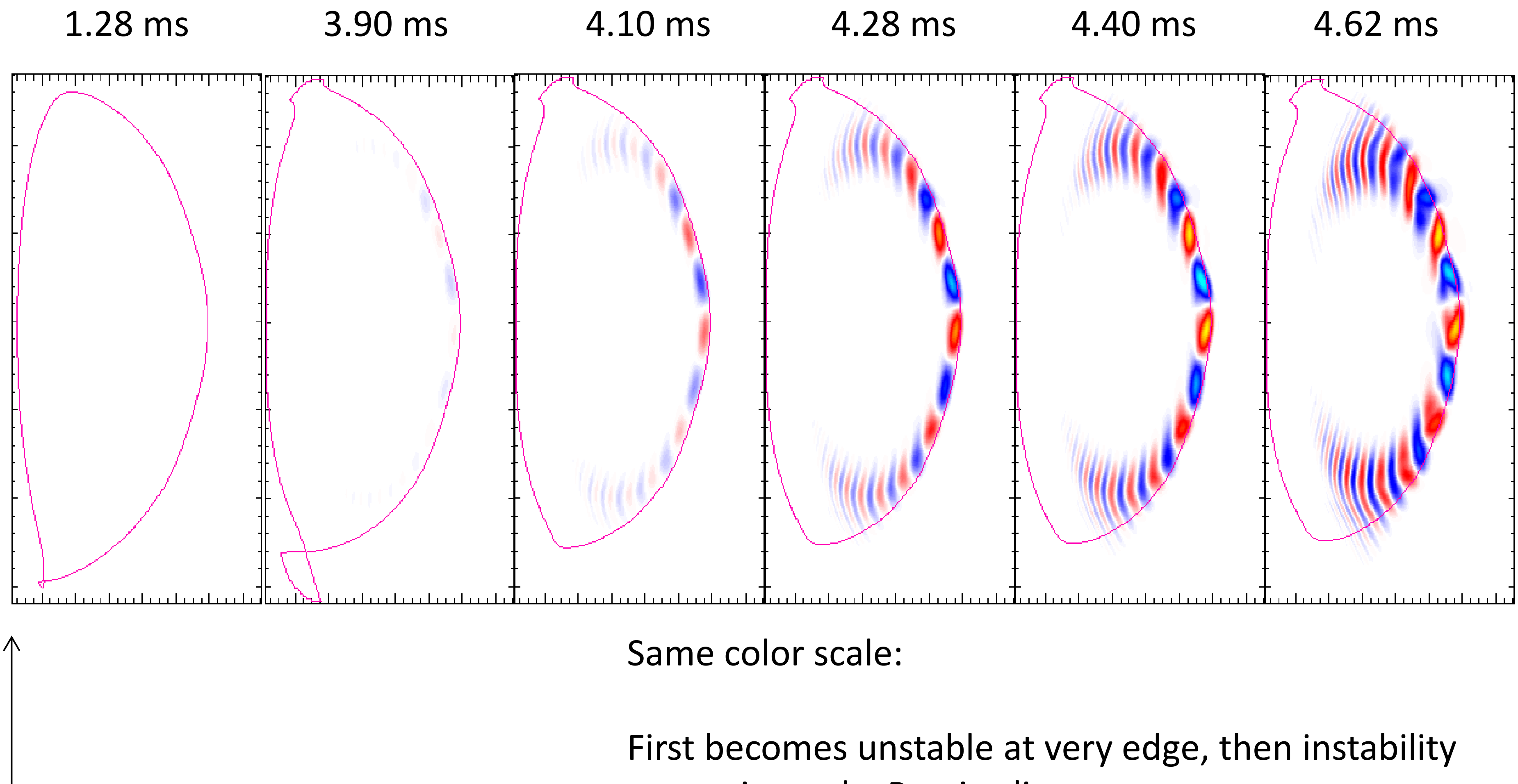
- Both current diffusion (transport) and ideal MHD (stability) time scales
- Requires high resolution for high-(m,n) modes
- Heating and particle sources
- Loop voltage prescribed at computational boundary
    - Control system to keep plasma current fixed before ramp-down
    - Switch to fixed negative value at start of current ramp-down

initial 64 plane run



- n=7,8,9,10,11,12 are most linearly unstable
- n=1,2,19,20 are nonlinearly driven
- Other modes not shown

Toroidal derivative of pressure at several time slices



Voltage reversed at 1.28 ms

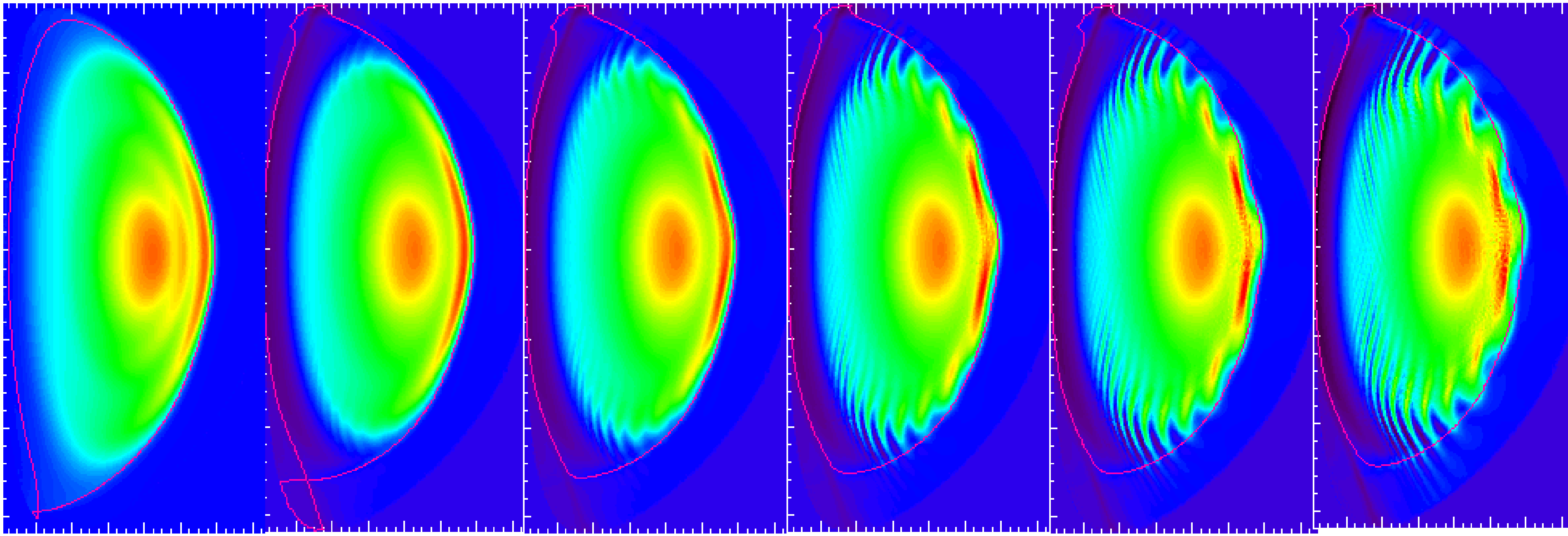
Same color scale:

First becomes unstable at very edge, then instability moves inward. Retains linear structure.

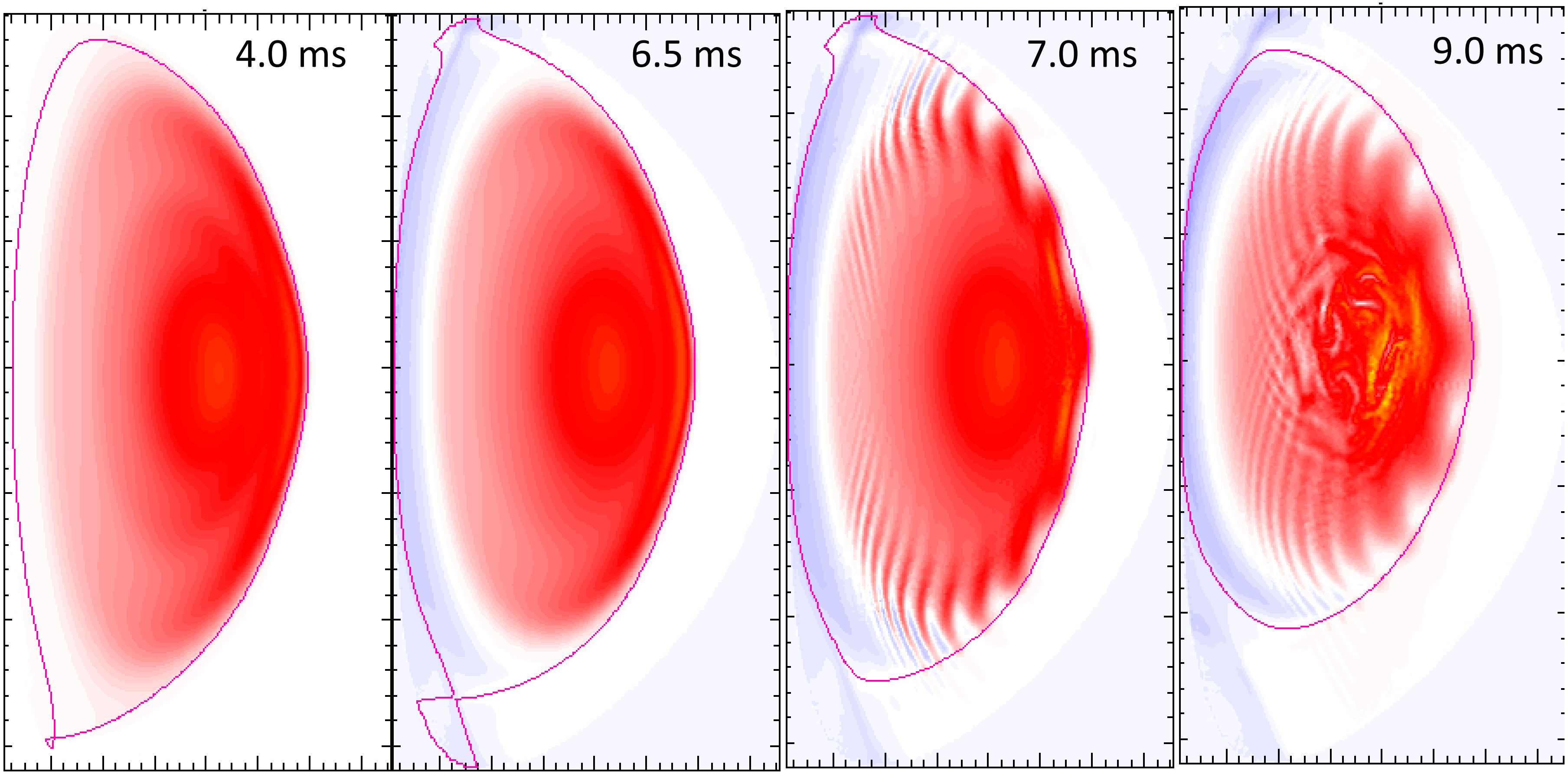
Becomes limited shortly after ramp-down starts. Impurity generation??

Plasma current density at several time slices

1.28 ms | 3.90 ms | 4.10 ms | 4.28 ms | 4.40 ms | 4.62 ms

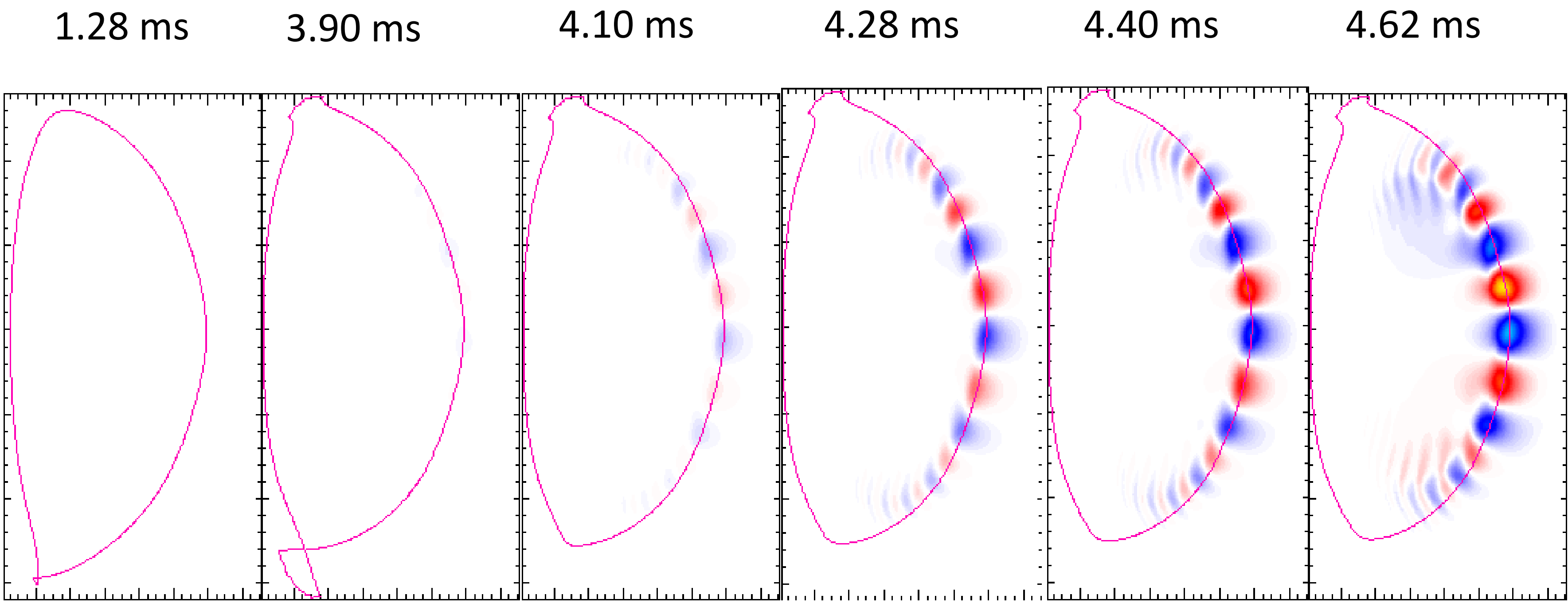


Plasma current density at several time slices



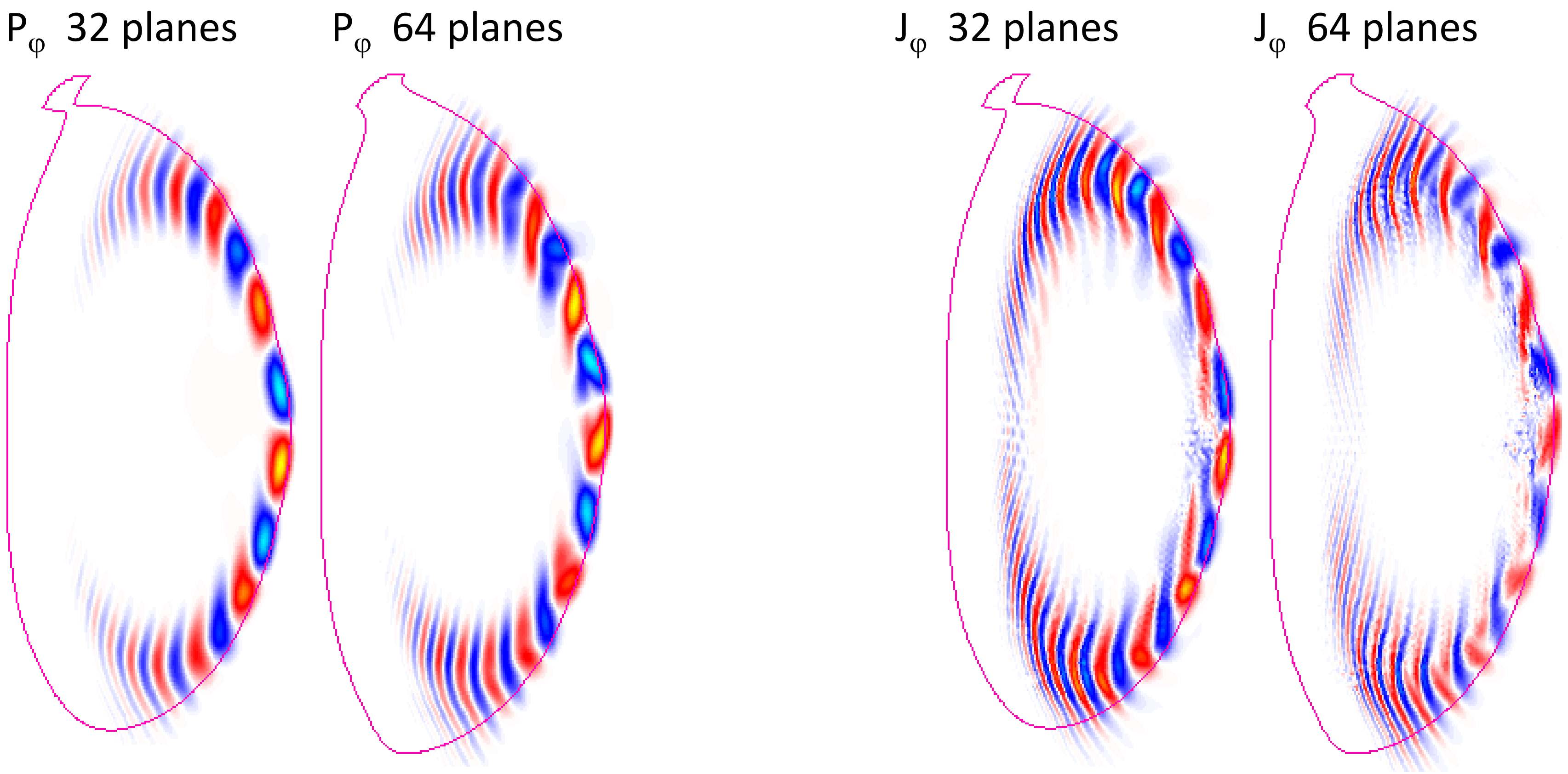
Different color scheme from previous viewgraph. Red and yellow are positive, blue is negative, zero is white.

Toroidal derivative of poloidal flux at several time slices

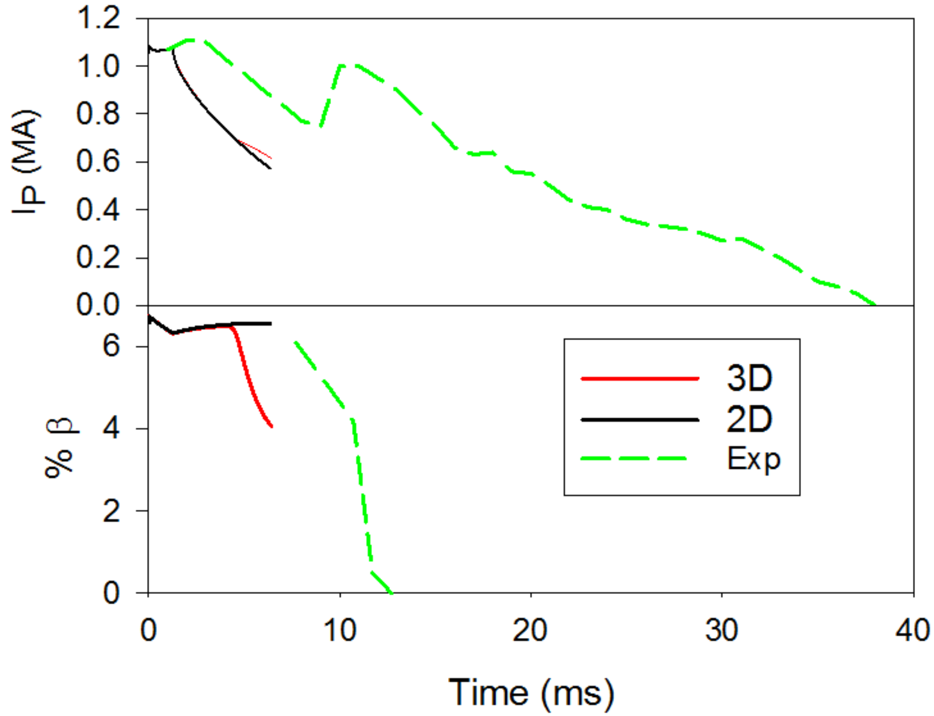


Same color scale for all times.   Same patter, just grows.

Perturbed pressure and currents at time of saturation are very similar for 32 plane and 64 plane cases



(approx) comparison with experiment



Experimental comparison not exact:

- Did not try and match Te profile
- Simulation used idealized V_L reversal
- Did not use realistic vessel

However:

- Fair agreement for initial I_P decay rate
- Fair agreement for initial β decay rate

Remaining issues:

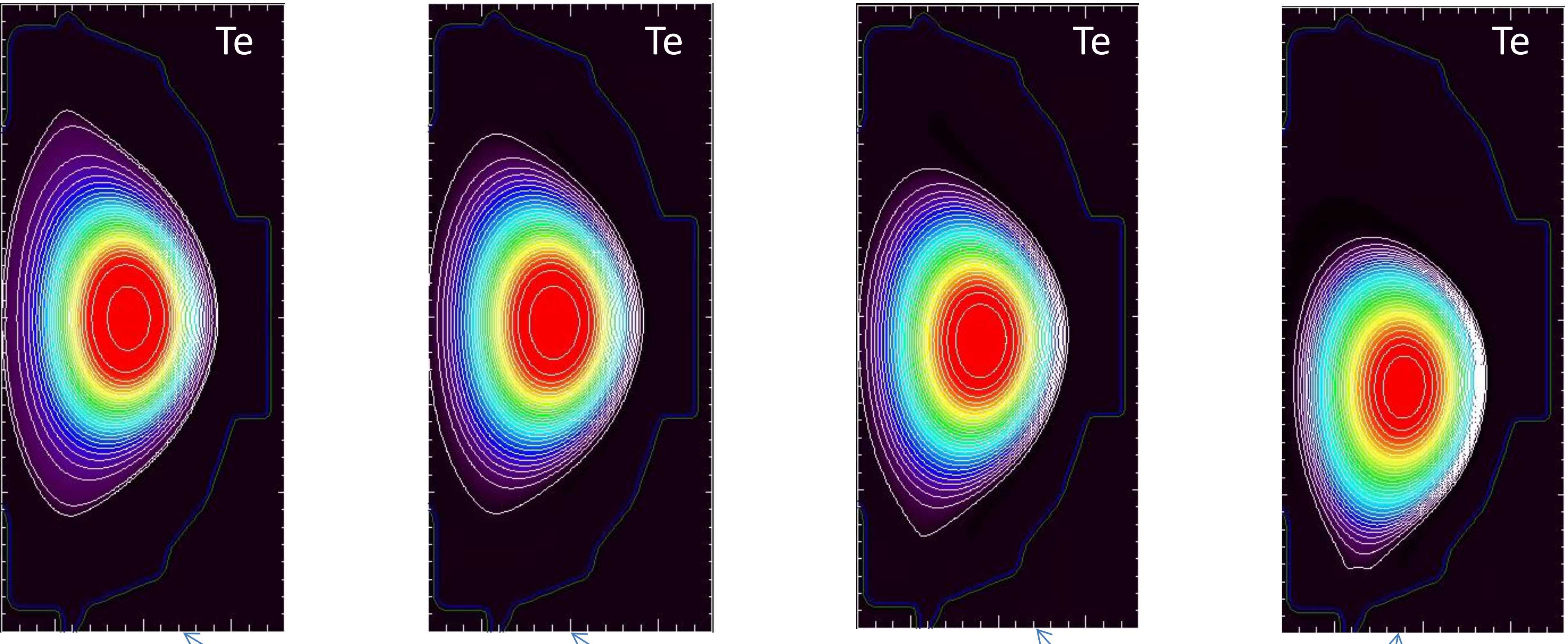
- Can we reproduce current spike?
- Can we reproduce later rapid β drop?
- Need to dissipate short toroidal wavelengths in simulation
- Hyper-resistivity?
- Long running time for 40 ms

Future Plans

- Improve preconditioner to allow larger time steps for runs with high toroidal resolution
- Investigate the effect of hyper-resistivity during the current ramp-down.   Can we get a current spike?
- Can we reproduce the rapid thermal quench? Is impurity radiation required?
- Determine what is an acceptable current ramp-down rate to avoid rapid thermal quench?   Compare with experimental result.

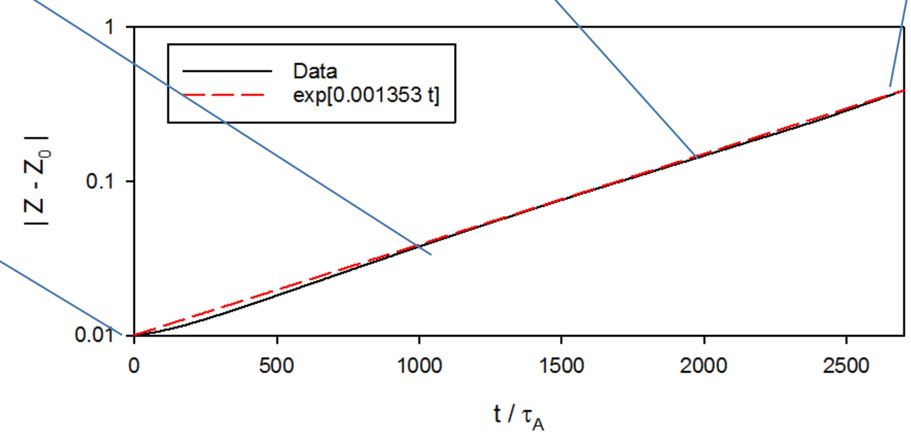
VDE

NSTX Shot 132859 η_W=0.00025



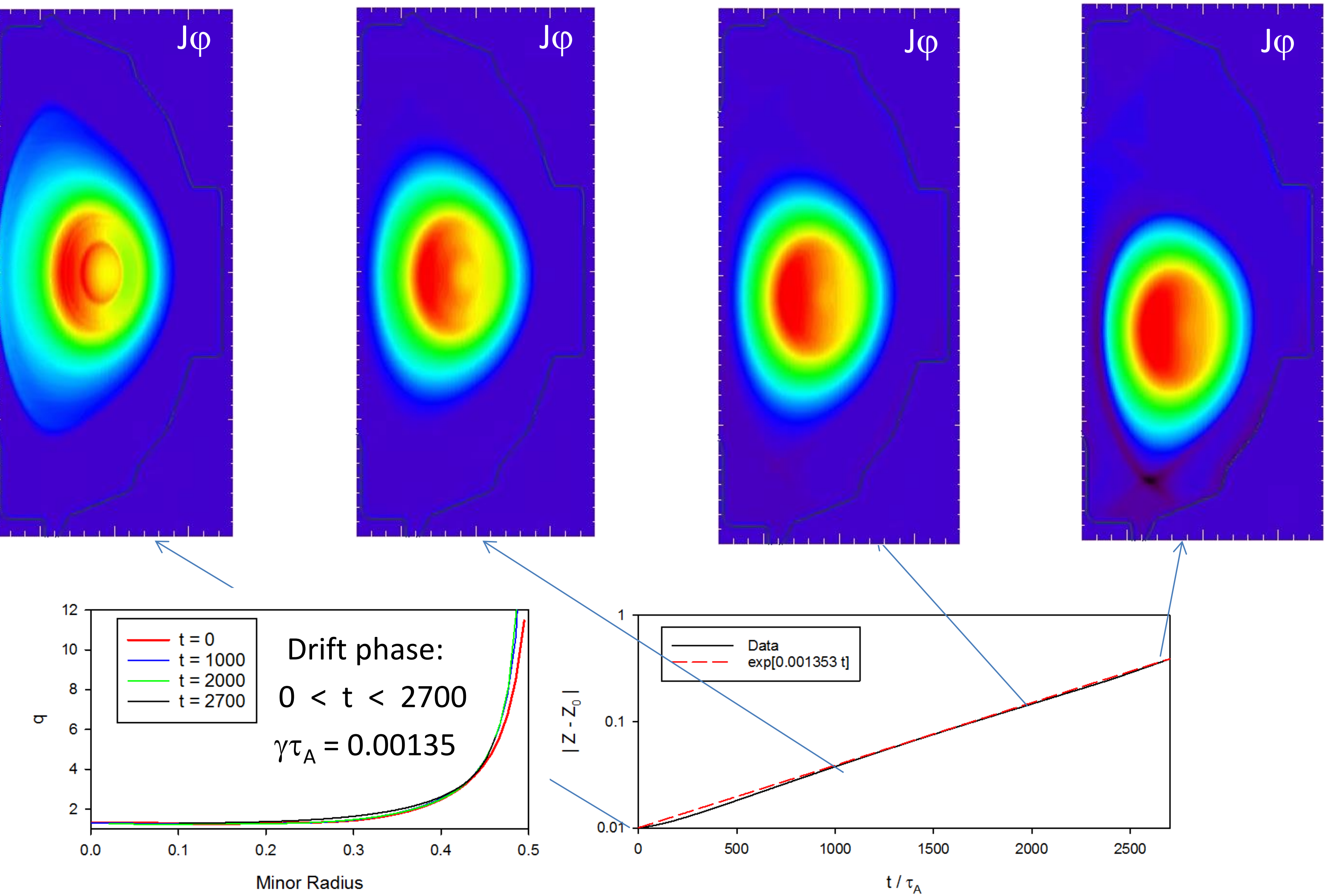
Drift phase:

$0 < t < 2700$

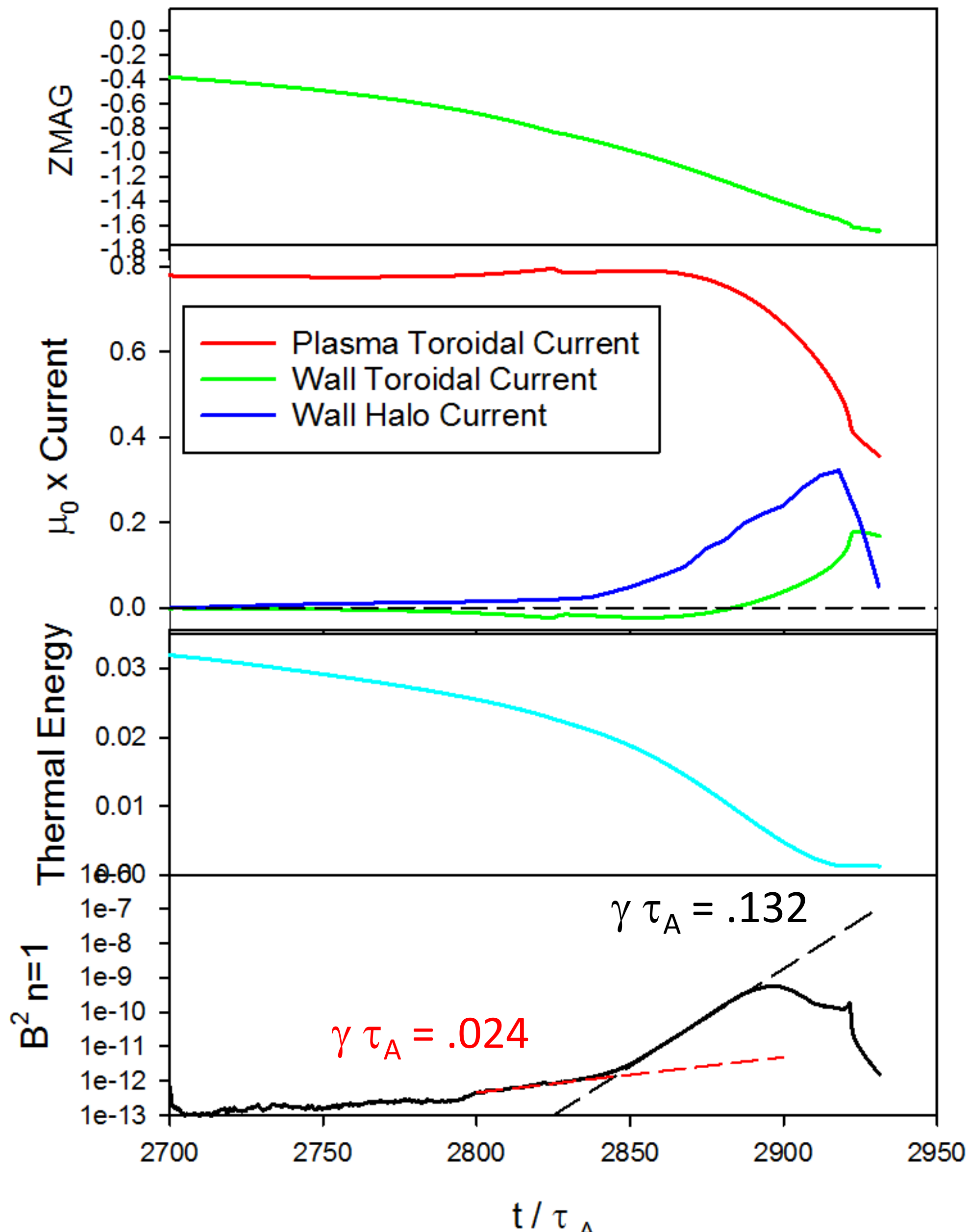


$\gamma\tau_A = 0.00135$

NSTX Shot 132859 η_W=0.00025

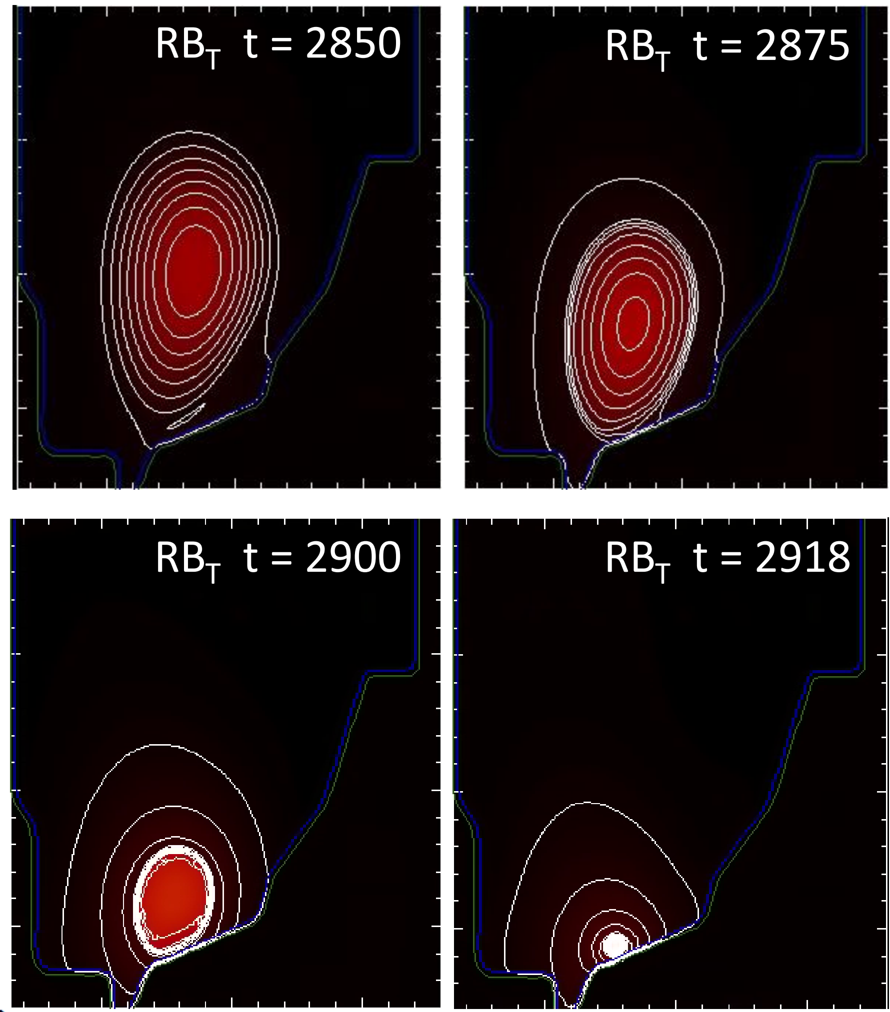


NSTX Shot 132859 η_W=0.00025



Disruption phase 2700 < t < 2950

Contours of RBT show halo currents

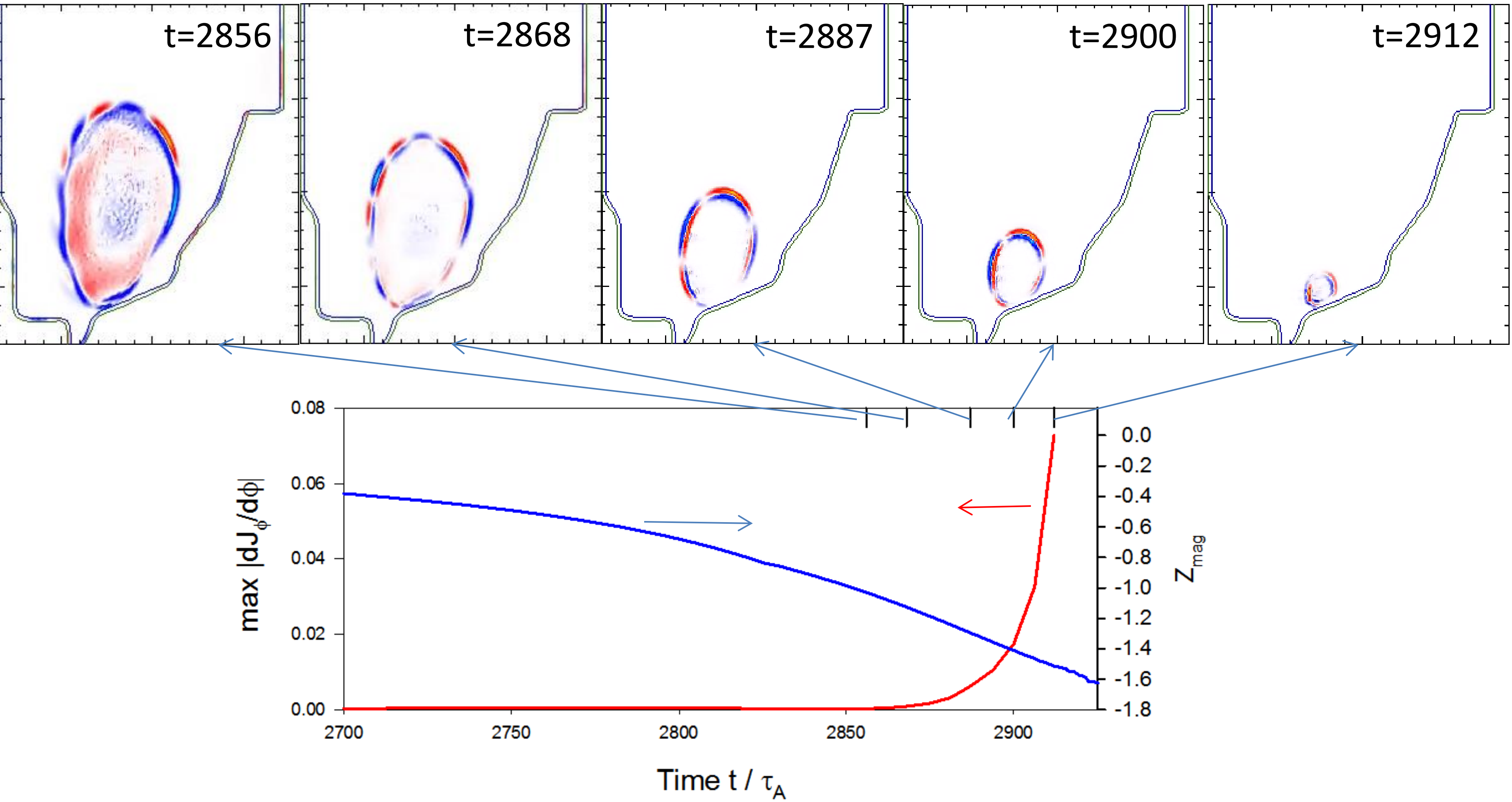


NSTX Shot 132859 η_W=0.00025

$$\partial(RJ_\varphi)/\partial\varphi$$

Disruption phase 2700 < t < 2950

Magnitude of the toroidal derivative of the toroidal current at one poloidal plane at the 5 times shown. Each color scale is adjusted to maximum range.

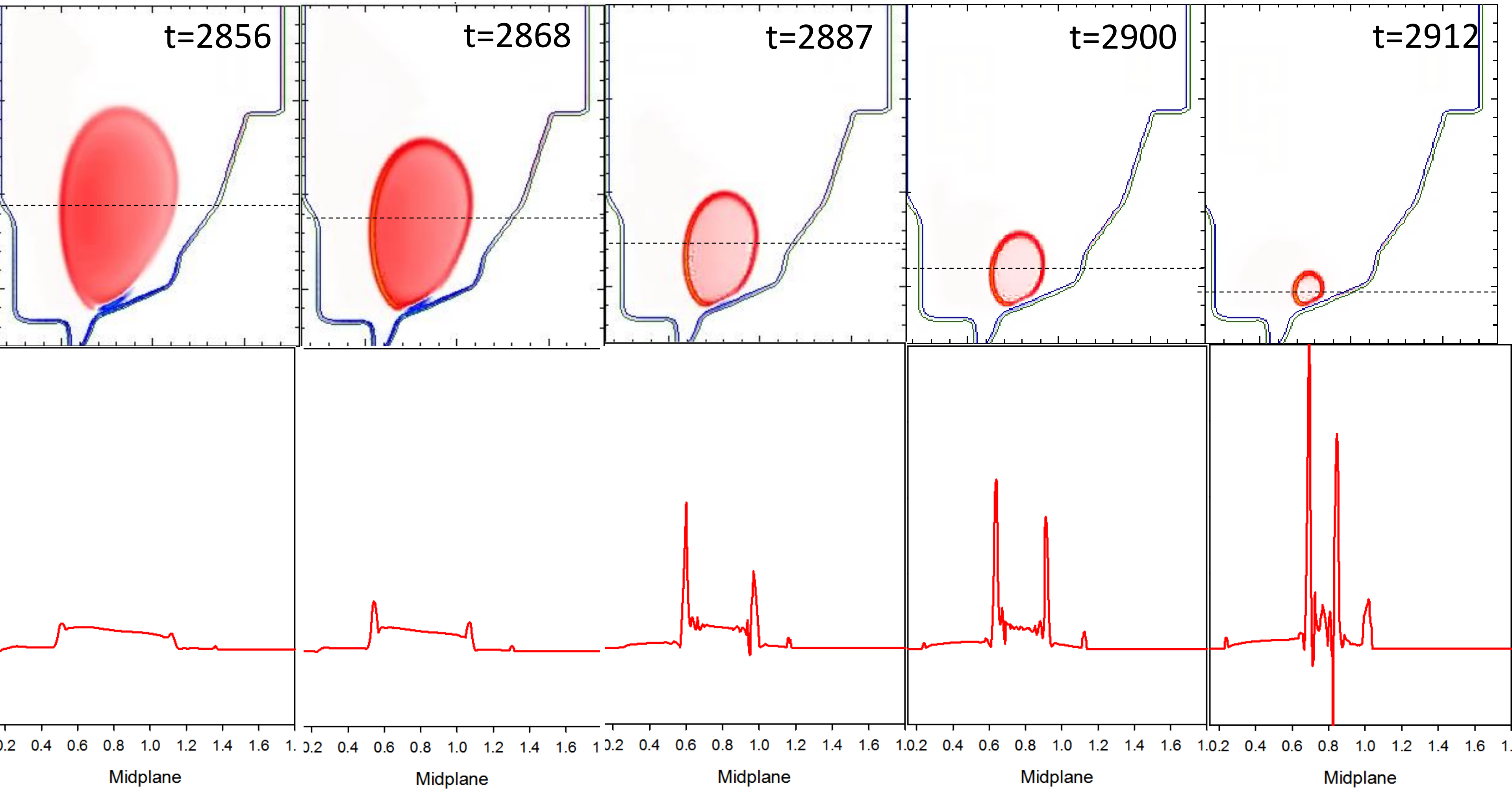


NSTX Shot 132859 η_W=0.00025

J_φ

Disruption phase 2700 < t < 2950

Top is magnitude of the toroidal current at one poloidal plane at the 5 times shown. Each color scale is adjusted to maximum range. Bottom is values along horizontal line of maximum current as shown.



NSTX Shot 132859 η_W=0.00025

Summary of first 3D M3D-C1 simulation of VDE in NSTX

- Plasma drifts downward with linear growth rate $\gamma\tau_A$ = 0.00135 for entire drift phase: $0 < t < 2700\ \tau_A$
- q-profile remains fixed during this phase and plasma nearly axisymmetric
- Slow n=1 mode with $\gamma\tau_A$ = 0.024 begins to grow at t=2800 τ_A (RWM?) and this mode accelerates to $\gamma\tau_A$ = 0.132 at t=2850 τ_A (external kink?)
- Wall current is initially negative (to repel plasma) and then becomes positive as plasma current decays. Halo currents begin to form at about at t=2825 τ_A when plasma makes contact with vessel.
- n=1 mode mostly external with m ~ nq. Continues to growth in amplitude until plasma disappears
- Strong shielding currents develop once plasma makes contact with vessel. Consequence of plasma staying hot in core until the end.

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Tech-X	Kruger	EHO, giant sawteeth, NTM, code performance
Utah State	Held	RSAE benchmark, NTM, giant sawteeth
U. Wisc.(EP)	Sovinec	Sheath bcs for VDEs, GS collab., ELM topics