M3D-C1 simulation of a NSTX disruption induced by rapid current ramp-down

Presented by S. C. Jardin
PPPL

Acknowledgments to:
Nate Ferraro (GA)
Brendan Lyons(GA)
Josh Breslau
Jin Chen
Guoyong Fu
Stefan Gerhardt
Stuart Hudson
Jesus Ramos (MIT)
Linda Sugiyama (MIT)
Isabel Krebs (IPP)
Seegyoung Seol (RPI)
Mark Shephard (RPI)
Fan Zhang (RPI)
Hank Strauss (HRS)

IEA Workshop:
Theory and Simulation of Disruptions
7/13/2015

PRINCETON
PLASMA PHYSICS
LABORATORY

outline

- Summary of experimental results
- M3D-C1 code
- M3D-C1 resistive wall capability
- NSTX shot 129922
- Numerical parameters and challenges
- Linear stability results
- 32 plane simulation results
- 64 plane simulation results and comparison
- Conclusions and future plans

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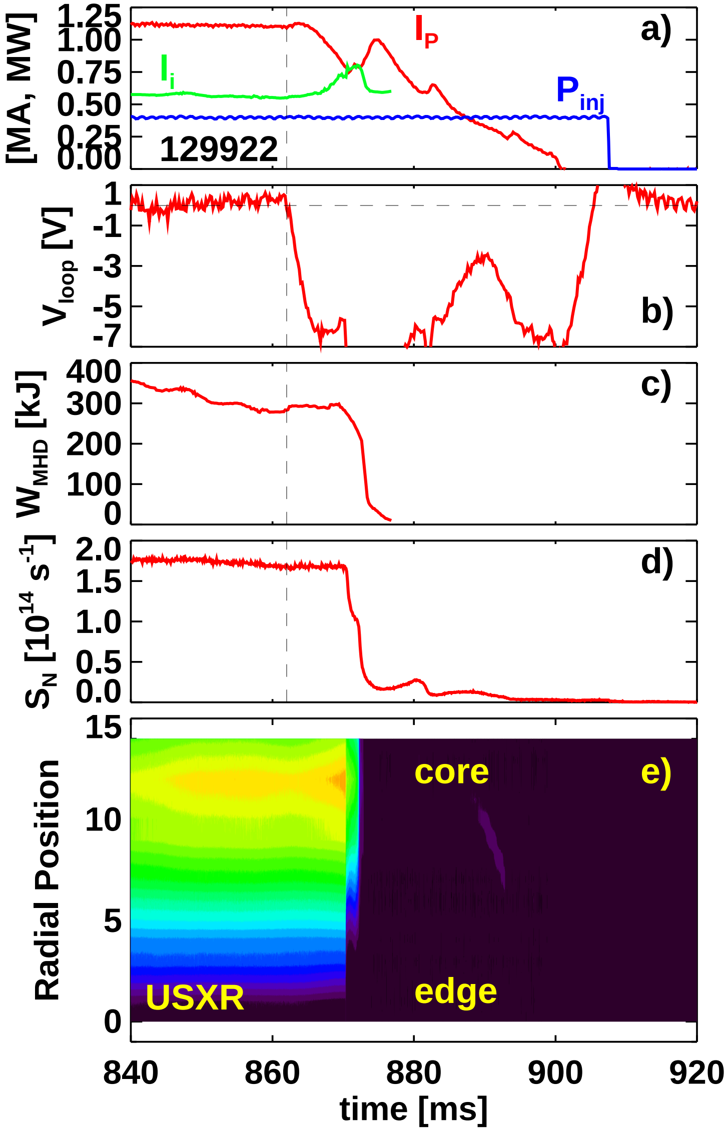
Unique Class of Major Disruptions Identified in NSTX

- 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]

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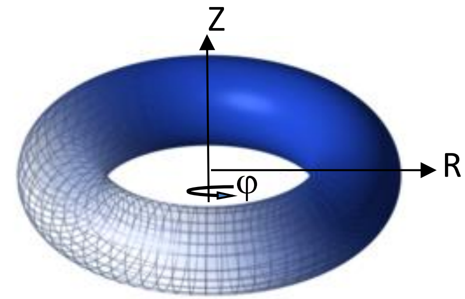
3D Extended MHD Equations in M3D-C1



$$\frac{\partial n}{\partial t} + \nabla \bullet (n\mathbf{V}) = S_n$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad \mathbf{B} = \nabla \times \mathbf{A} \qquad \mathbf{J} = \nabla \times \mathbf{B}$$

$$nM_i\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V}\right) + \nabla p = \mathbf{J} \times \mathbf{B} - \nabla \cdot \mathbf{\Pi}_i + \mathbf{S}_m$$

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{ne}\left(\mathbf{R_c} + \mathbf{J} \times \mathbf{B} - \nabla p_e - \nabla \cdot \mathbf{\Pi}_e\right) - \frac{m_e}{e}\left(\frac{\partial \mathbf{V}_e}{\partial t} + \mathbf{V}_e \cdot \nabla \mathbf{V}_e\right) + \mathbf{S}_{CD}$$

$$\frac{3}{2}\left[\frac{\partial p_e}{\partial t} + \nabla \cdot \left(p_e \mathbf{V}\right)\right] = -p_e \nabla \cdot \mathbf{V} + \frac{\mathbf{J}}{ne} \cdot \left[\frac{3}{2}\nabla p_e - \frac{5}{2}\frac{p_e}{n}\nabla n + \mathbf{R}_c\right] + \nabla\left(\frac{\mathbf{J}}{ne}\right) : \mathbf{\Pi}_e - \nabla \cdot \mathbf{q}_e + Q_\Delta + S_{eE}$$

$$\frac{3}{2}\left[\frac{\partial p_i}{\partial t} + \nabla \cdot \left(p_i \mathbf{V}\right)\right] = -p_i \nabla \cdot \mathbf{V} - \mathbf{\Pi}_i : \nabla \mathbf{V} - \nabla \cdot \mathbf{q}_i - Q_\Delta + S_{iE} \qquad \mathbf{V}_e = \mathbf{V}_i - \mathbf{J} / ne$$

$$\mathbf{R}_c = \eta ne\mathbf{J}, \qquad \mathbf{\Pi}_i = -\mu\left[\nabla \mathbf{V} + \nabla \mathbf{V}^\dagger\right] - 2(\mu_c - \mu)(\nabla \cdot \mathbf{V})\mathbf{I} + \mathbf{\Pi}_i^{GV} \qquad \mathbf{q}_{e,i} = -\kappa_{e,i} \nabla T_{e,i} - \kappa_\parallel \nabla_\parallel T_{e,i}$$

$$\mathbf{\Pi}_e = (\mathbf{B} / B^2)\nabla \cdot \left[\lambda_h \nabla\left(\mathbf{J} \cdot \mathbf{B} / B^2\right)\right], \qquad Q_\Delta = 3m_e\left(p_i - p_e\right) / \left(M_i \tau_e\right)$$

Kinetic closures extend these to include neo-classical, energetic particle, and turbulence effects.

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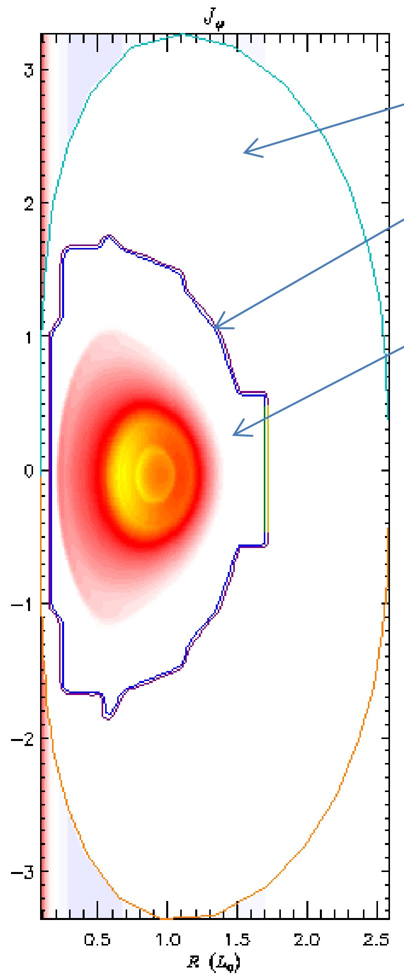
*M3D-C^1 has been extended to 3 regions for RW**



Vacuum (**J**=0)

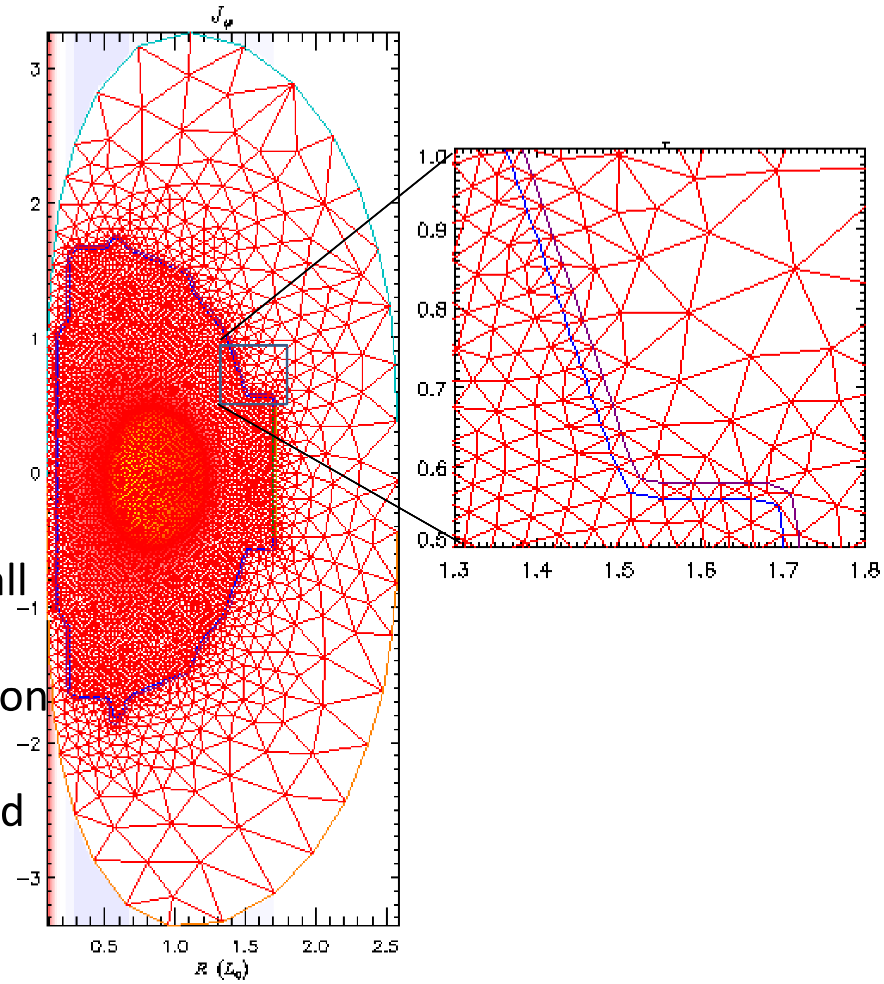
RW (**E** = η_W **J**)

Plasma (X-MHD)

BC:

- **v**, p, n set at inner wall
- **B** set at outer (ideal) wall

- No boundary conditions on **B** or **J** at the resistive wall
- Current can flow into and through the wall

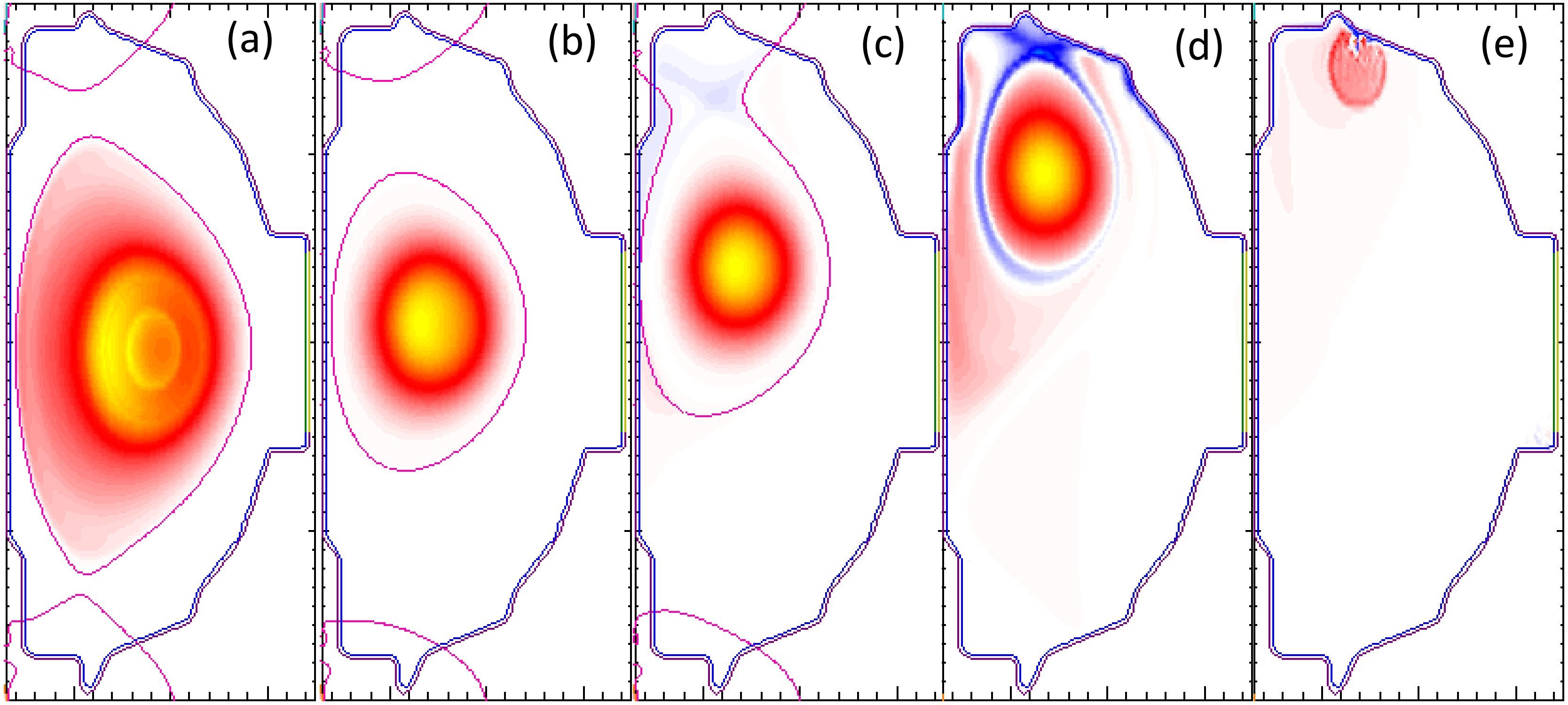


*Ferraro, APS and CEMM: 2014

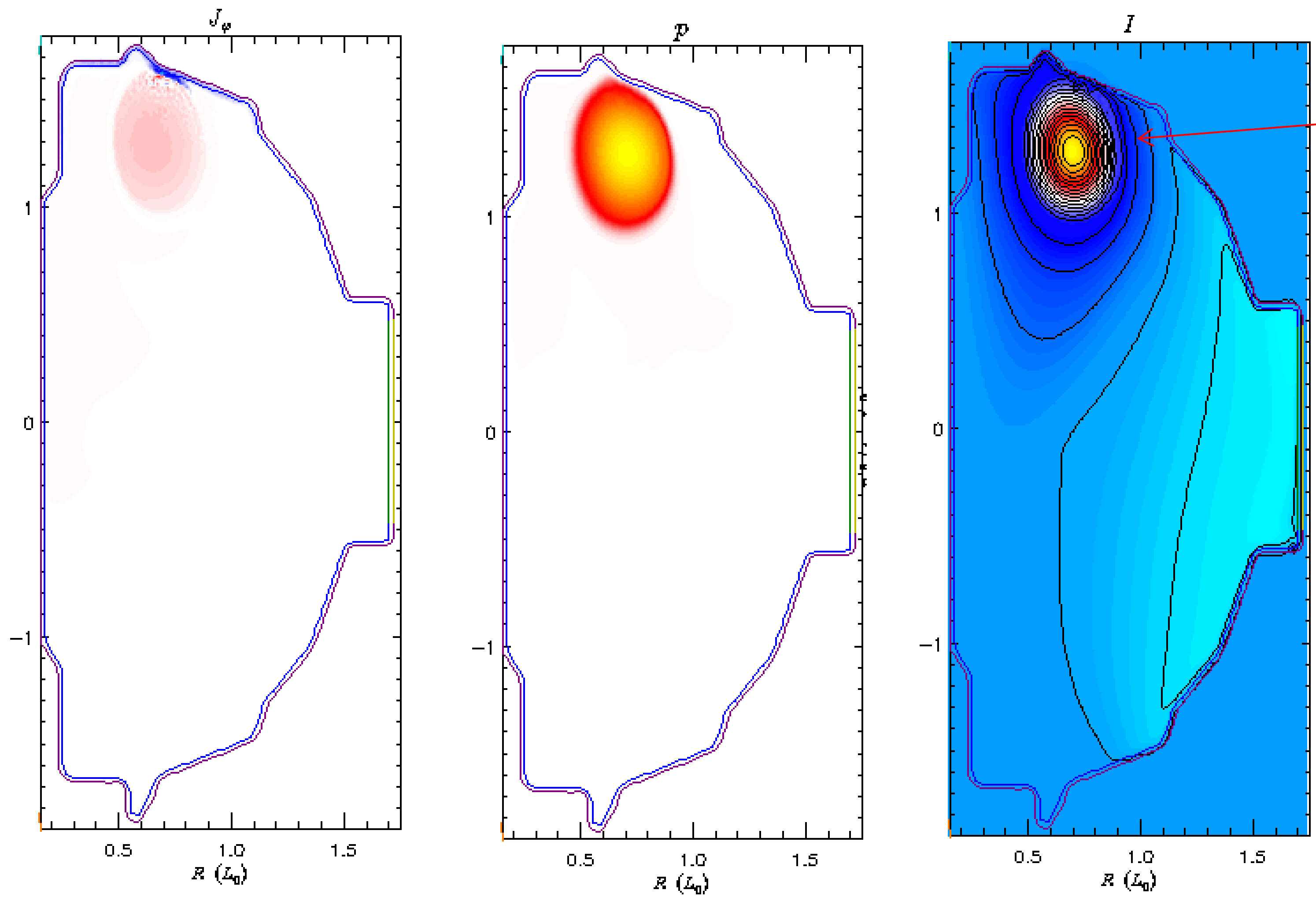
Initial simulation of VDE in NSTX with M3D-C[1]

- Initial results from 2D low-resolution calculation
- Both Positive and Negative (counter-current) currents are found
- Now extending these results to 3D and realistic η_W and 3D RWM

Toroidal current density at 5 times in VDE simulation

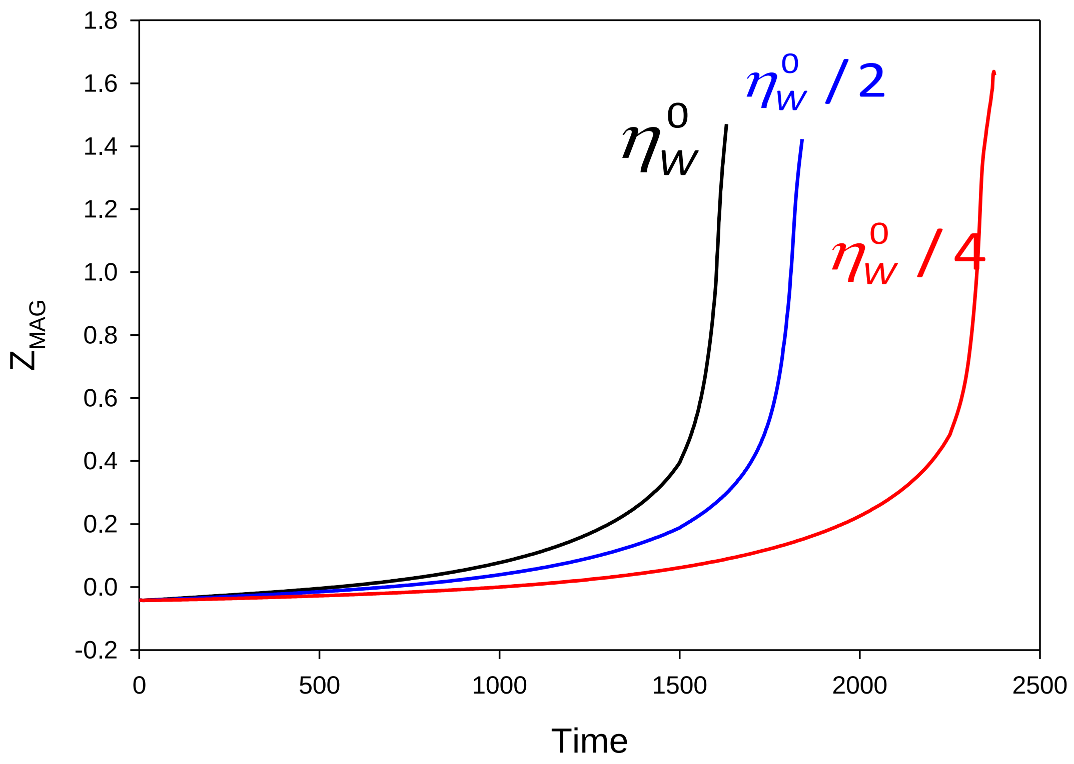


M3D-C^1 J_φ, p, and $I=RB_T$ at a late time



Note halo currents

Dependence of NSTX VDE on η_W



Growth rate scales inversely with wall resistivity η_W as expected

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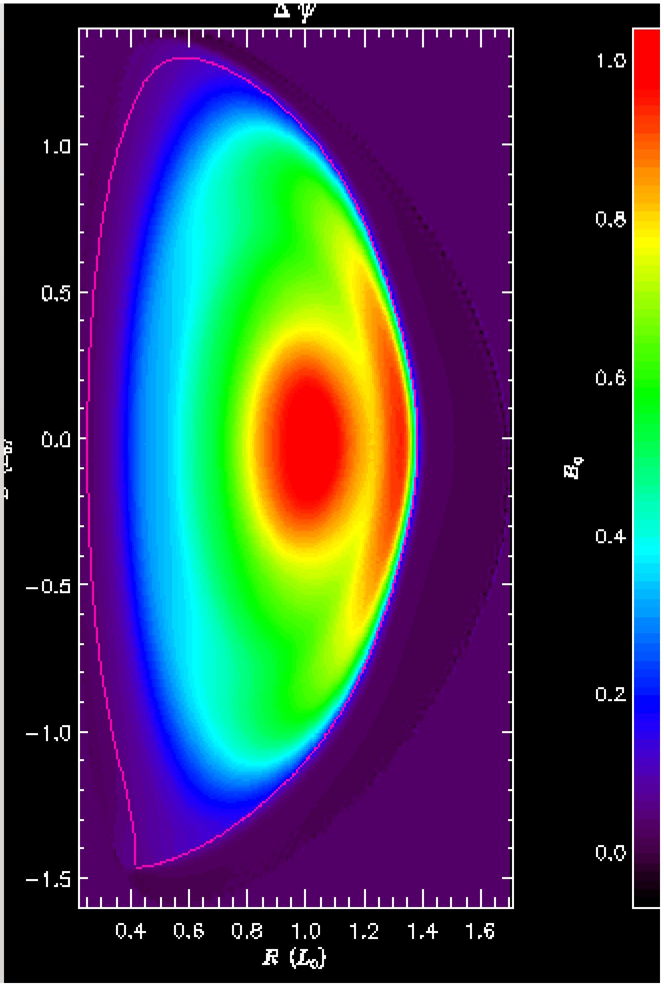
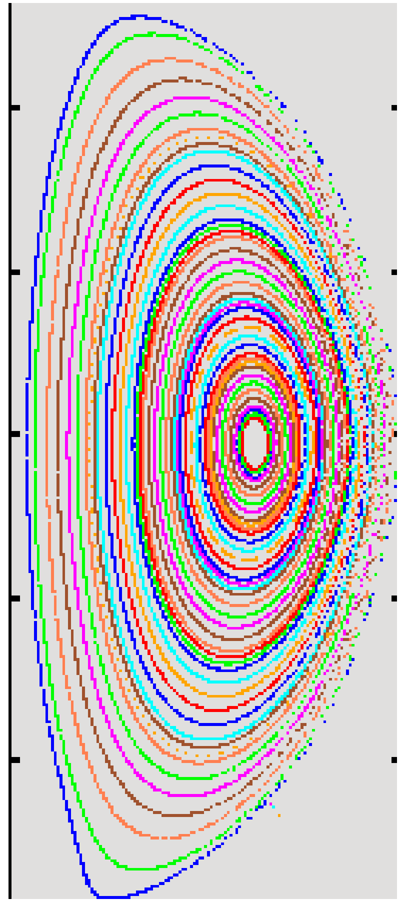
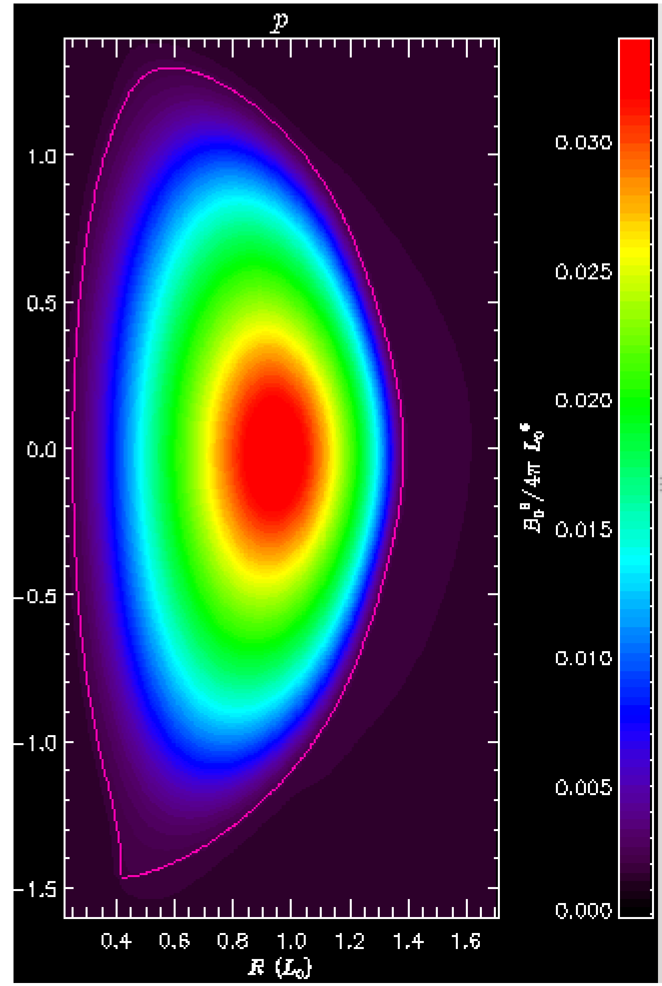
R J_φ



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

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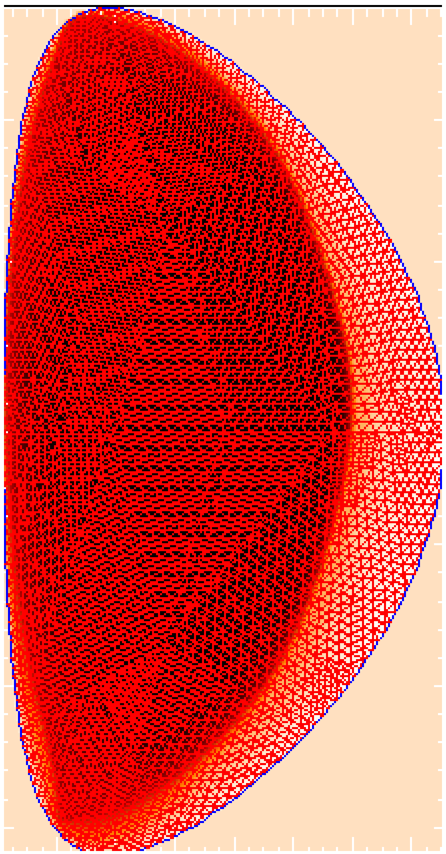
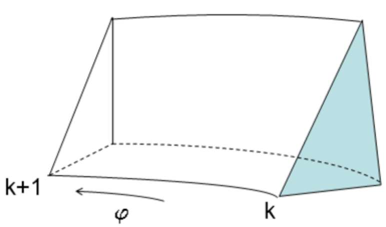
Numerical Parameters:

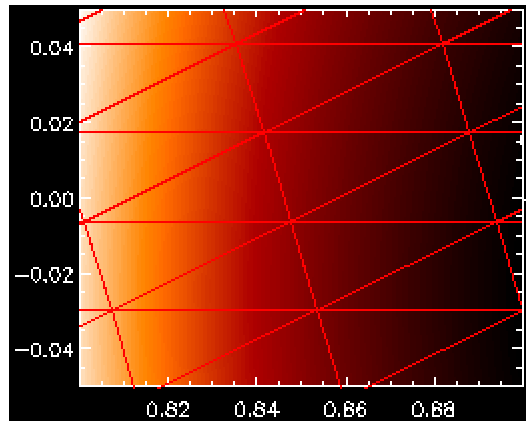
Entire domain





Triangular prism finite elements

10 cm x 10 cm patch



S = 10^7 (in center)

2D triangle size: 2 – 4 cm

32 and 64 toroidal planes

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

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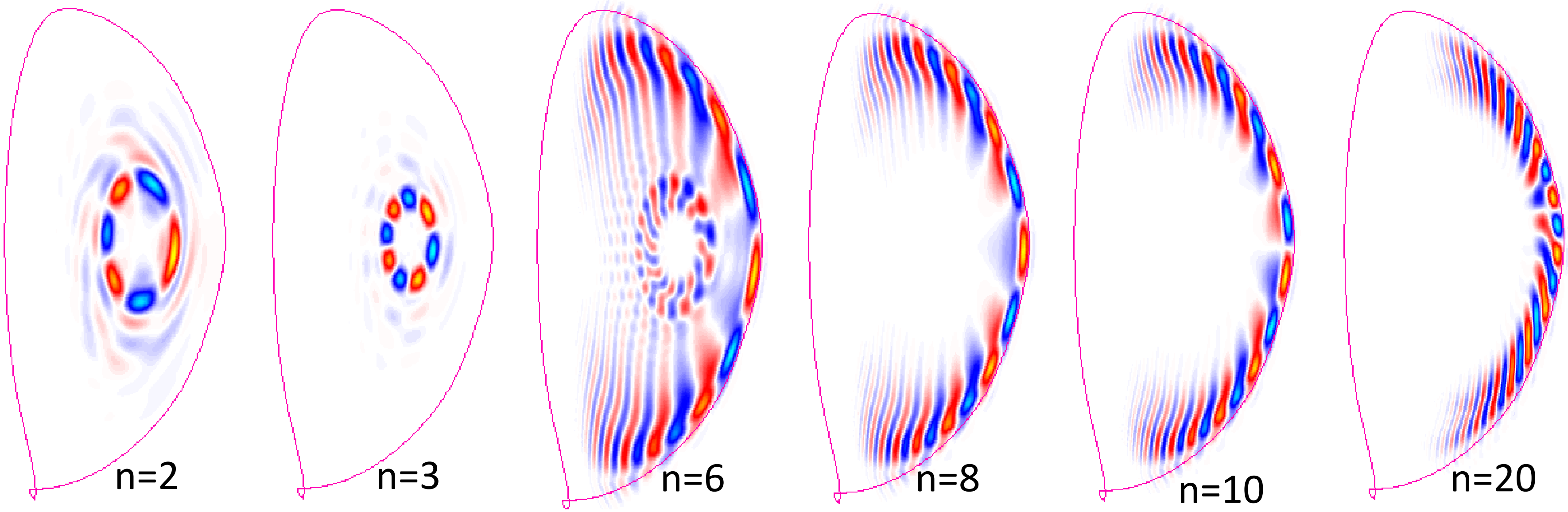
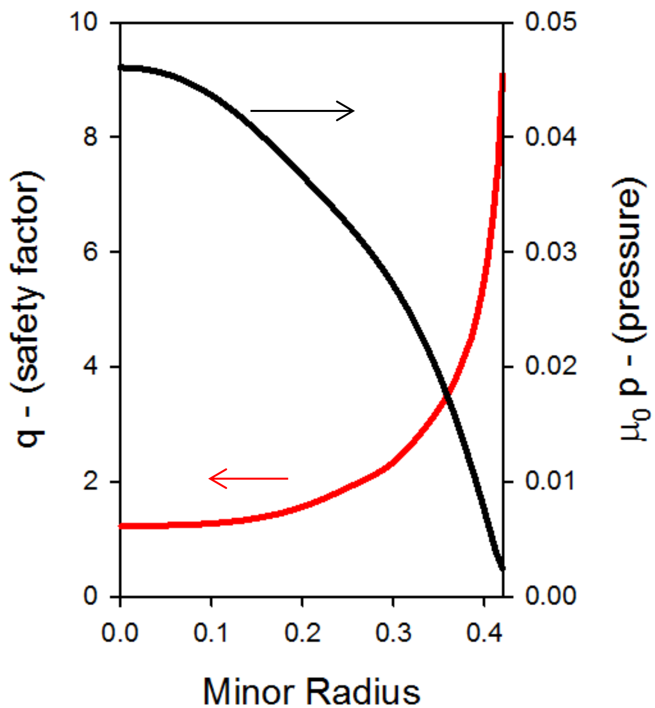
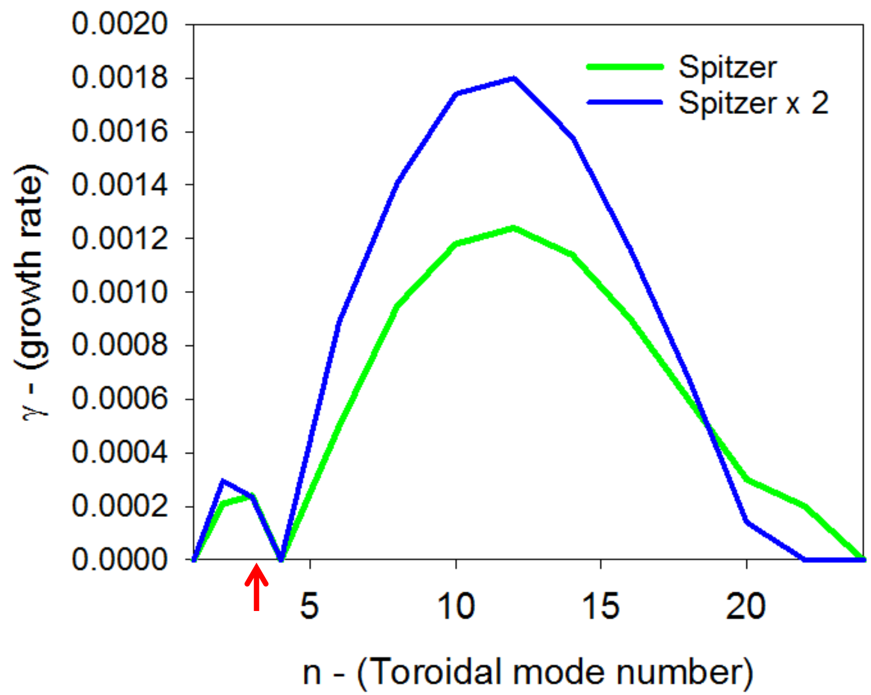
Linear stability shows many weakly unstable modes







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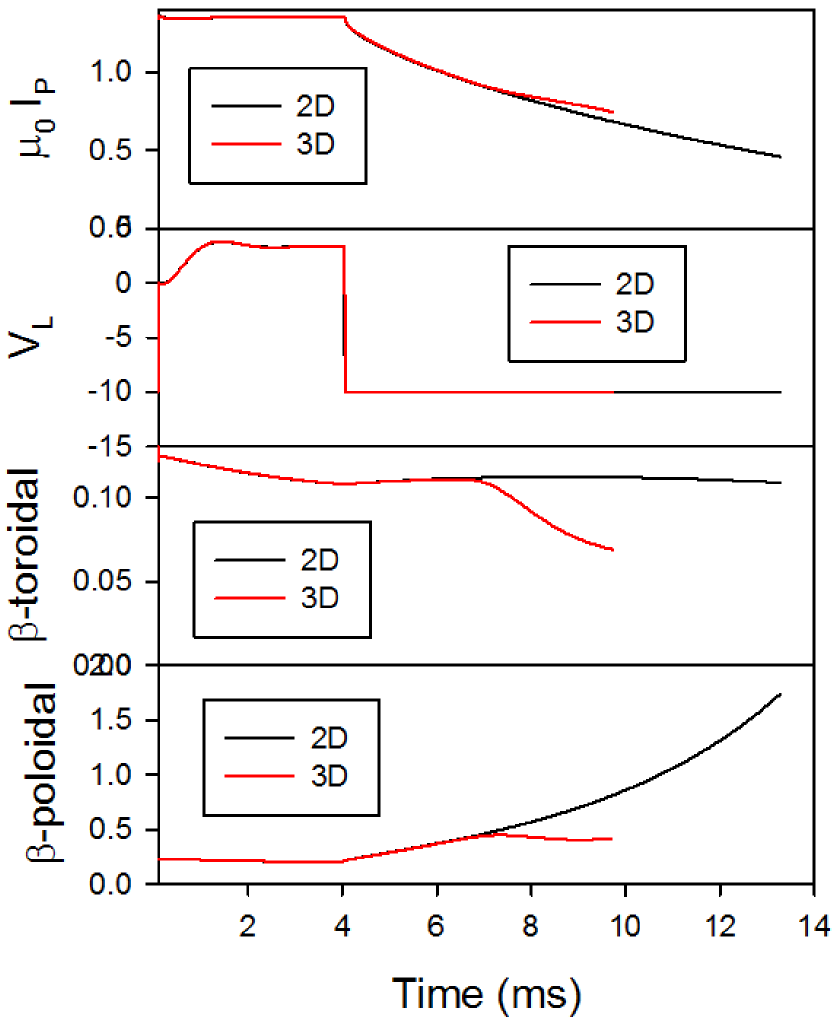
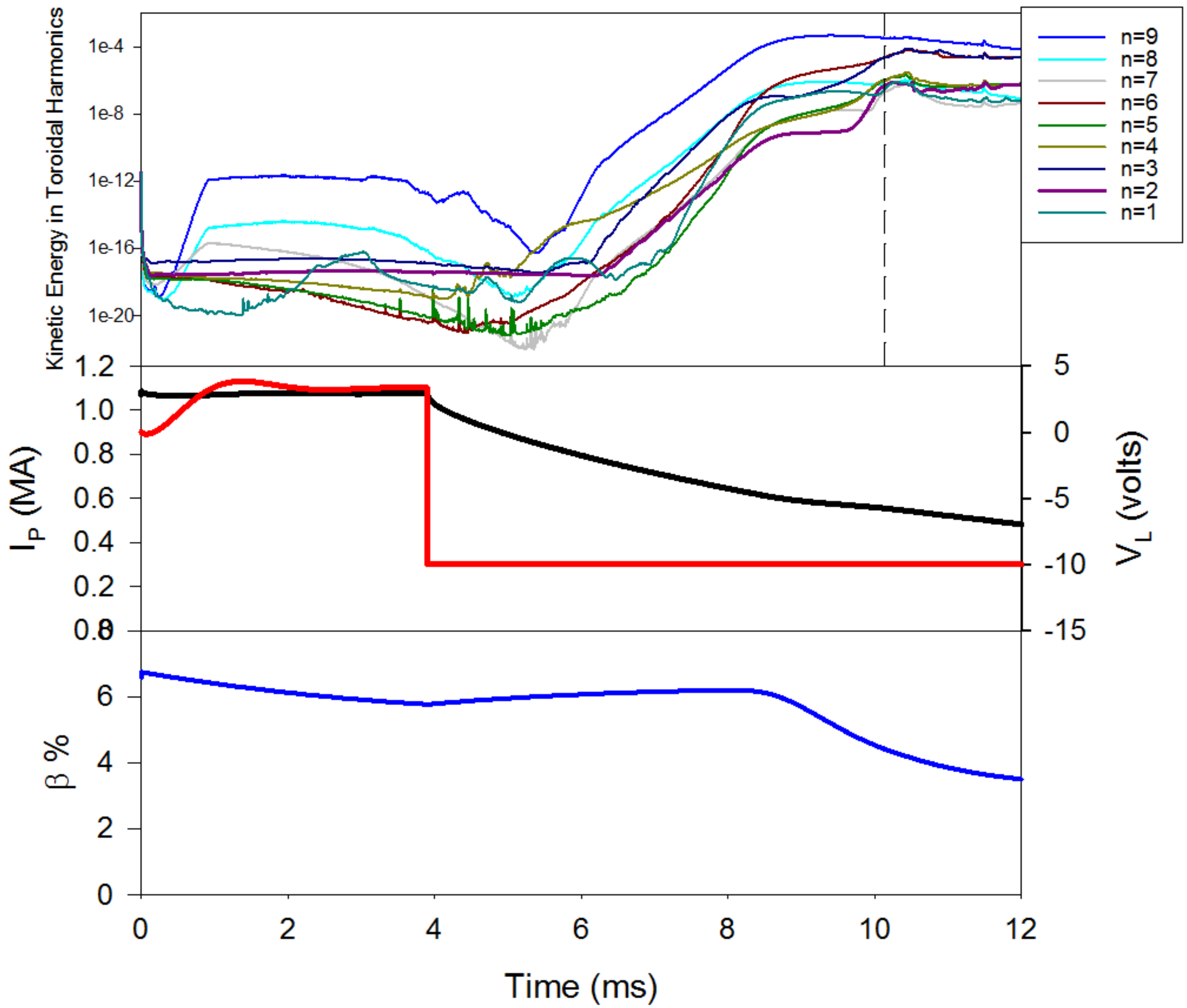
First (of 2) 3D M3D-C1 simulations



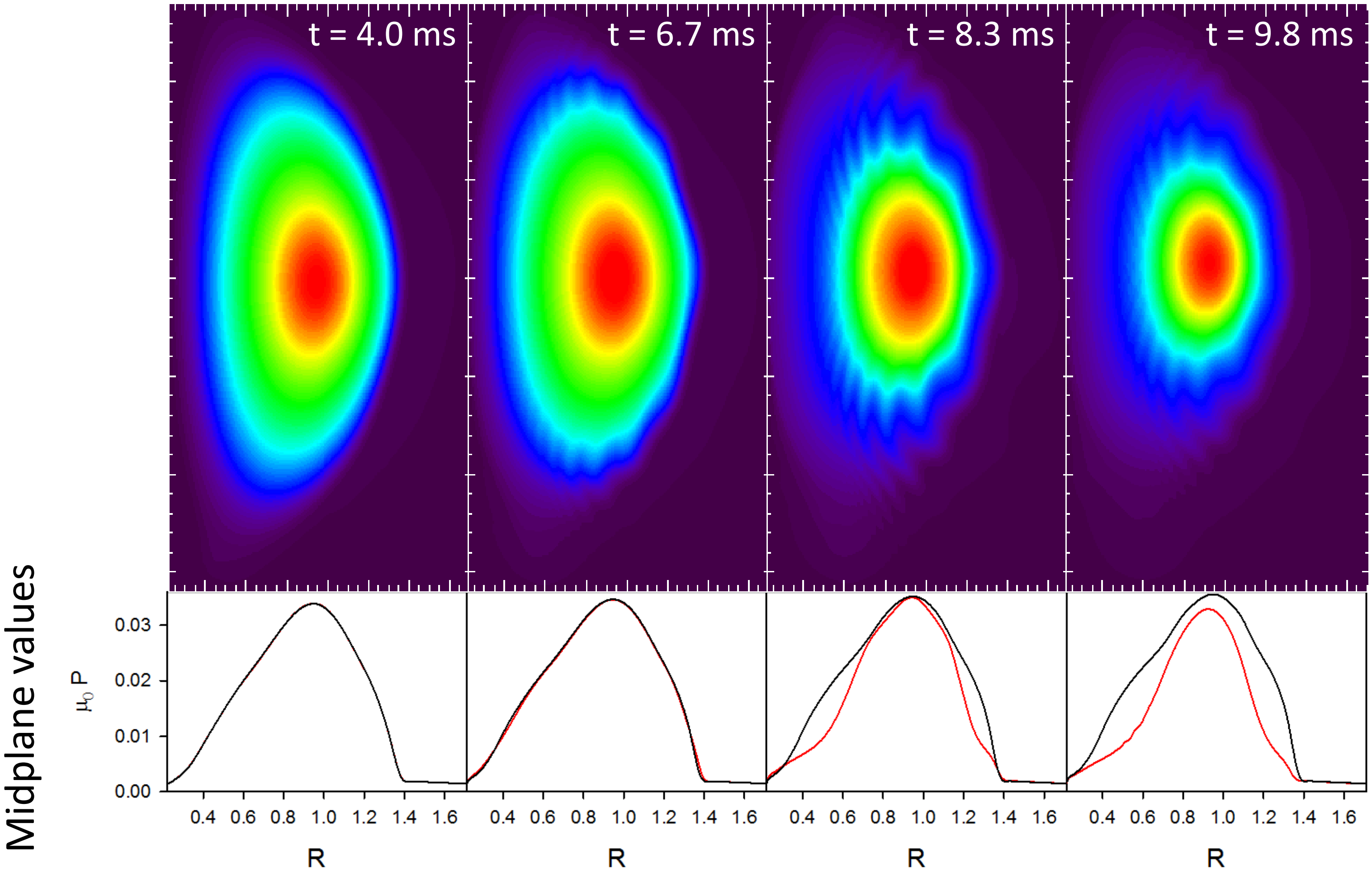
- 32 toroidal planes. Relatively large iteration tolerance
- Code was run in both 2D (axisymmetric) and 3D mode with near experimental parameters
- Difference in 2D and 3D behavior is due to 3D instabilities.
- Start of β collapse about 4 ms after V_L reversal.
- Some indication of (weak) current spike at start of β collapse
- Numerically resolved ???

Summary of first attempt (32 planes)



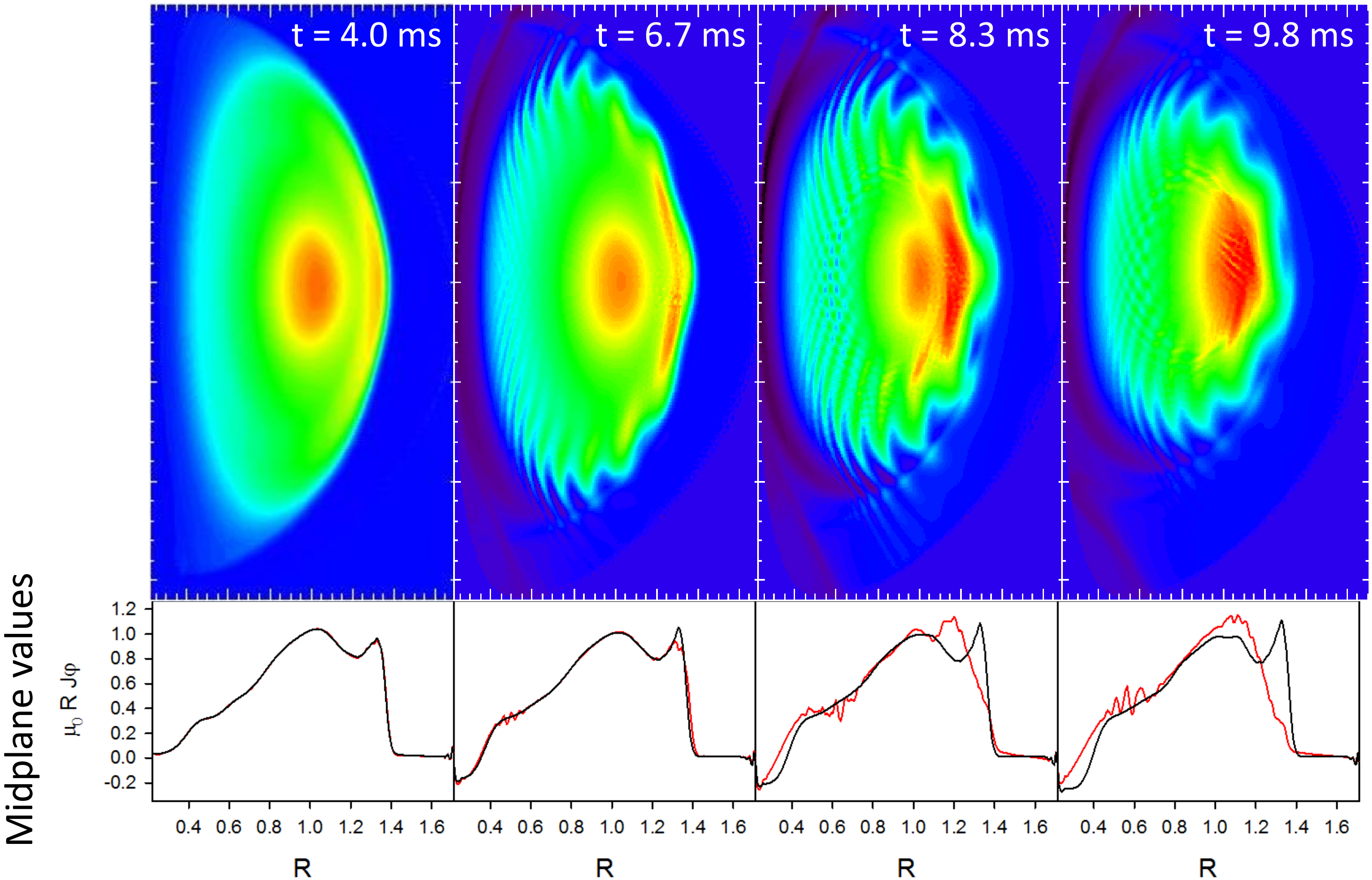
- Only have diagnostic plots for toroidal mode numbers 0-9
- Iteration convergence criteria for GMRES probably not sufficient to resolve very small amplitude modes (at beginning)
- At about 10 ms, short wavelength (gridscale) modes (in toroidal angle φ) start developing. Code still runs, but clearly not resolved.

Pressure Contours at select times (32 planes)



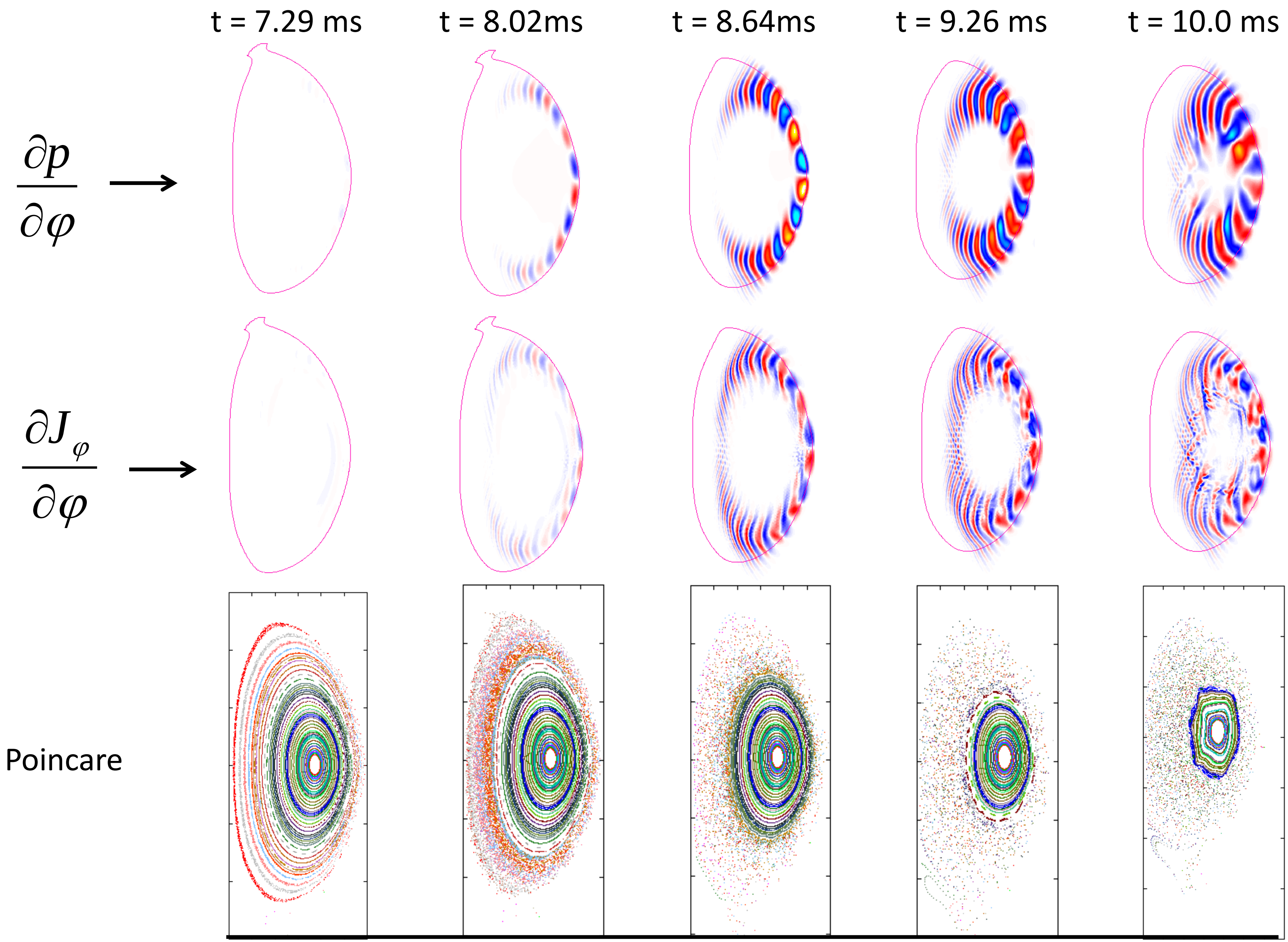
Pressure in 2D (black) and 3D (red) at 4 times

Current Contours at select times (32 planes)



Toroidal current density in 2D (black) and 3D (red) at 4 times

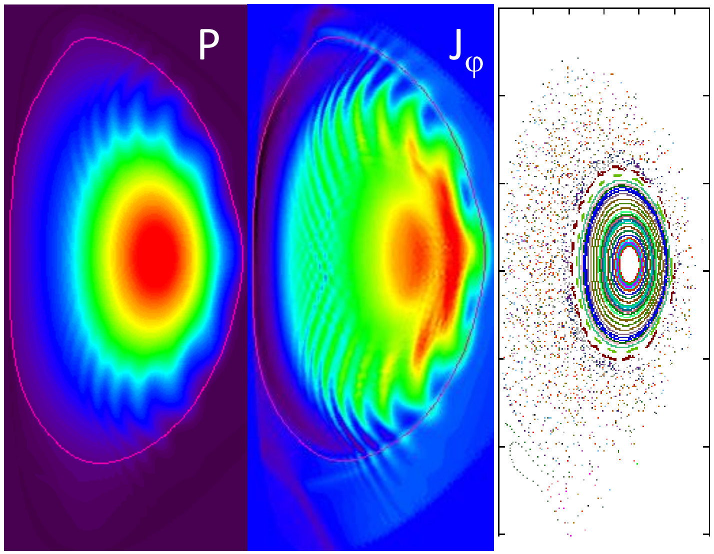
32 Planes



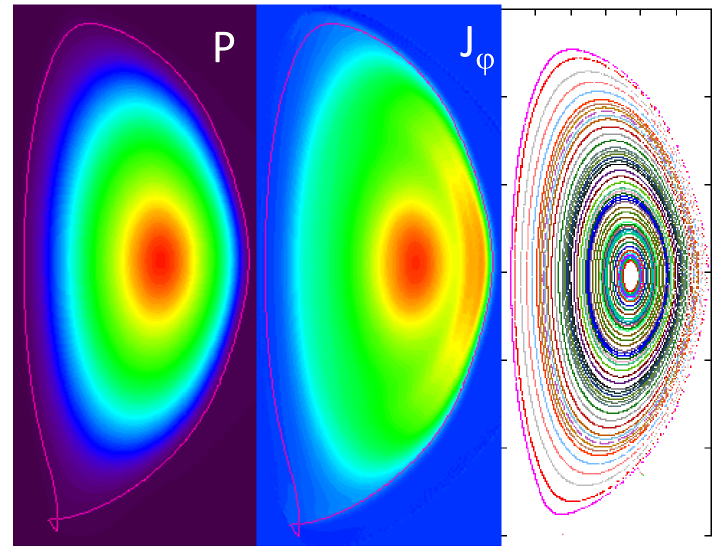
t = 7.29 ms
t = 8.02ms
t = 8.64ms
t = 9.26 ms
t = 10.0 ms
$\frac{\partial p}{\partial \varphi} \longrightarrow$
$\frac{\partial J_\varphi}{\partial \varphi} \longrightarrow$
Poincare

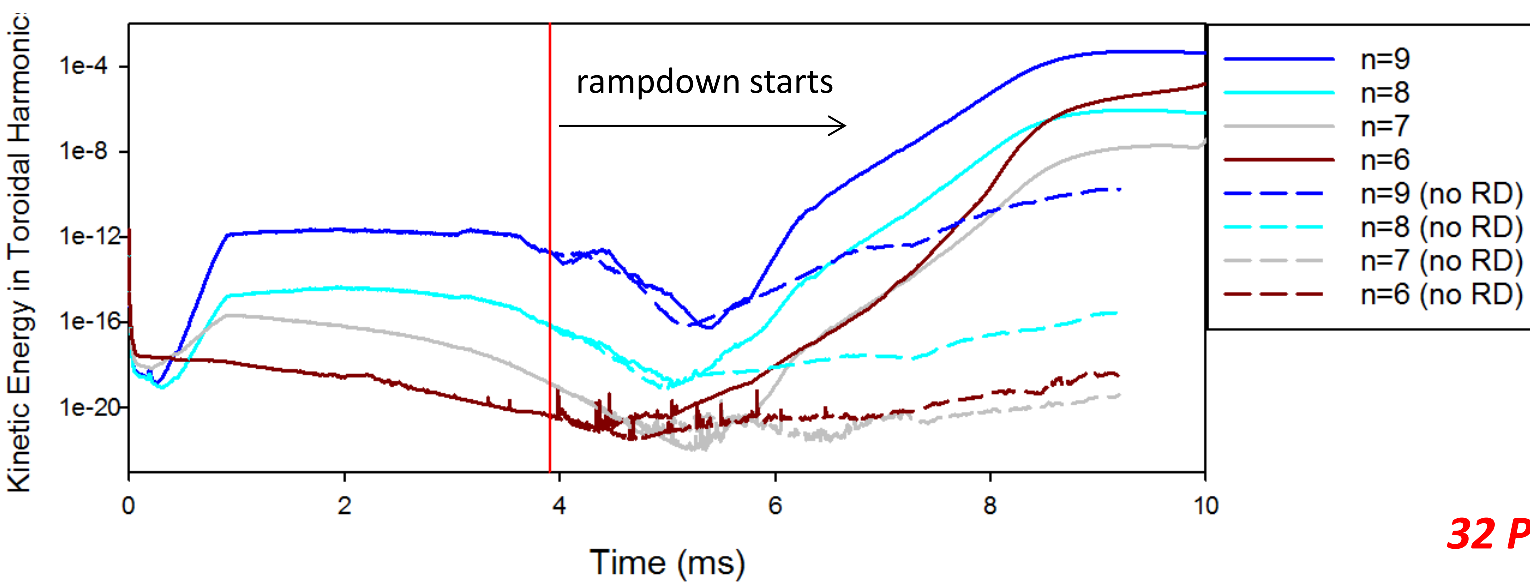
Comparison of plasmas at t=9.3 ms w and wo rampdown (RD)

with rampdown



with*out* rampdown





32 Planes

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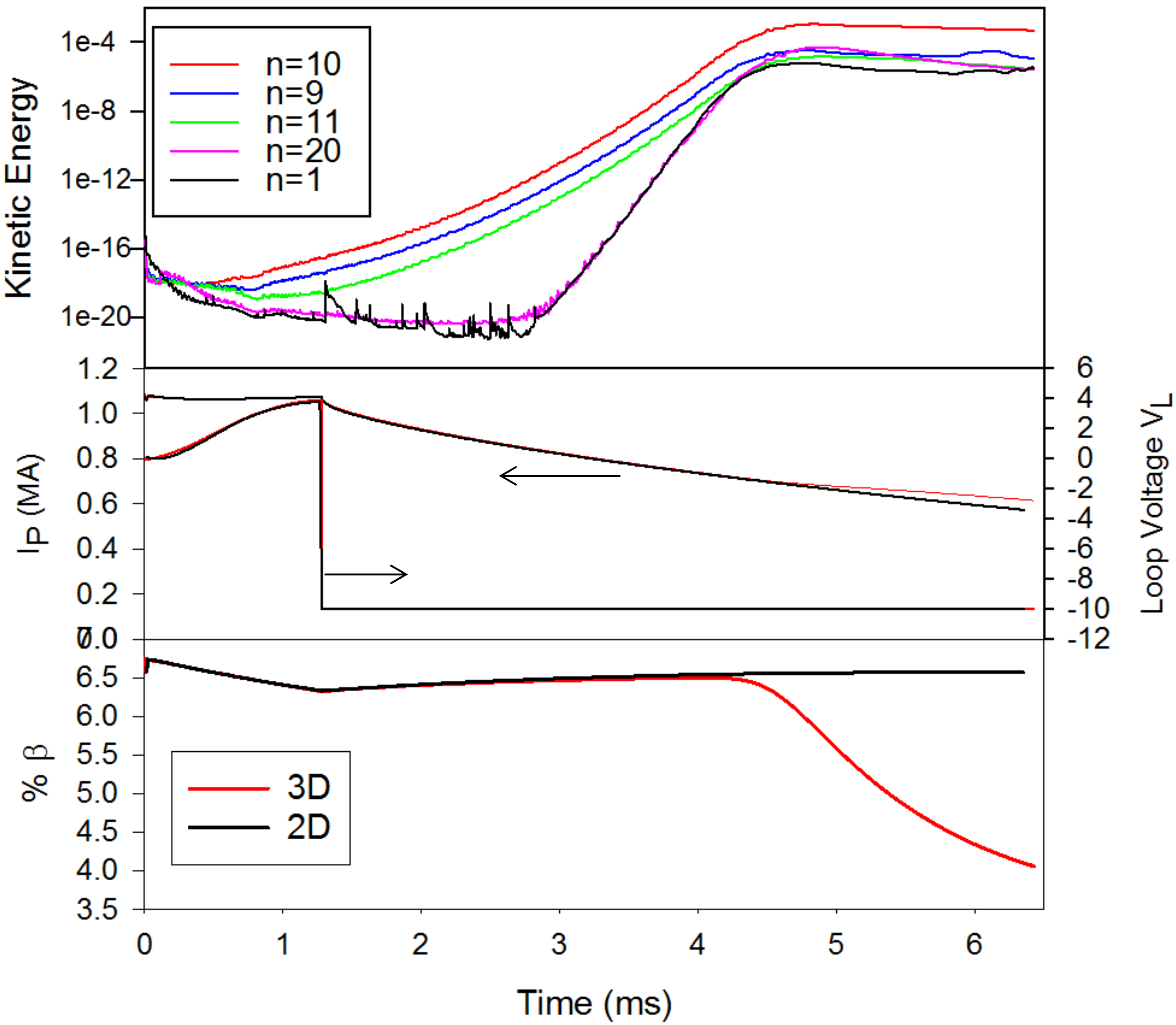
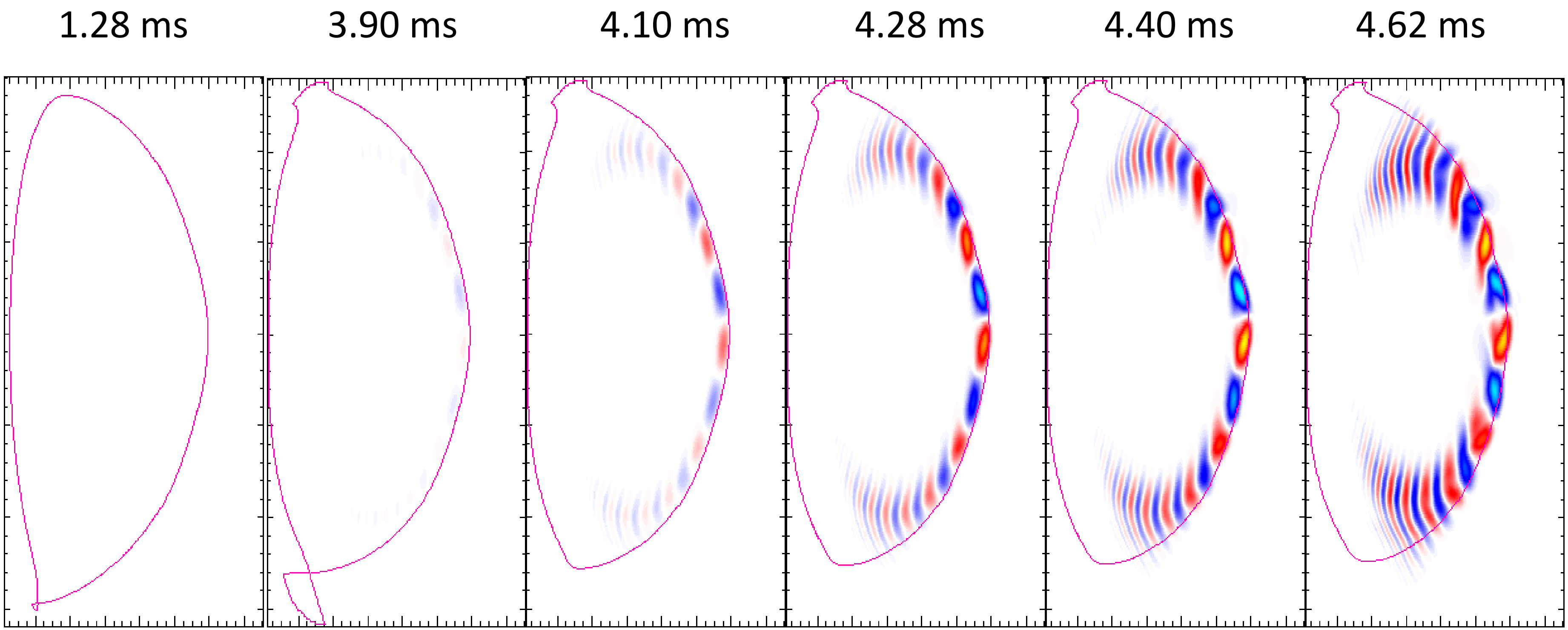
2nd run has 64 planes and more stringent convergence criteria



- 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

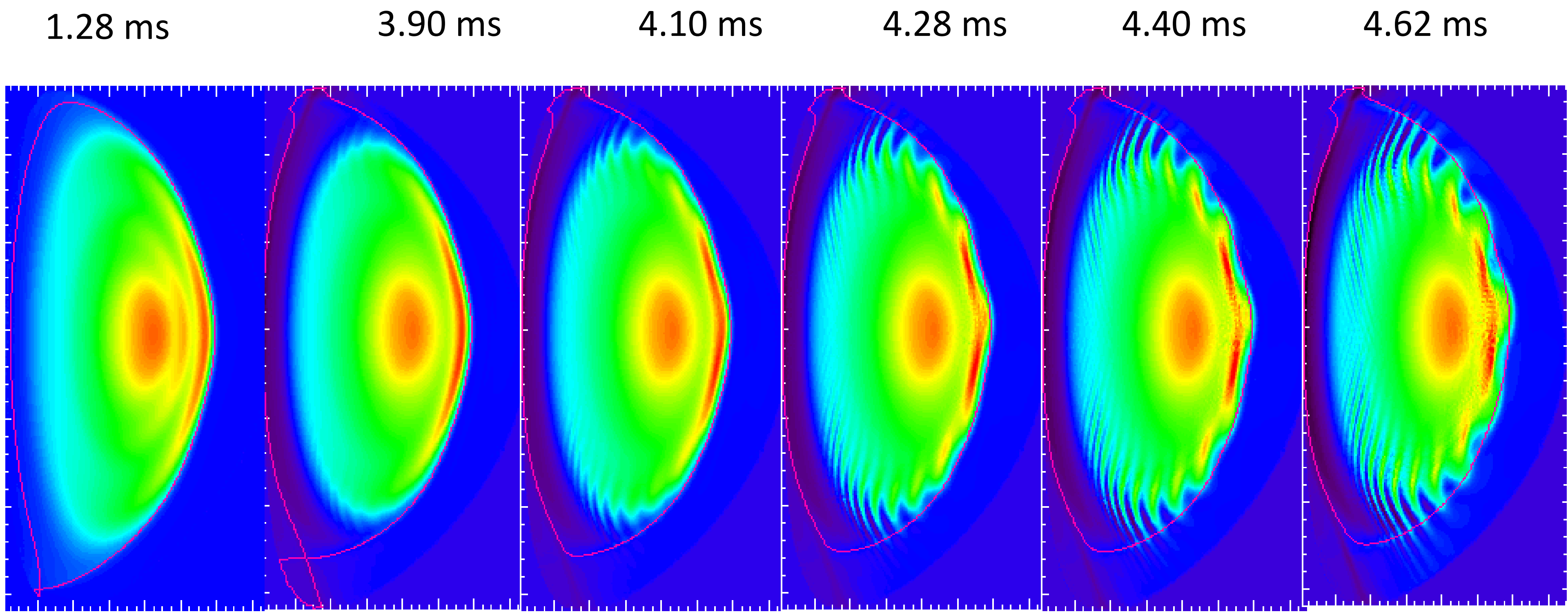
Same color scale:

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

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

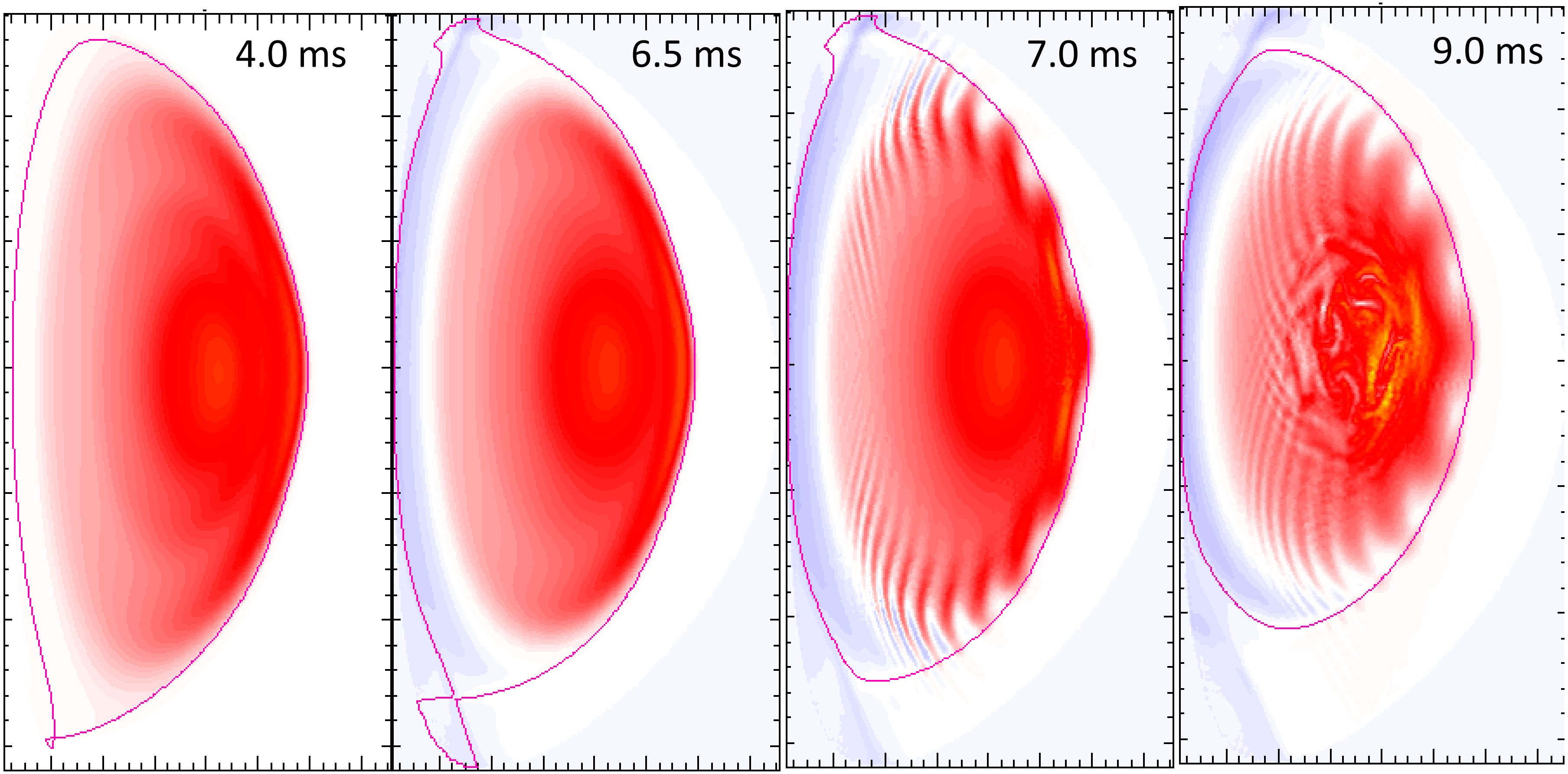
64 planes

Plasma current density at several time slices



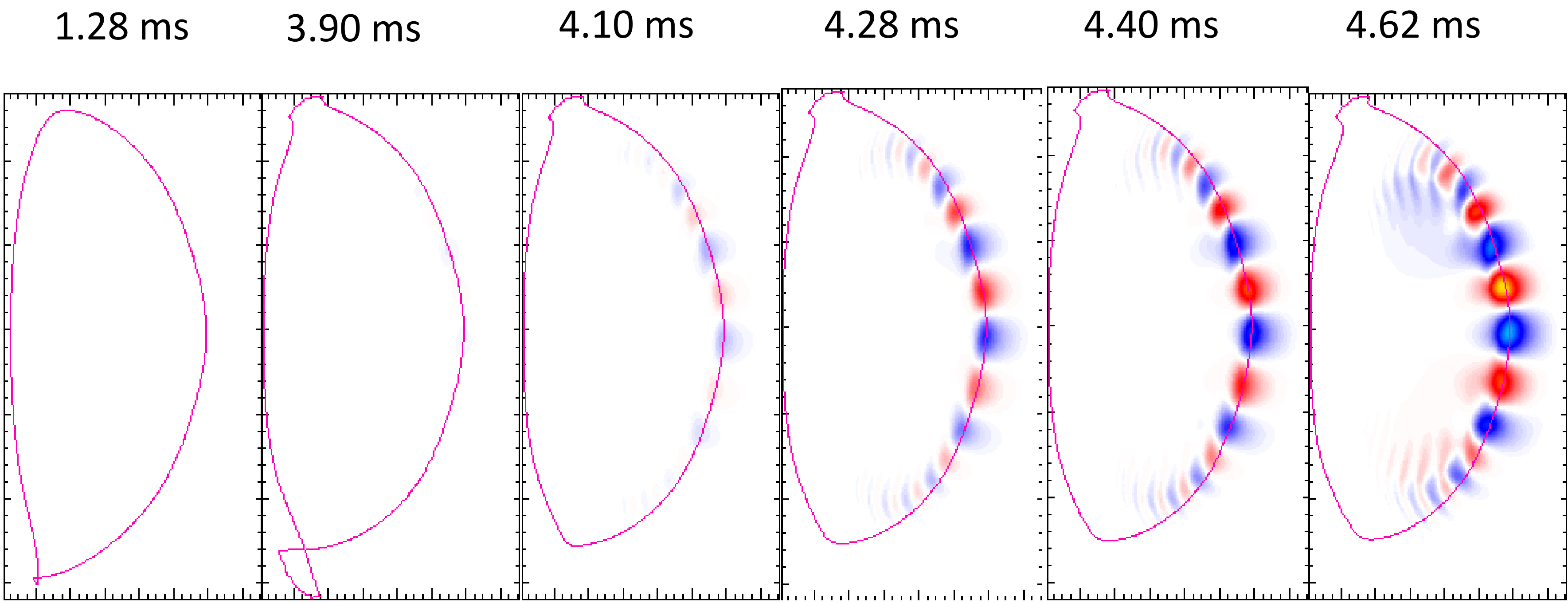
64 planes

Plasma current density at several time slices



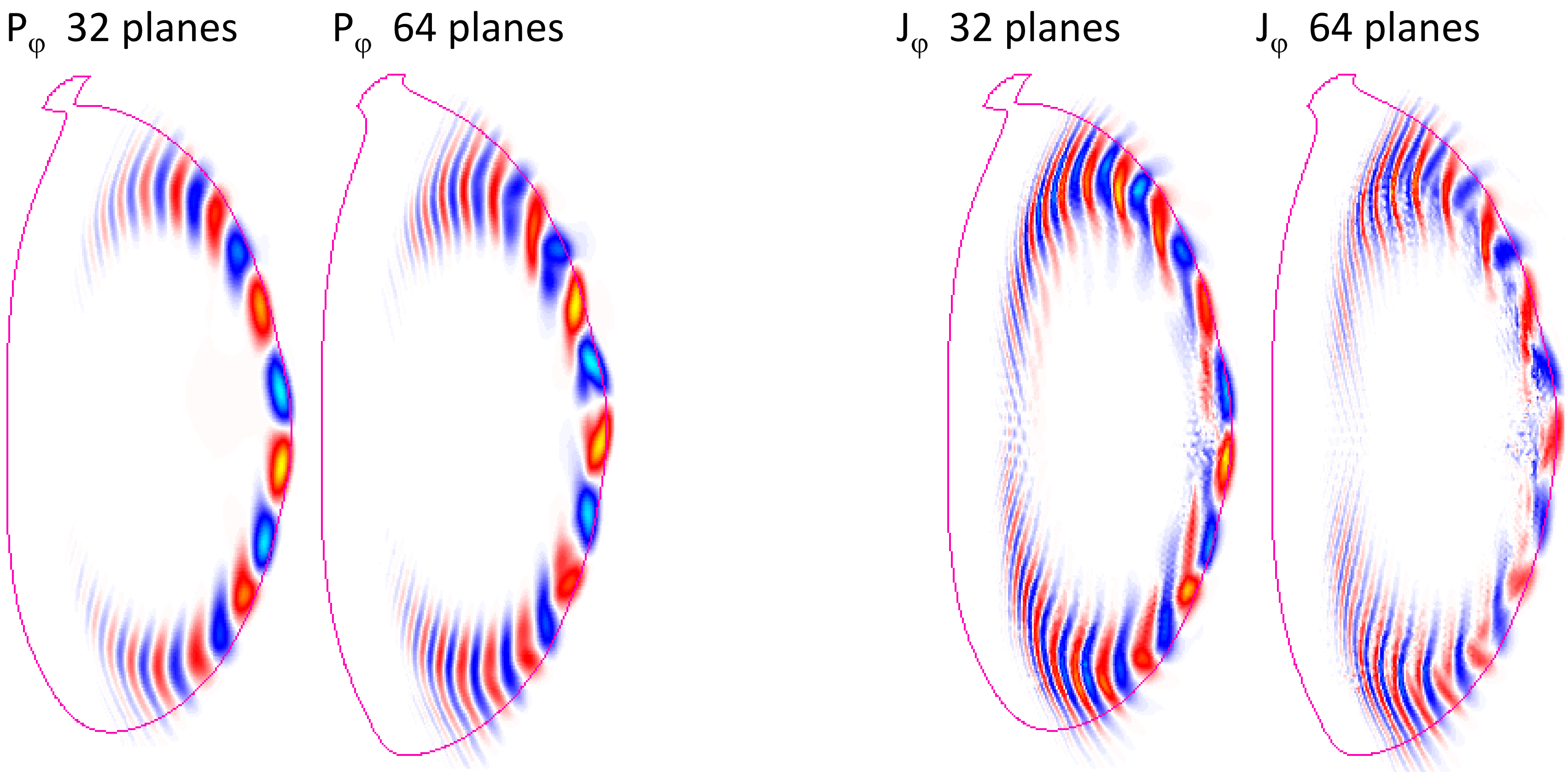
Different color scheme from previous viewgraph. Red and yellow are positive, blue is negative, zero is white.

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



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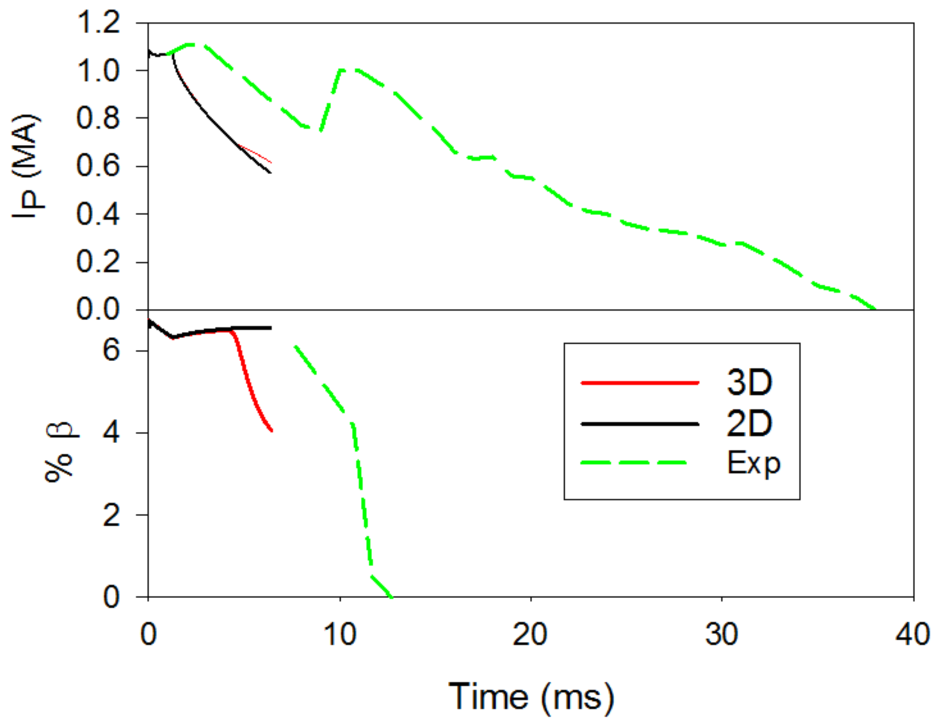
(approx) comparison with experiment



Experimental comparison not exact:

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

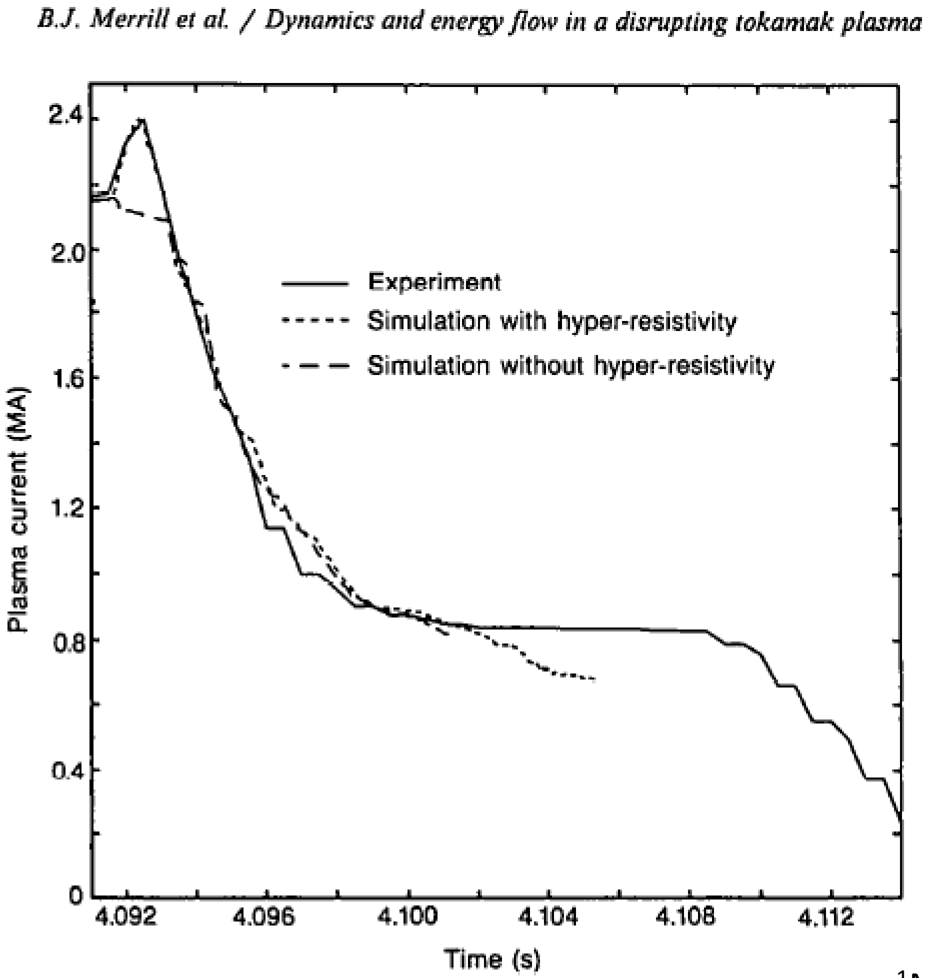
However:

- 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

Hyper-resistivity can reproduce current spike even in a 2D simulation



- TSC simulation[1] of TFTR shot 19960 could match observed current spike with hyper-resistivity[2] included
- This may also be required in 3D.

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} + \cdots - \nabla \cdot \mathbf{\Pi}_e$$

$$\mathbf{\Pi}_e = (\mathbf{B} / B^2) \nabla \cdot \left[\lambda_h \nabla \left(\mathbf{J} \cdot \mathbf{B} / B^2 \right) \right],$$

  - Dissipates energy for $\lambda_h > 0$
  - Conserves Helicity

[1]Merrill, et al, Fusion Eng. & Design **15** (1991) 163
[2]Boozer, Plasma Physics **35** (1986) 133

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.