M3D-C1 Simulation of NSTX Disruption during current ramp-down

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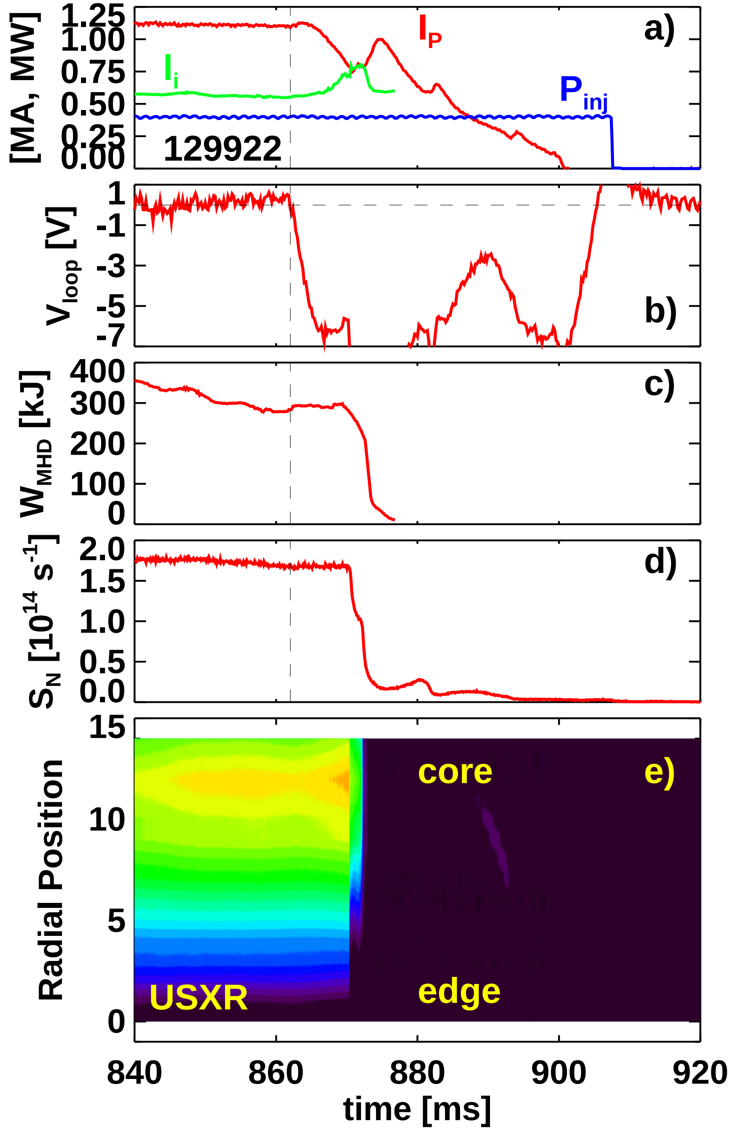
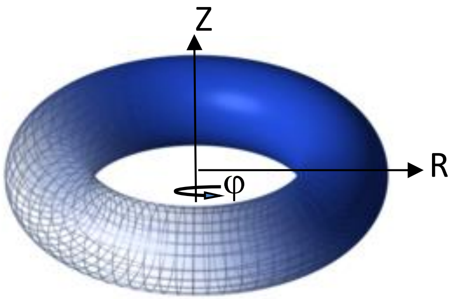
Unique Class of Major Disruptions Identified in NSTX

- 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]

3D Extended MHD Equations in M3D-C1



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

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

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

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

$\frac{3}{2}\left[\frac{\partial p_e}{\partial t} + \nabla\right.$ [redacted]

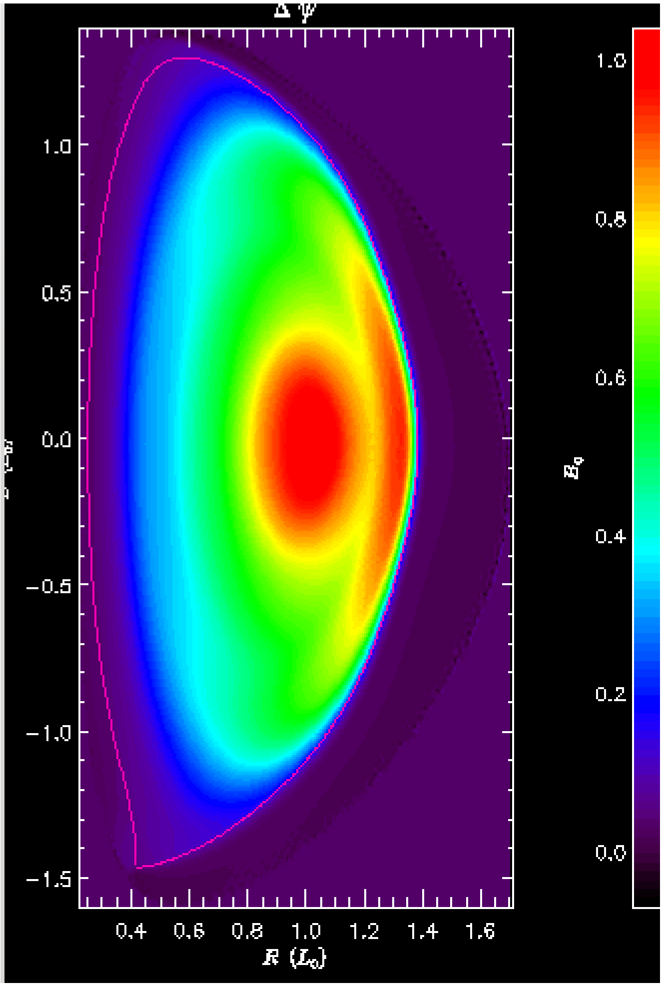
$$\frac{3}{2}\left[\frac{\partial p_i}{\partial t} + \nabla \bullet \left(p_i \mathbf{V}\right)\right] = -p_i \nabla \bullet \mathbf{V} - \mathbf{\Pi}_i : \nabla \mathbf{V} - \nabla \bullet \mathbf{q}_i - Q_\Delta + S_{iE} \qquad \mathbf{V}_e = \mathbf{V}_i - \mathbf{J}/ne$$

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

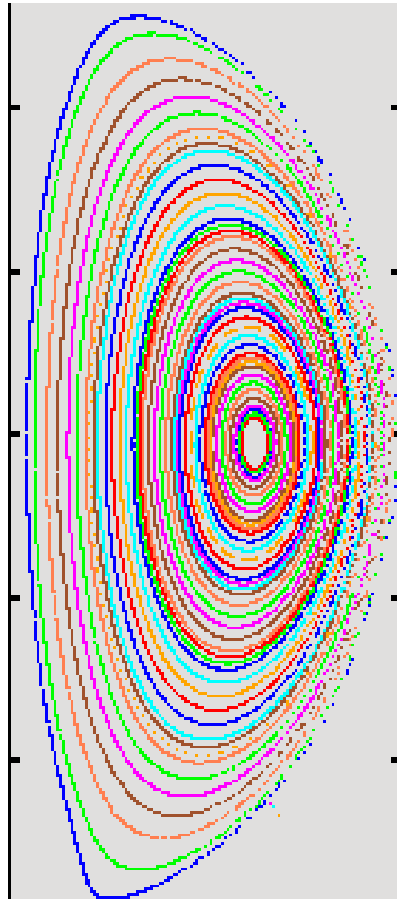
$$\mathbf{\Pi}_e = (\mathbf{B}/B^2)\nabla \bullet \left[\lambda_h \nabla\left(\mathbf{J} \bullet \mathbf{B}/B^2\right)\right], \qquad Q_\Delta = 3m_e(p_i - p_e)/\left(M_i \tau_e\right)$$

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

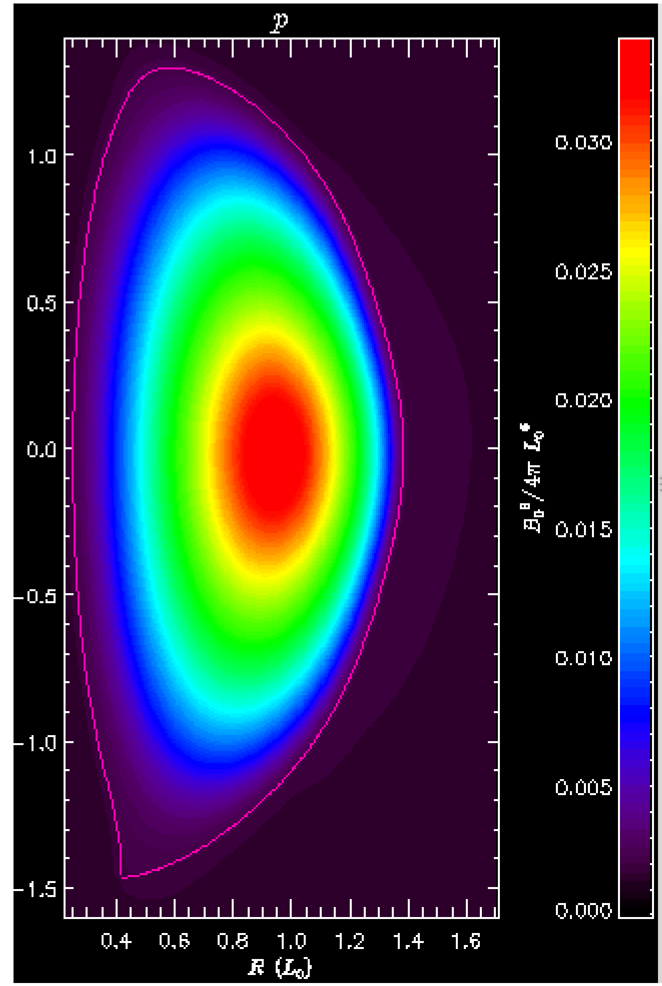
R J_φ



Poincare



Pressure



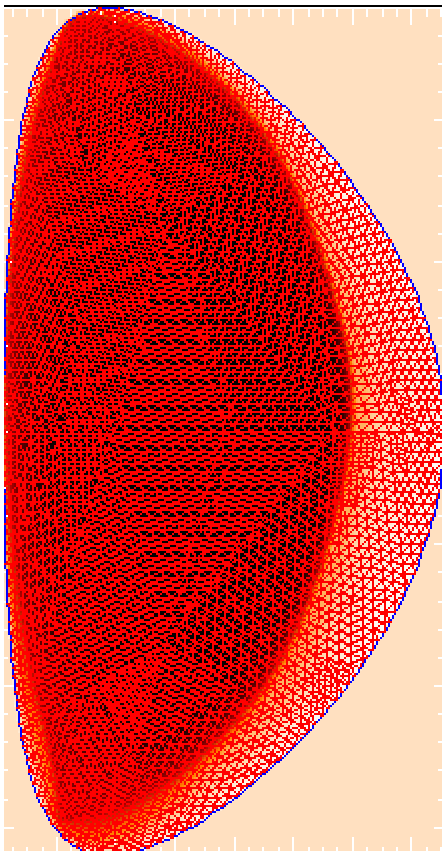
shot 129922
Time 860 ms

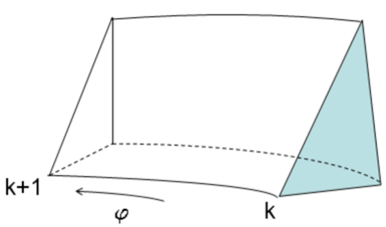
I_P ~ 1.1 MA
q_0 ~ 1.22
β ~ 6 %

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

Numerical Parameters:

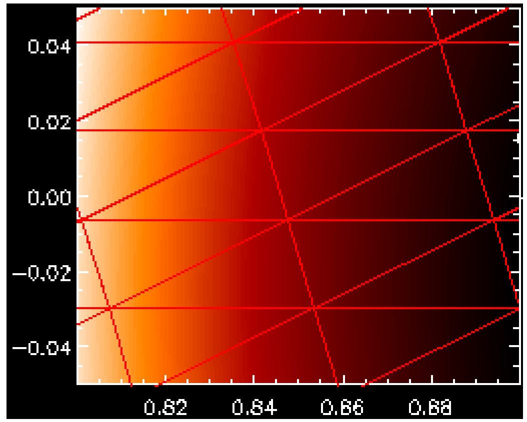
Entire domain





Triangular prism finite elements

10 cm x 10 cm patch



S = 10^7 (in center)

2D triangle size: 2 – 4 cm

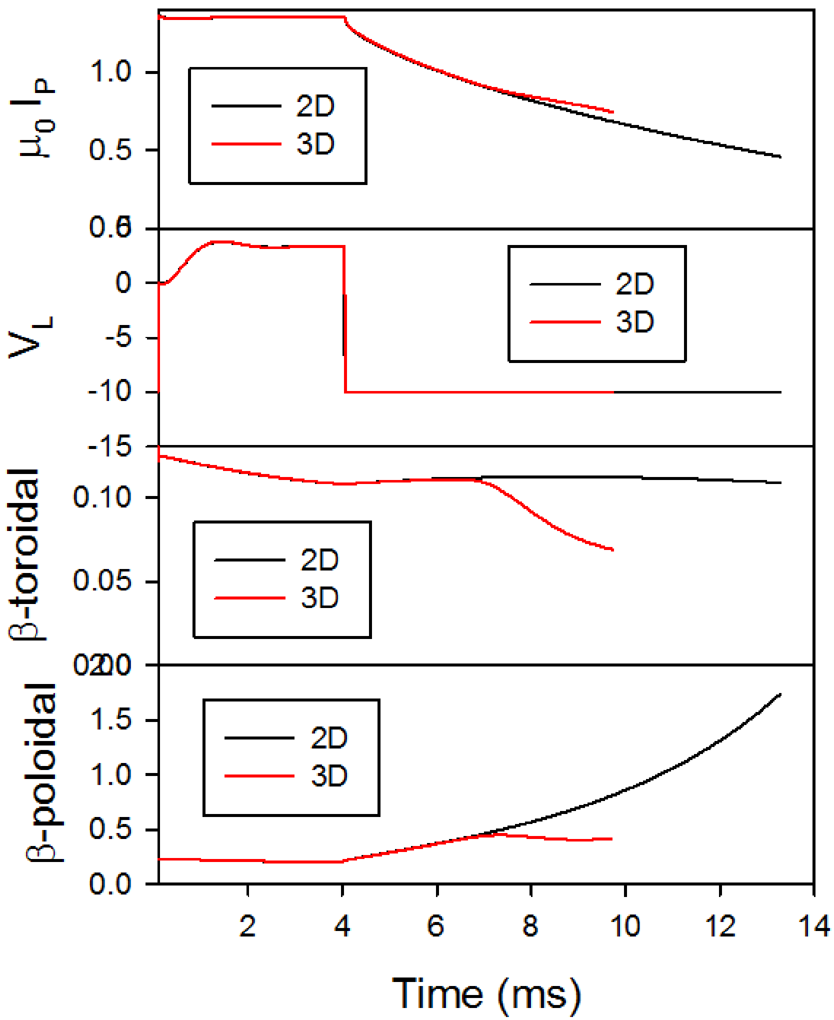
32 and 64 toroidal planes

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:

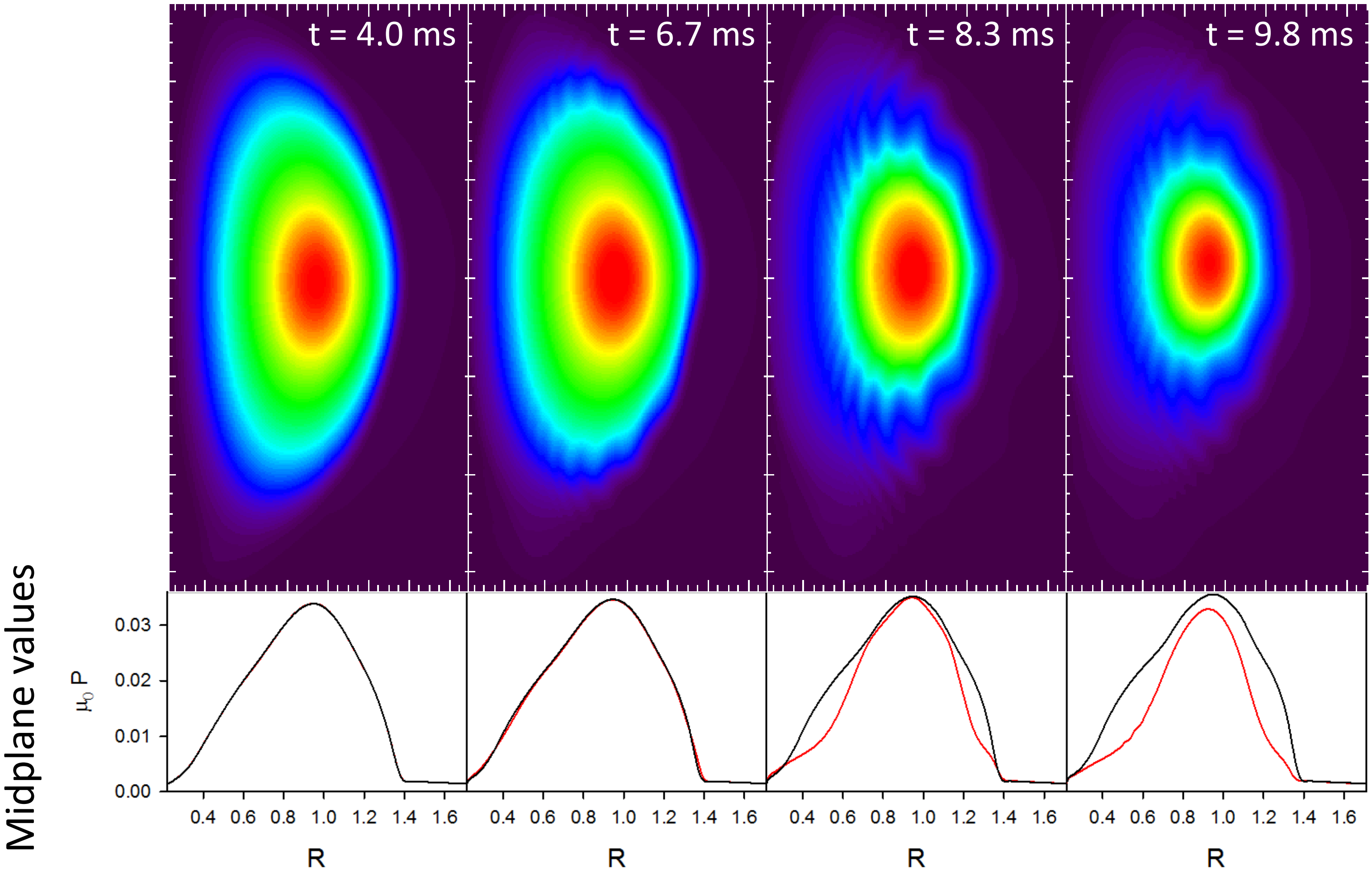
- Both current diffusion (transport) and ideal MHD (stability) time scales
- Requires high resolution for high-(m,n) modes
- Heating and particle sources
- Loop voltage prescribed at computational boundary
  - Control system to keep plasma current fixed before ramp-down
  - Switch to fixed negative value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

First (of 2) 3D M3D-C1 simulations



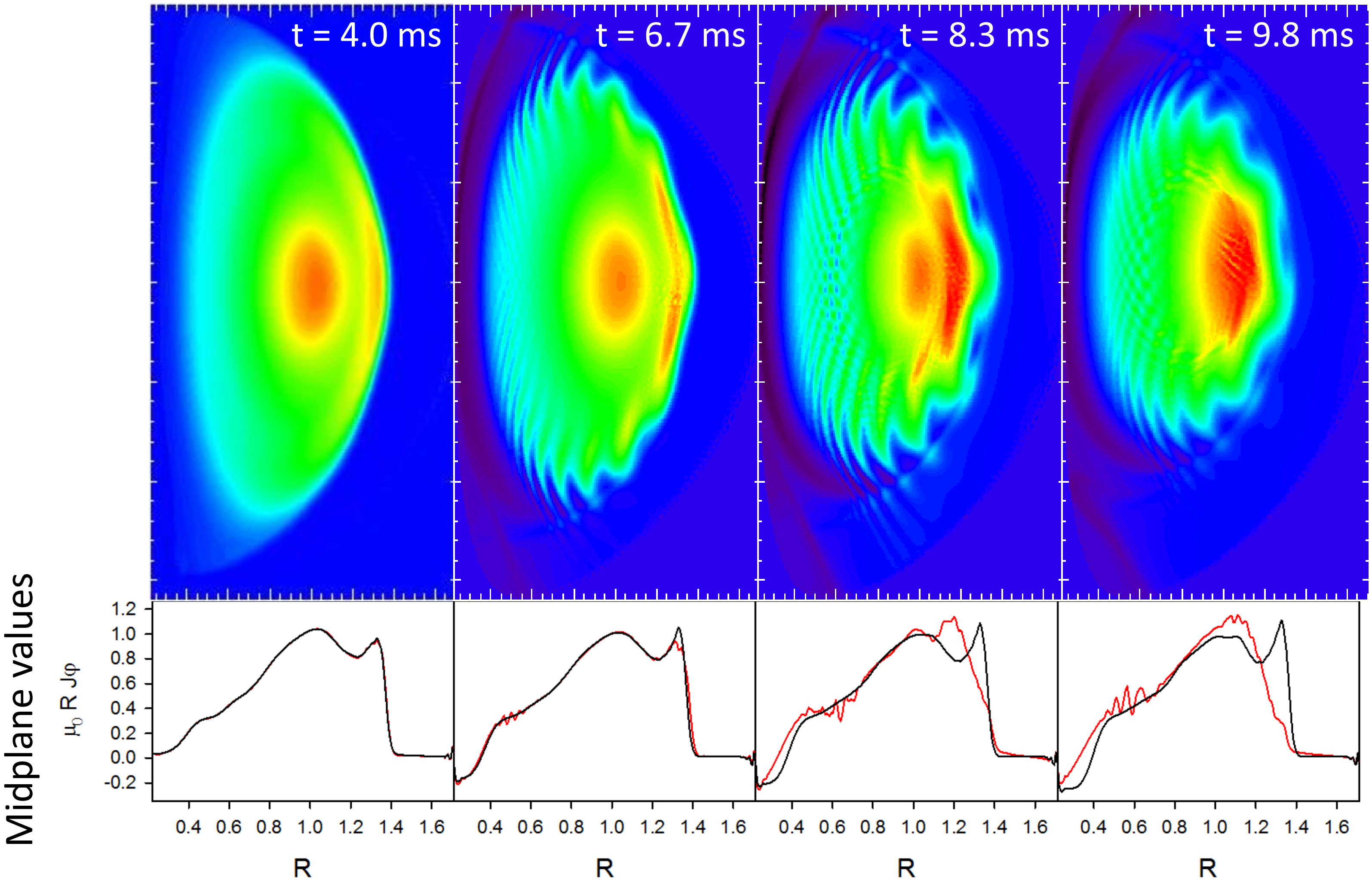
- 32 toroidal planes. Relatively large iteration tolerance
- Code was run in both 2D (axisymmetric) and 3D mode with near experimental parameters
- Difference in 2D and 3D behavior is due to 3D instabilities.
- Start of β collapse about 4 ms after V_L reversal.
- Some indication of (weak) current spike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

Pressure Contours at select times (32 planes)



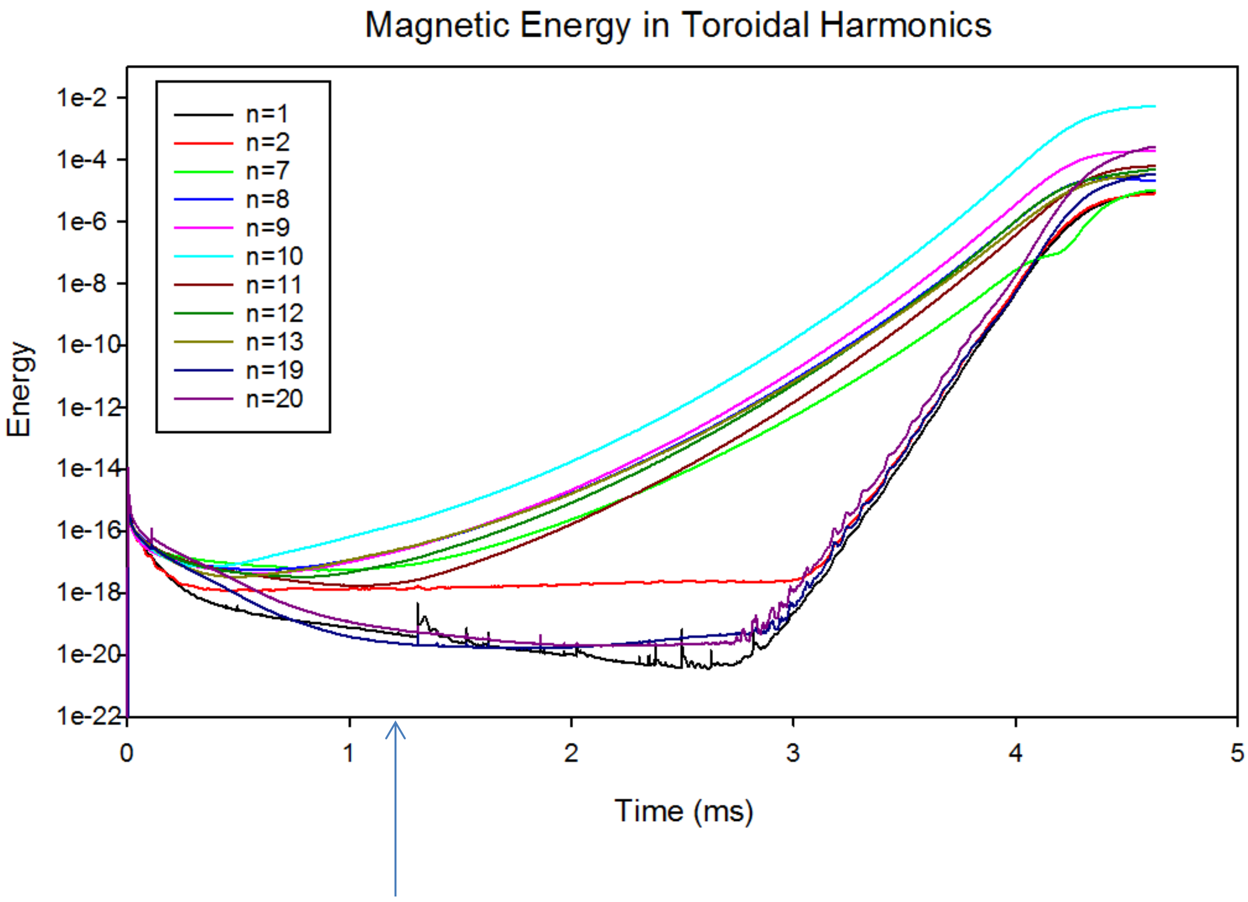
Pressure in 2D (black) and 3D (red) at 4 times

Current Contours at select times (32 planes)



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

New run has 64 planes and more stringent convergence criteria

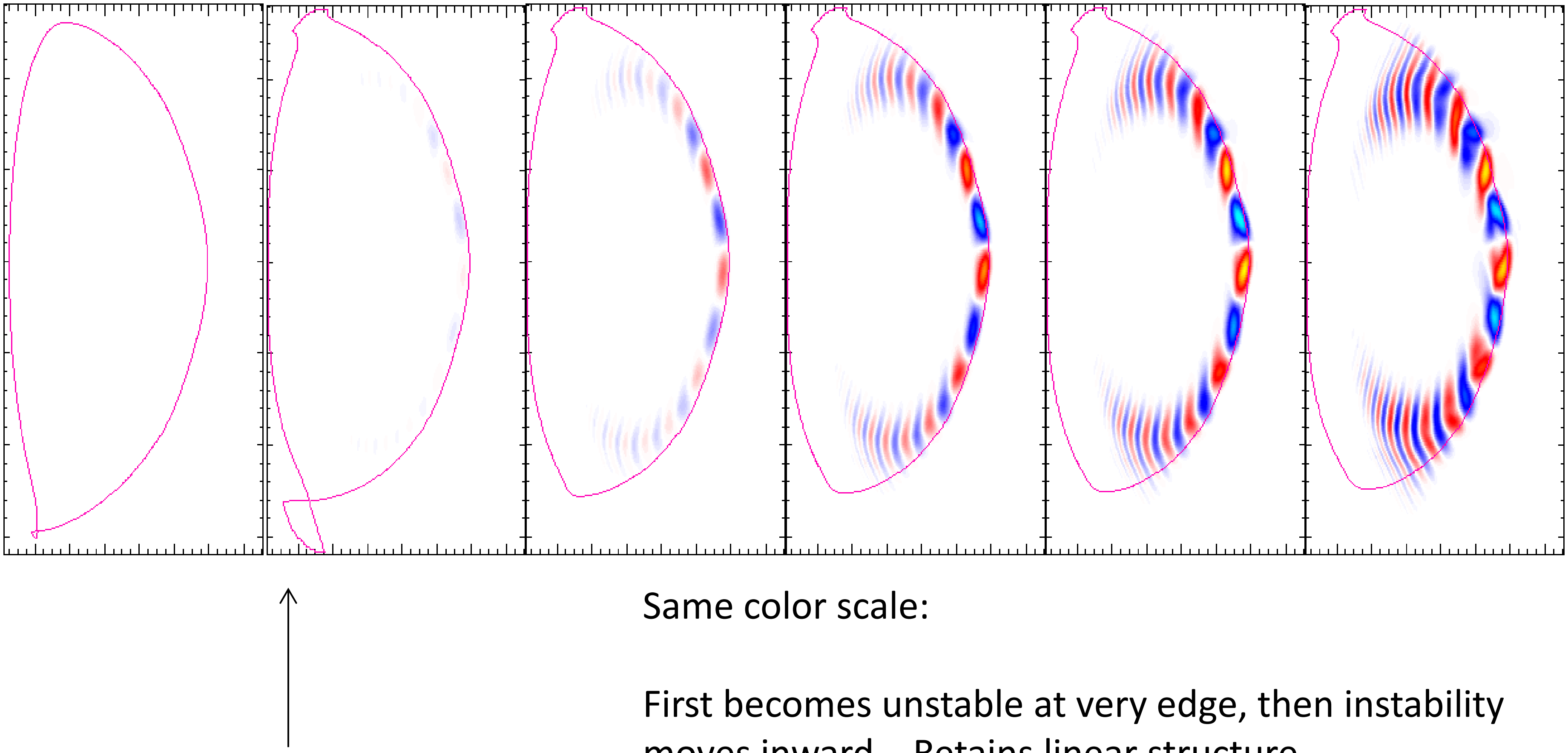


Voltage reversed

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

Toroidal derivative of pressure at several time slices

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



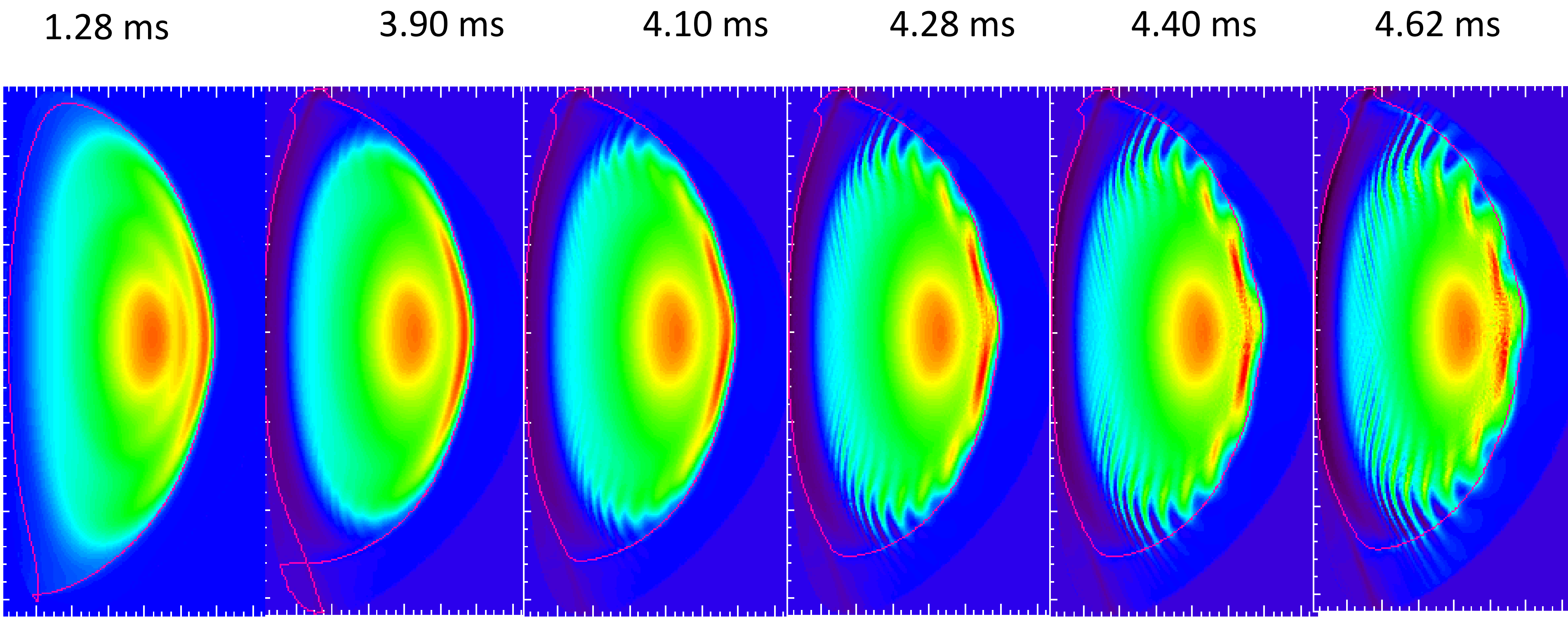
Voltage reversed at 1.28 ms

Same color scale:

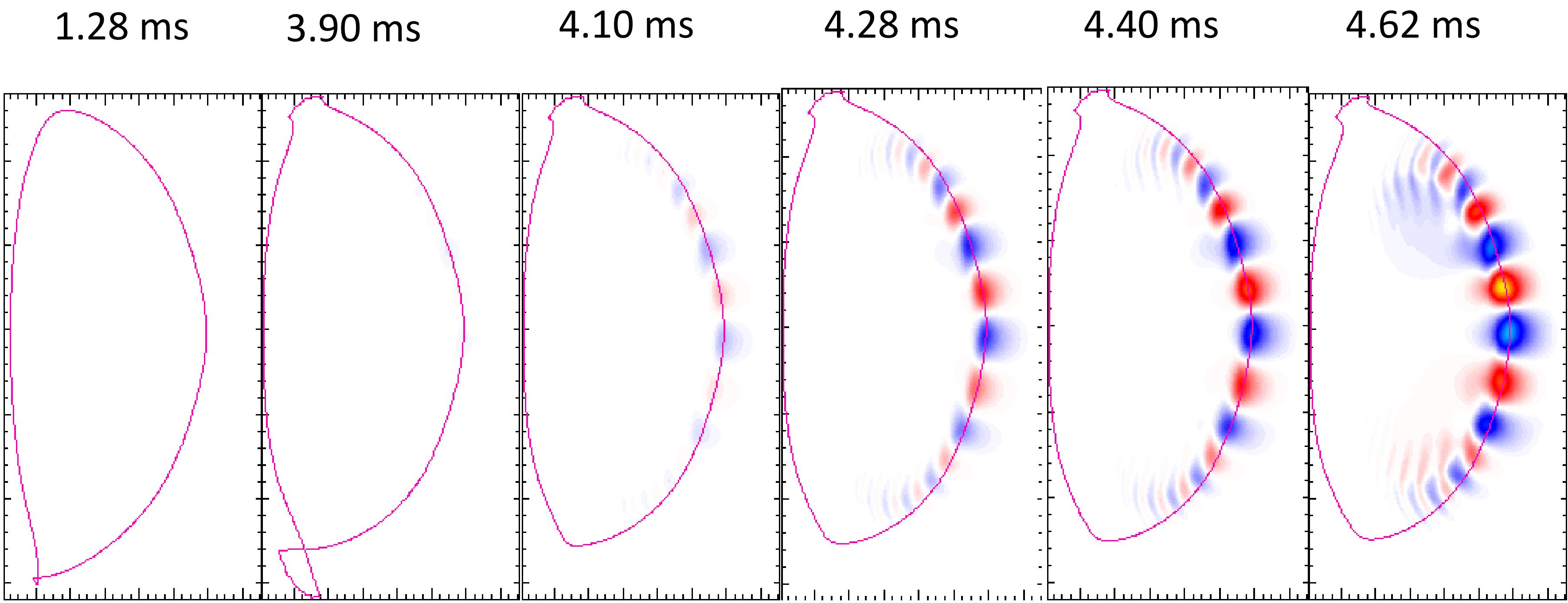
First becomes unstable at very edge, then instability moves inward. Retains linear structure.

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

Plasma current density at several time slices

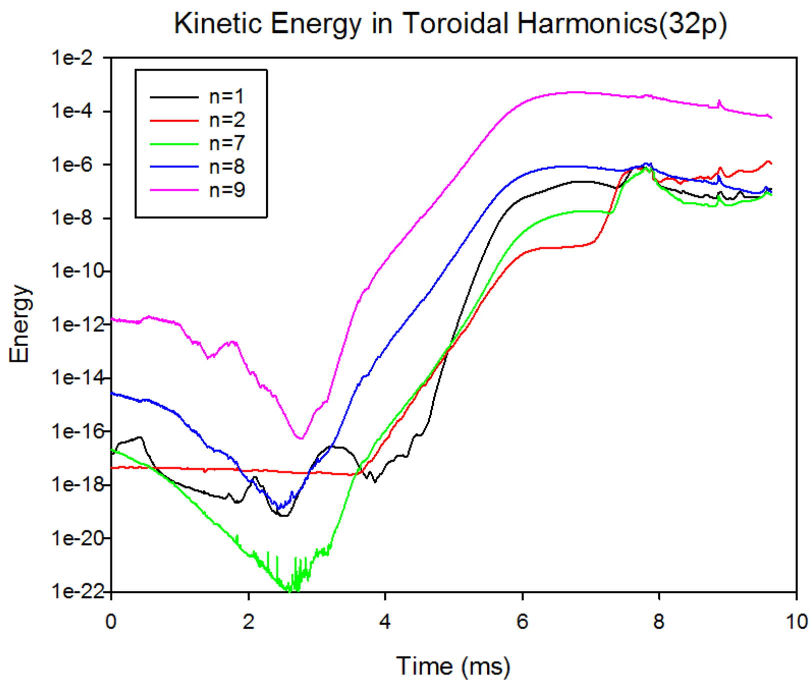


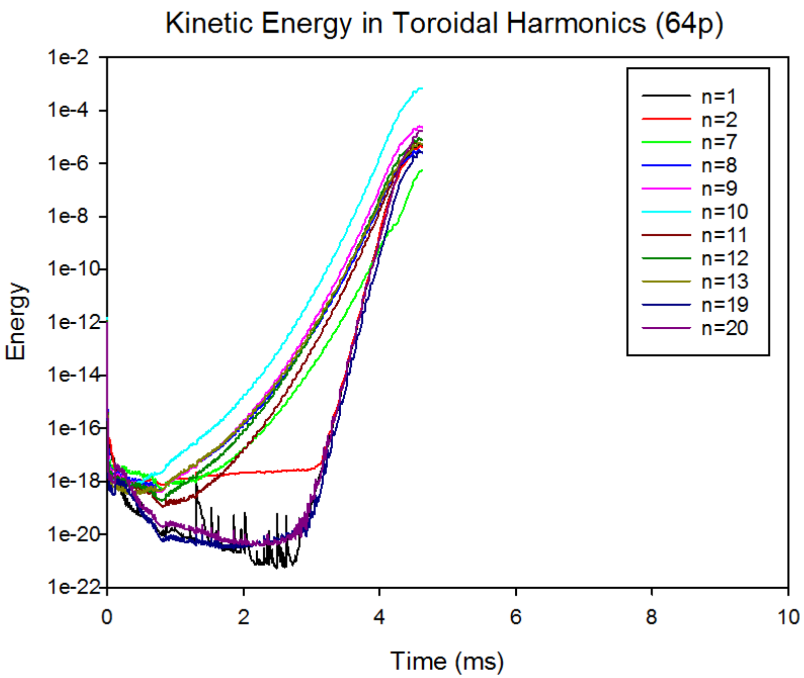
Toroidal derivative of poloidal flux at several time slices



Same color scale for all times

Comparison of 32p and 64p (still running) cases





- 64p case also has more stringent convergence criteria
- Significant differences !
- Should start 128 plane case

Proposal

- Perform series of high beta current ramp-down experiments with differing negative loop voltages (and associated ramp-down rates)
- Magnetic and ECE diagnostics to determine dominant mode number for unstable mode
- Importance of control system to keep plasma centered both radially and vertically
- Is impurity radiation important in thermal quench?
- Do all cases that exhibit mode activity disrupt? Hard vs soft beta limit.
- Support this with increased modeling….both linear and nonlinear