# MHD Simulations of Disruptions in NSTX

J.A. Breslau[1], H.R. Strauss[2], R. Paccagnella[3], S.C. Jardin[1]

[1]Princeton Plasma Physics Laboratory, Princeton, NJ

[2]HRS Fusion, West Orange, NJ

[3]Consorzio RFX, Padua, Italy

NSTX

PRINCETON PLASMA PHYSICS LABORATORY

# Abstract

Research tokamaks such as ITER must be designed to tolerate a limited number of disruptions without sustaining significant damage. It is therefore vital to have numerical tools that can accurately predict the effects of these events. The 3D nonlinear extended MHD code M3D [1] has been augmented with models of the vacuum/halo region and a thin axisymmetric resistive shell that allow it to simulate disruptions and calculate the associated wall currents and forces [2]. Its reliability, however, must be assessed with careful validation studies against disruption databases from existing experiments. Here we compare M3D VDE/kink disruption calculations with data from NSTX. The results of high-resolution numerical simulations at realistic Lundquist numbers show reasonable agreement with experimental data and provide confidence that M3D will be a useful tool for future ITER calculations. The effects of different choices of plasma outflow boundary conditions will also be reported.

[1] W. Park, et al., *Phys. Plasmas* **6** (1999) 1796.

[2] H. R.  Strauss, et al., *Phys. Plasmas* **17** (2010) 082505.

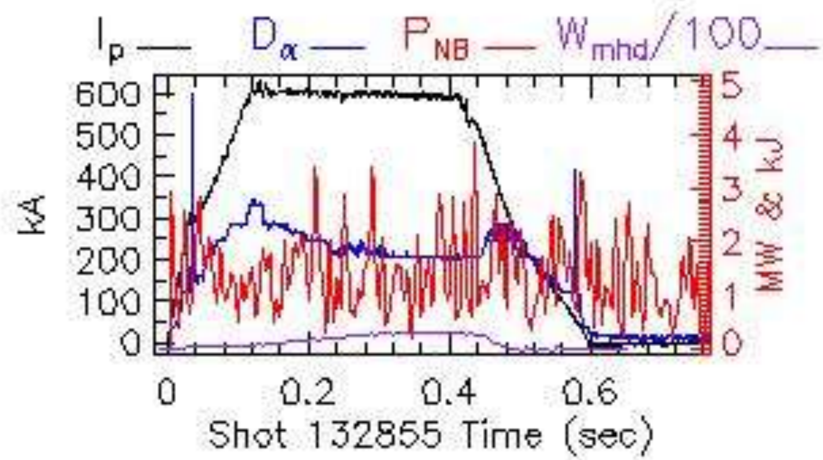
# Motivation

- A significant fraction of tokamak discharges at fusion-relevant parameters terminate in disruptions.
- As experiments are scaled up, the stored energy becomes higher, and the potential structural damage due to each disruption increases.
- Accurate quantitative prediction of the distributions of transient currents and attendant forces in conducting structures surrounding a disrupting ITER plasma is vital so that these structures can be designed to survive them.
- 3D nonlinear MHD codes with resistive wall boundary conditions are an appropriate tool for calculating currents and forces due to disruptions, but must first be validated against data from experiments such as NSTX, in which they are not catastrophic.

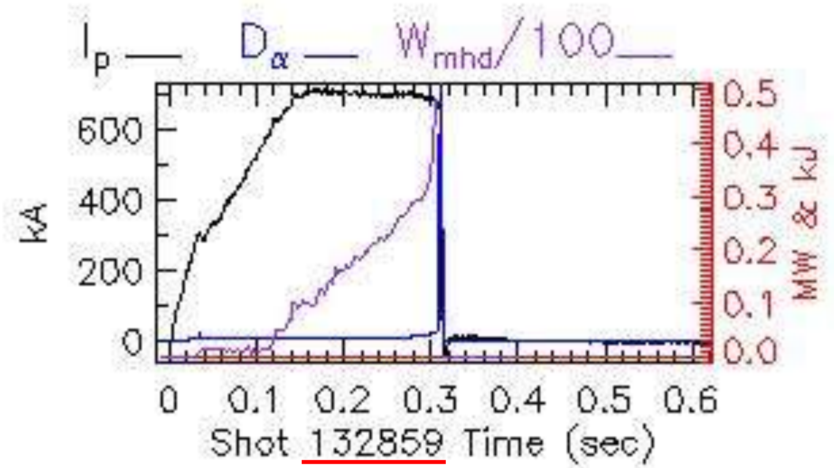
# NSTX XP833 (2010):

## Halo current dependencies on $I_p/q_{95}$, vertical velocity, and halo resistance

Reference shot without forced disruption drive, based on 129416:




Shot 132859, with deliberately misadjusted vertical field control, terminates in VDE:




S. Gerhardt

# The M3D Code

M3D (multi-level 3D) is a parallel 3D nonlinear extended MHD code in toroidal geometry maintained by a multi-institutional collaboration.

- Physics models include ideal and resistive MHD; two-fluid with just $\omega^*$ or $\omega^*$ and Hall terms; or hybrid with kinetic hot ions or kinetic bulk ions and fluid electrons.
- Uses linear, 2nd, or 3rd-order finite elements in-plane.
- Uses 4th-order finite differences between planes or pseudo-spectral derivatives.
- Partially implicit treatment allows efficient advance over dissipative and fast wave time scales but requires small time steps relative to $\tau_A$.
- <u>Linear</u> operation: full nonlinear + filtering, active equilibrium maintenance to find fastest-growing toroidal eigenmodes.
- <u>Nonlinear</u> operation: all components of all quantities evolve nonlinearly.
- The PETSc library is used for parallelization and linear solves with Krylov methods.

# Extended MHD Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}_i) = 0$$

$$\rho \left[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + (\mathbf{v}_i^* \cdot \nabla) \mathbf{v}_\perp \right] = -\nabla \mathbf{p} + \mathbf{J} \times \mathbf{B} + \mu \nabla^2 \mathbf{v}$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} - \frac{\nabla_\parallel p_e}{ne}$$

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

$$\mathbf{J} = \nabla \times \mathbf{B}$$

$$\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p = -\gamma p \nabla \cdot \mathbf{v} + \nabla \cdot n \chi_\perp \nabla \left( \frac{p}{\rho} \right) - \mathbf{v}_i^* \cdot \nabla p - \gamma p \nabla \cdot \mathbf{v}_i^* + \frac{\mathbf{J} \cdot \nabla p_e}{ne} + \gamma p_e \mathbf{J} \cdot \nabla \left( \frac{1}{ne} \right)$$

$$\frac{\partial p_e}{\partial t} + \mathbf{v} \cdot \nabla p_e = -\gamma p_e \nabla \cdot \mathbf{v} + \nabla \cdot n \chi_{\perp e} \nabla \left( \frac{p_e}{\rho} \right) + \frac{\mathbf{J}_\parallel \cdot \nabla p_e}{ne} - \gamma p_e \nabla \cdot \left( \mathbf{v}_e^* - \frac{\mathbf{J}_\parallel}{ne} \right)$$

where

$$\mathbf{v}_e^* \equiv -\frac{\mathbf{B} \times \nabla p_e}{neB^2}, \quad \mathbf{v}_i^* \equiv \mathbf{v}_e^* + \frac{\mathbf{J}_\perp}{ne},$$

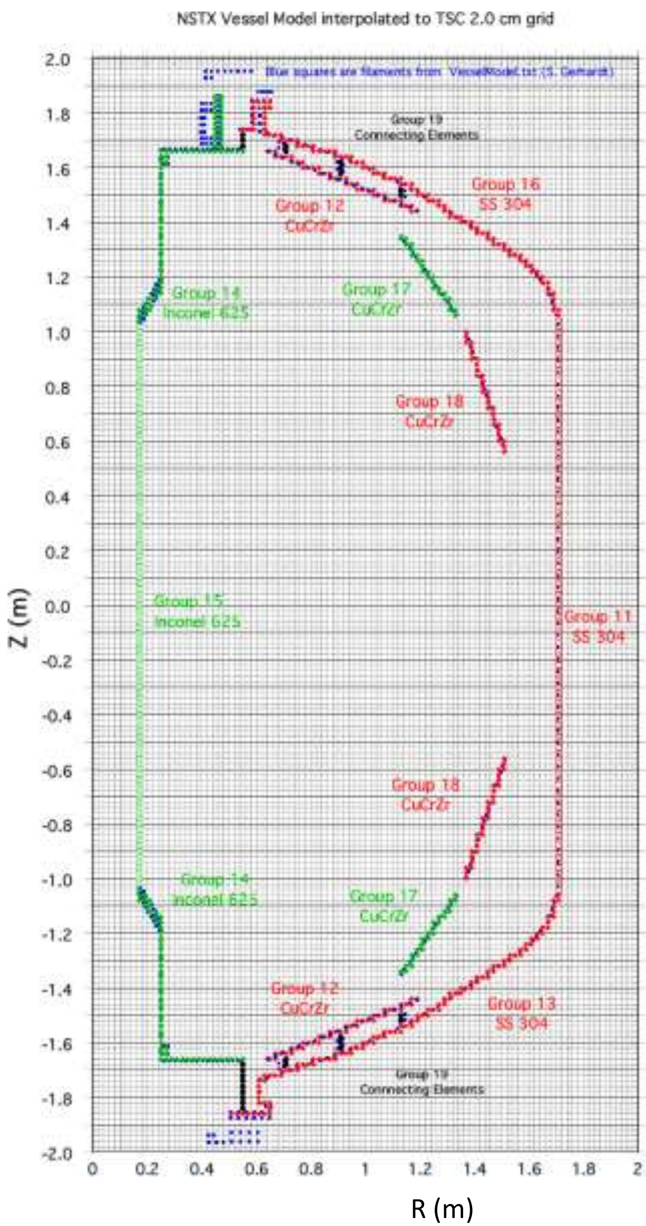
$$\mathbf{v} \equiv \mathbf{v}_i - \mathbf{v}_i^* = \mathbf{v}_e - \mathbf{v}_e^* + \frac{\mathbf{J}_\parallel}{ne}$$

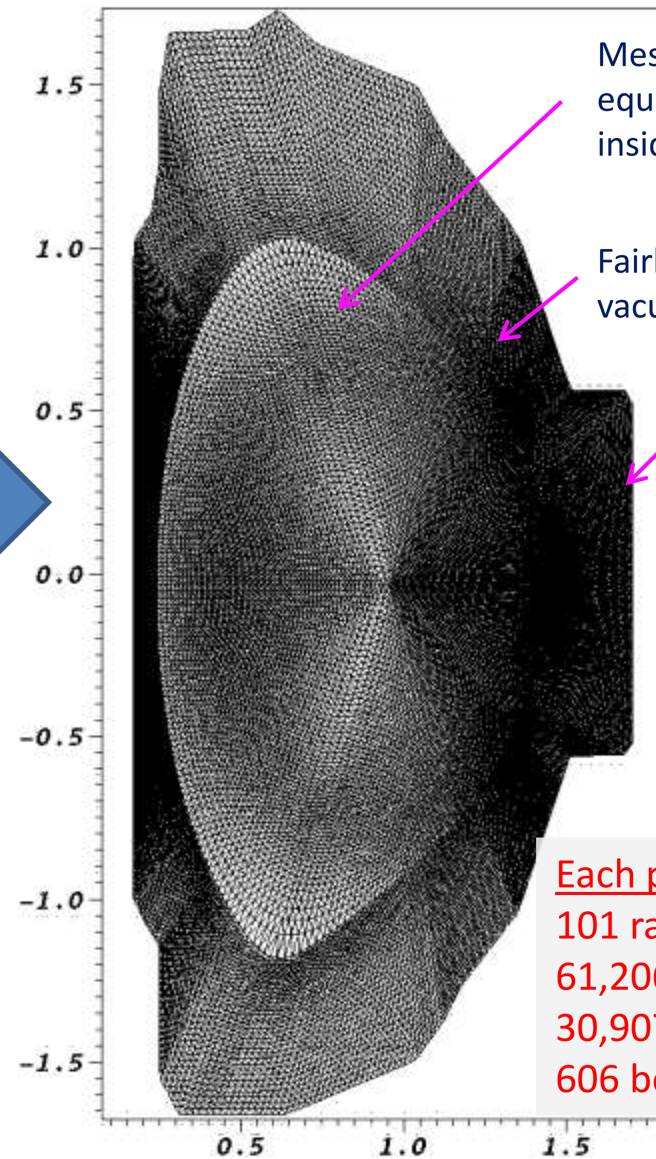
Artificial sound wave model for $\kappa_\parallel$:

$$\frac{\partial T}{\partial t} = s \frac{\mathbf{B} \cdot \nabla u}{\rho}$$

$$\frac{\partial u}{\partial t} = s \mathbf{B} \cdot \nabla T + \nu \nabla^2 u$$

# Meshing the NSTX Vessel




Mesh aligned to equilibrium flux surfaces inside separatrix

Fairly uniform spacing in vacuum region

Axisymmetric resistive shell

<u>Each poloidal section has</u>
101 radial zones
61,206 triangular elements
30,907 vertices
606 boundary vertices

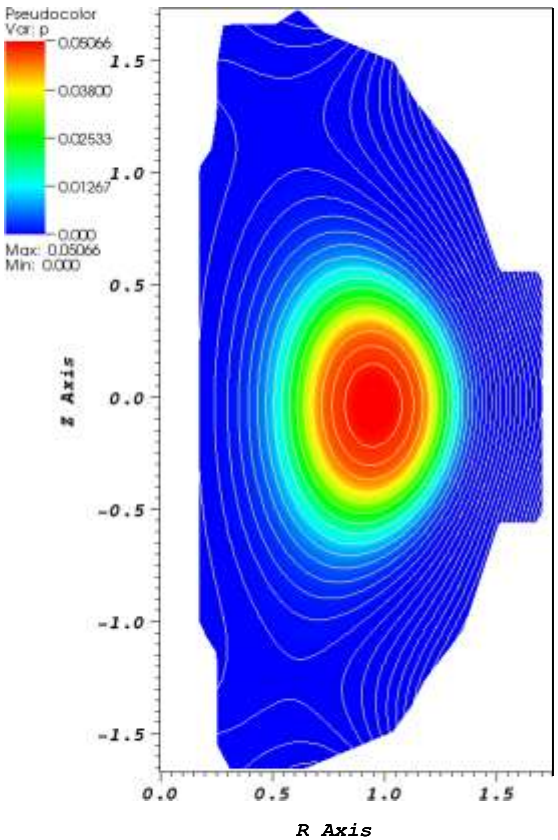
# Case 1 parameters

| | |
|---|---|
| Plasma resistivity on axis* $\eta_0$=$S^{-1}$ | $10^{-4}$ |
| $\eta_{vacuum} / \eta_0$ | 100 |
| $\eta_{wall} / \eta_0$ | 500 ($\tau_w/\tau_A$ = 20) |
| Prandtl number $\mu / \eta_0$ | 1 |
| Perpendicular heat conduction $\kappa_\perp / \eta_0$ | 1 |
| Effective parallel heat conduction $v_{Te} / v_A$ | 2 |
| Density evolution | Off (uniform, constant) |
| Size of initial $n$=1 perturbation | $5 \times 10^{-3}$ |
| Number of toroidal modes | 4 (12 poloidal planes) |

*In the plasma, $\eta(T) / \eta_0 = (T / T_0)^{-3/2}$, where $T_0$ is the initial temperature on axis.

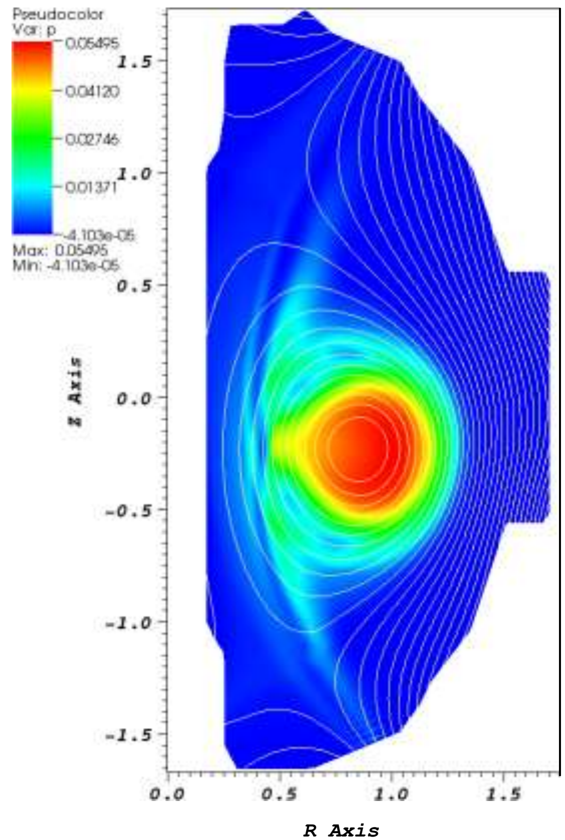
# Recreation of Shot 132859 from 0.280 s

$t = 0.0$



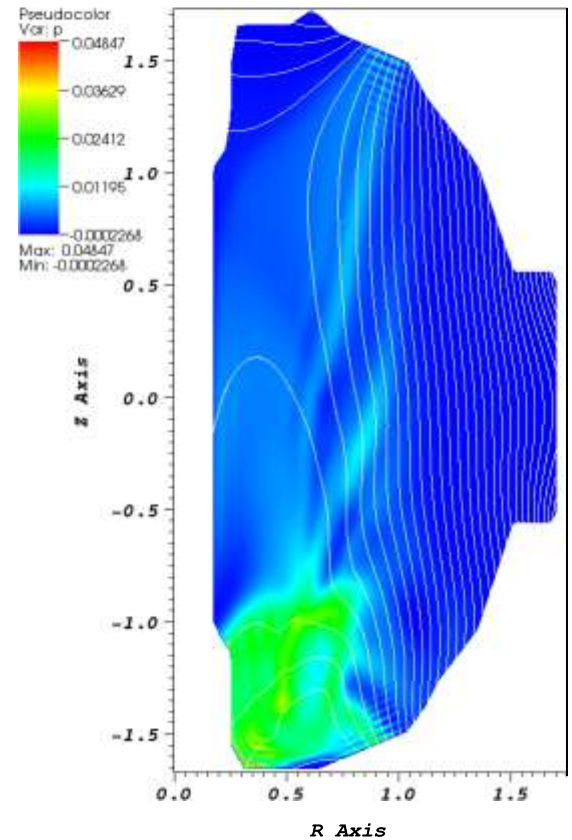

Initial equilibrium is VDE-unstable.
$q_0 \approx 1$.

$t = 100.66\ \tau_A$




Plasma is displaced downward, along with growth of $n$=1 instability.

$t = 129.77\ \tau_A$




Confinement is lost, heat deposited in divertor region.

# Toroidally Asymmetric Halo Current Figures of Merit

Toroidal peaking factor (TPF): If there are $N$ poloidal planes, $j$=1,2,3,…,$N$, then

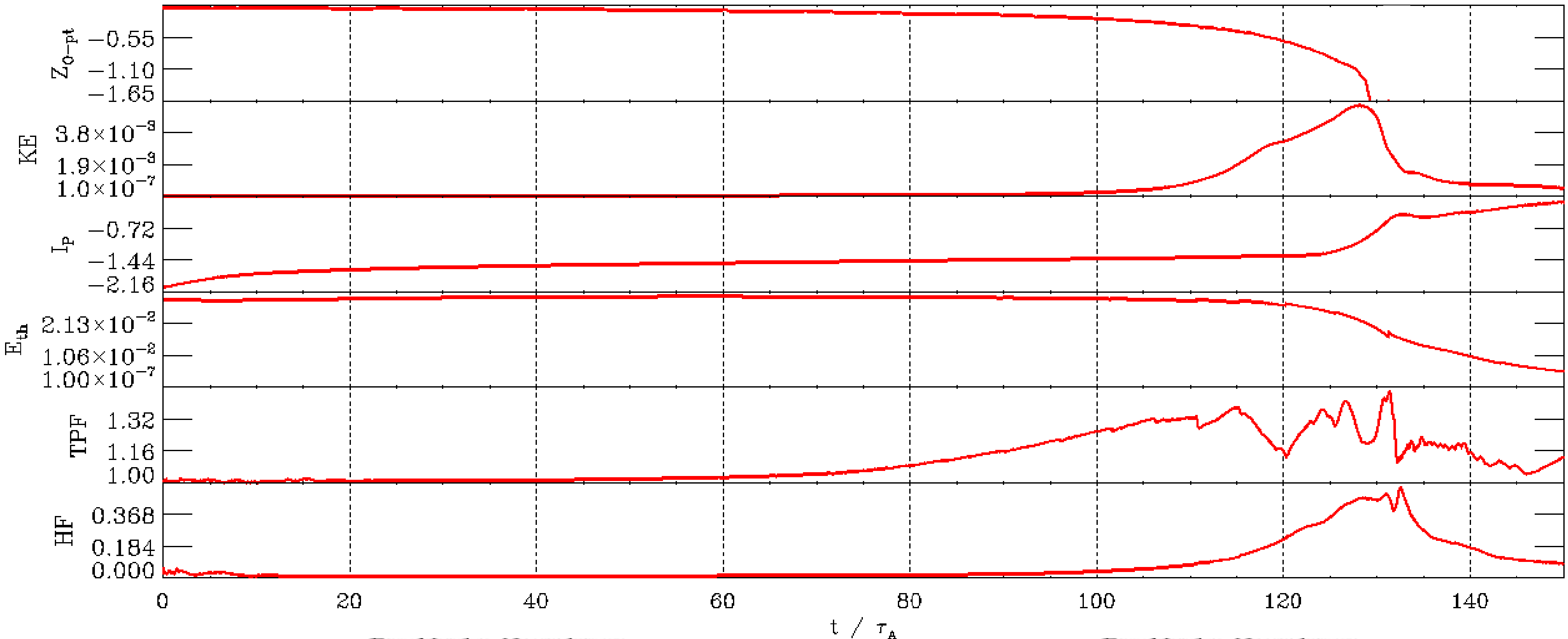
$$TPF \equiv \frac{\mathrm{Max}_{j=1}^{N}\left\{\oint_{\Gamma_j} R\left|\mathbf{J}\cdot\hat{n}\right|dl\right\}}{\frac{1}{N}\sum_{j=1}^{N}\left\{\oint_{\Gamma_j} R\left|\mathbf{J}\cdot\hat{n}\right|dl\right\}}$$

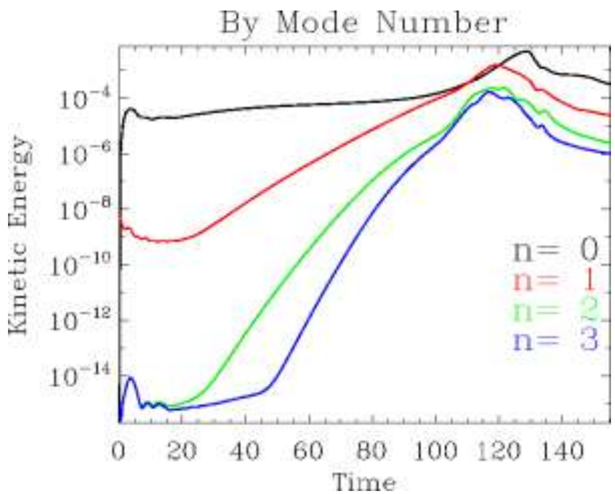
Halo fraction (HF):

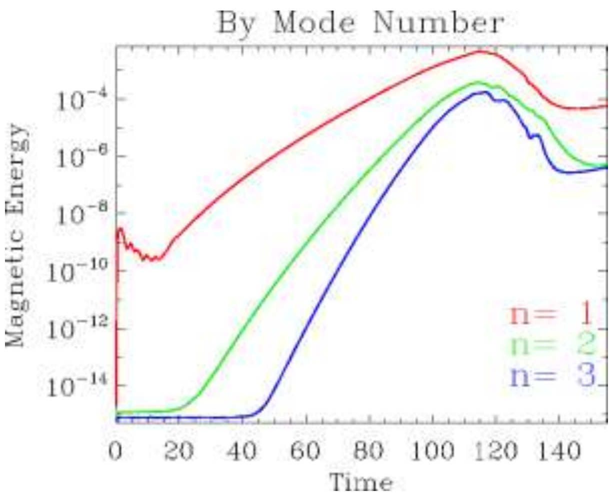
$$HF \equiv \frac{\frac{2\pi}{N}\sum_{j=1}^{N}\left\{\oint_{\Gamma_j} R\left|\mathbf{J}\cdot\hat{n}\right|dl\right\}}{I_{p0}},$$

where $I_{p0}$ is the total plasma current in the initial equilibrium.

# Time History



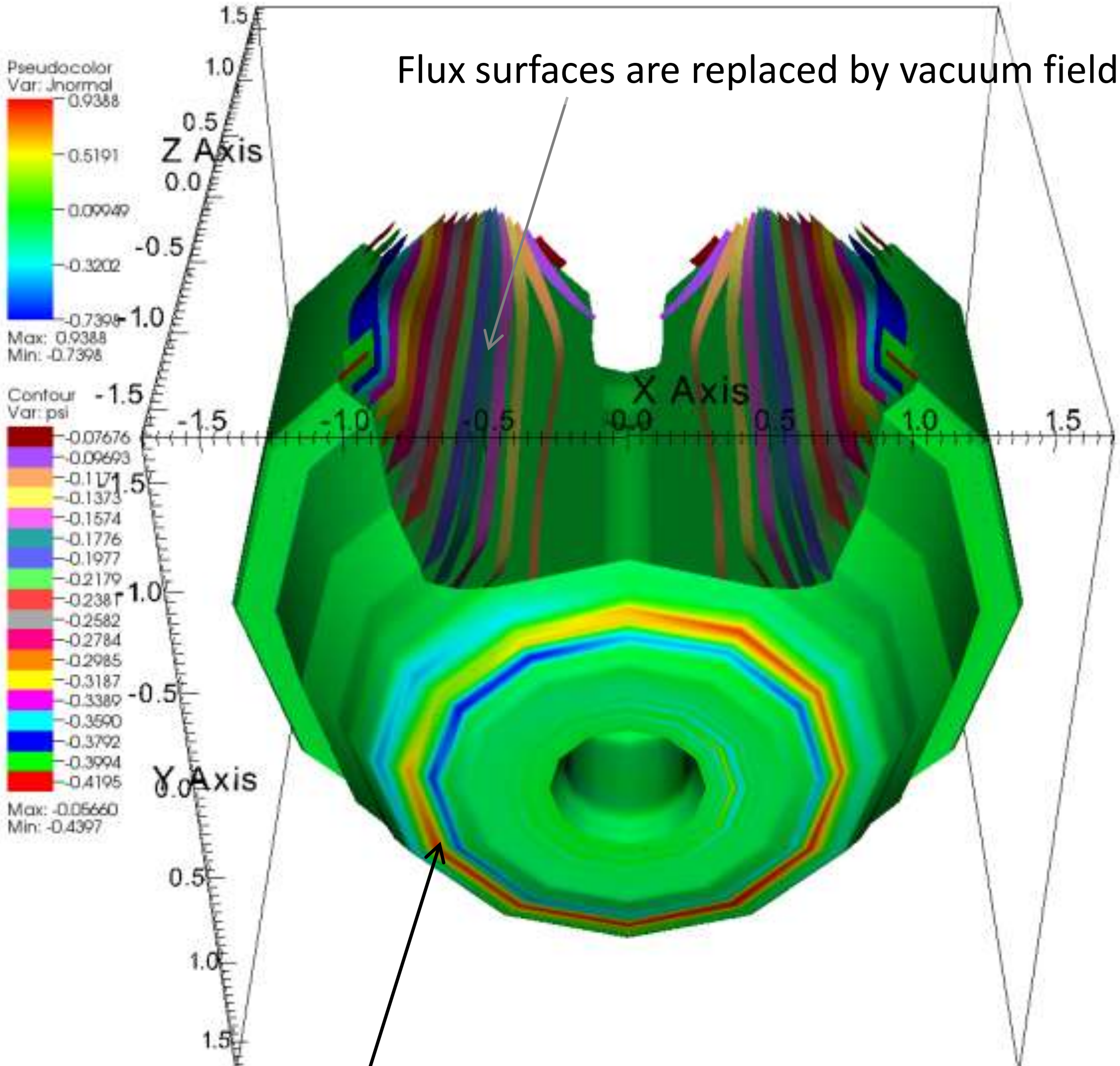



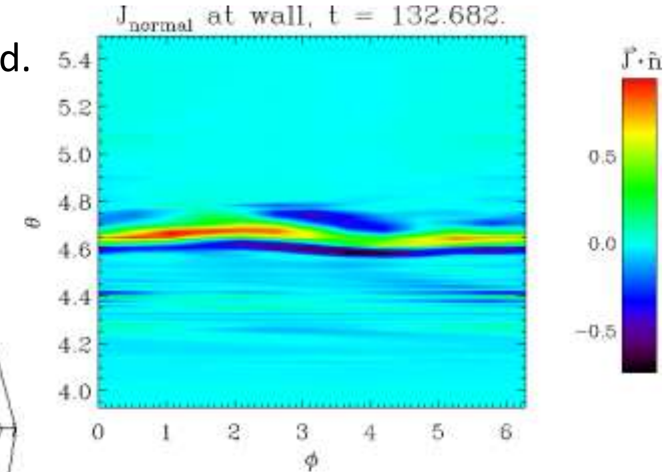
# Halo Current Distribution at Peak

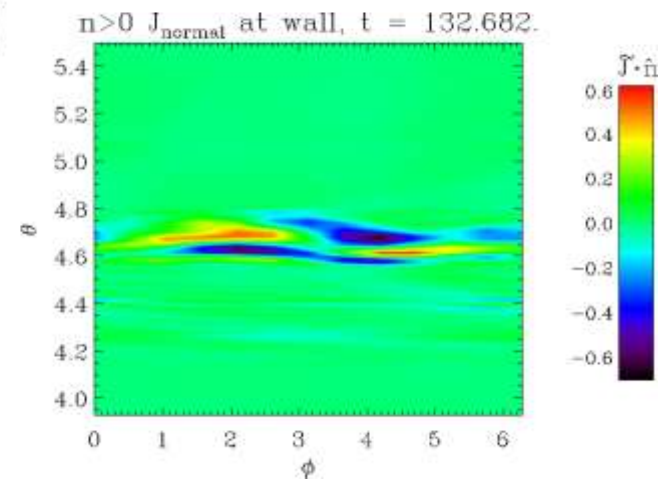
*t* = 132.68

Flux surfaces are replaced by vacuum field.



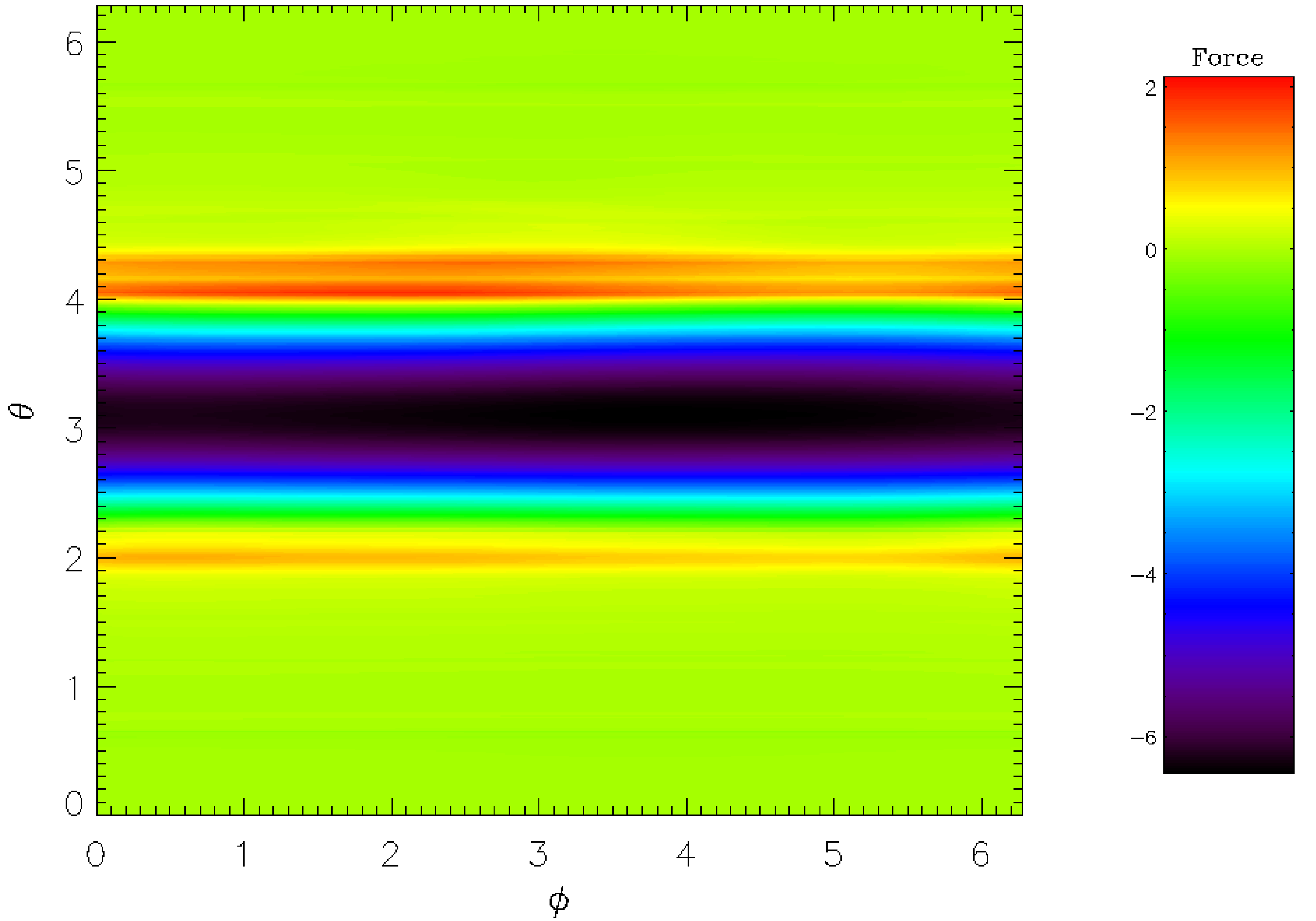

Current peaks on lower Group 12 plate.




*n*=1 component is of comparable size to *n*=0.

# Non-equilibrium Wall Force Distribution, $t$=132.68




- Net horizontal force = 0.246, in direction $\varphi$ = 4.910.
- Net vertical force = -0.591.

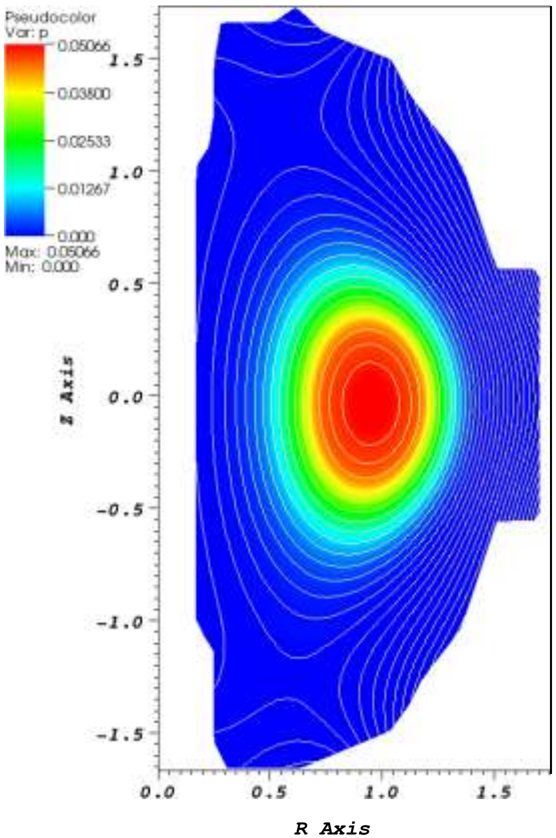
# Case 2 parameters

| | |
|---|---|
| Plasma resistivity on axis* $\eta_0$=$S^{-1}$ | $10^{-5}$ |
| $\eta_{vacuum} / \eta_0$ | 5000 |
| $\eta_{wall} / \eta_0$ | 250 ($\tau_w/\tau_A$=400) |
| Prandtl number $\mu / \eta_0$ | 10 |
| Perpendicular heat conduction $\kappa_\perp / \eta_0$ | 10 |
| Effective parallel heat conduction $v_{Te} / v_A$ | 2 |
| Density evolution | Off (uniform, constant) |
| Size of initial $n$=1 perturbation | $5 \times 10^{-3}$ |
| Number of toroidal modes | 4 (12 poloidal planes) |

*In the plasma, $\eta(T) / \eta_0 = (T / T_0)^{-3/2}$, where $T_0$ is the initial temperature on axis.

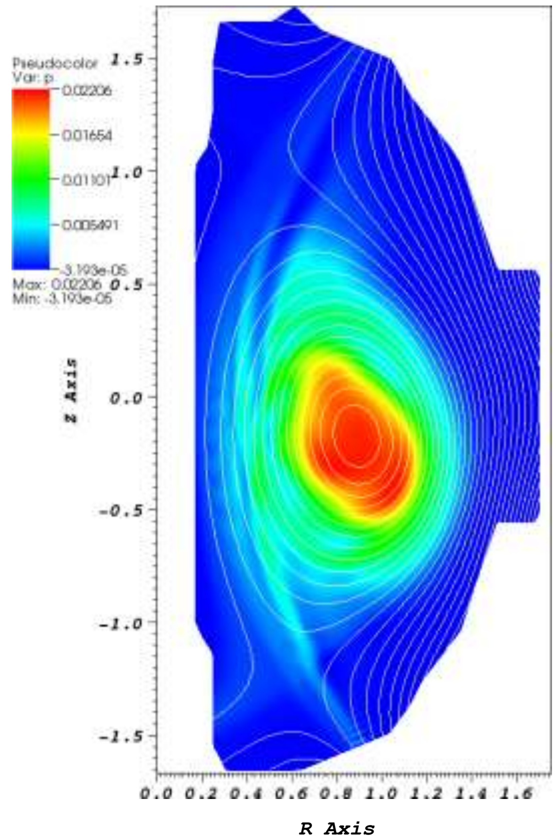
# Case 2 Snapshots

$t = 0.0$



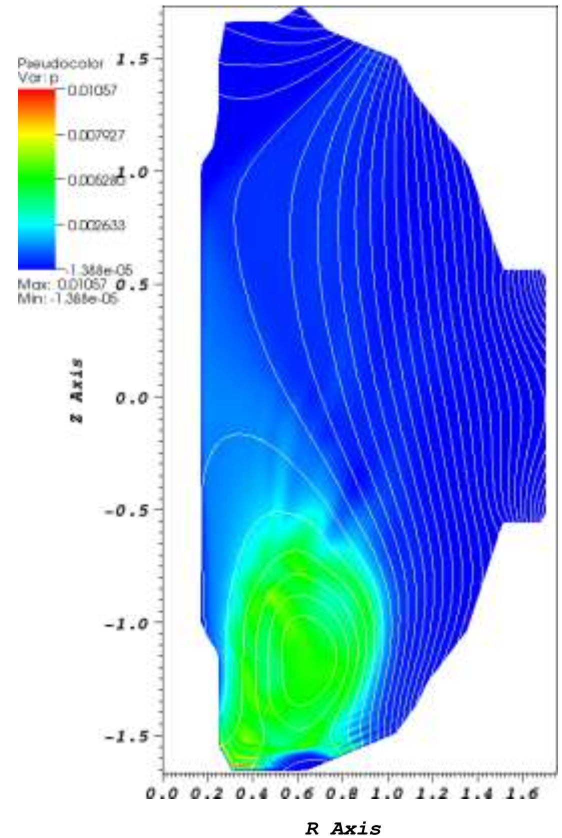

Initial VDE-unstable equilibrium

$t = 634.81\ \tau_A$



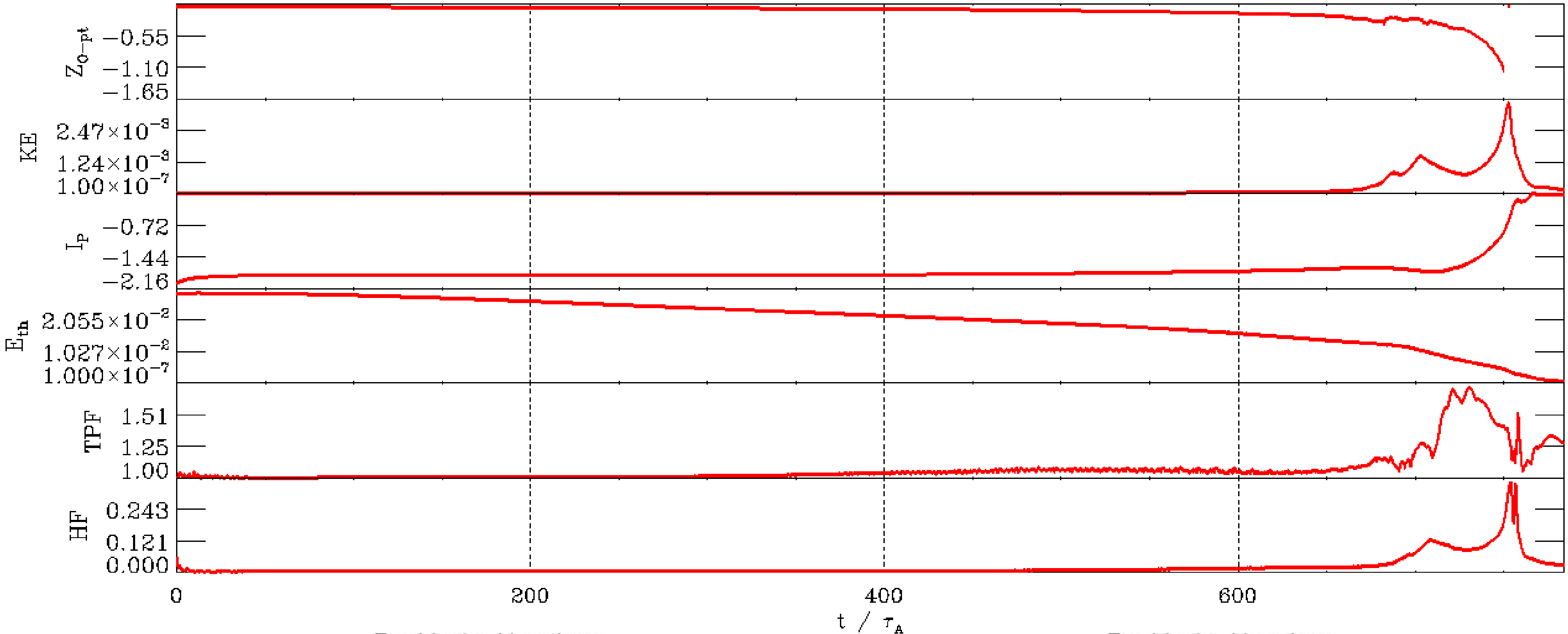

Plasma is displaced downward, along with growth of $n$=1 instability.

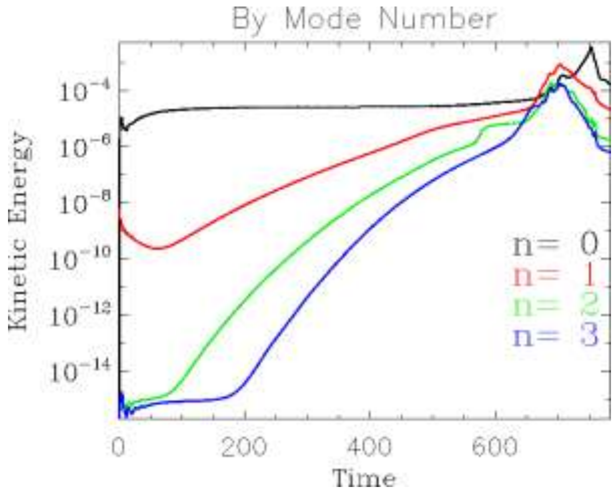
$t = 750.55\ \tau_A$

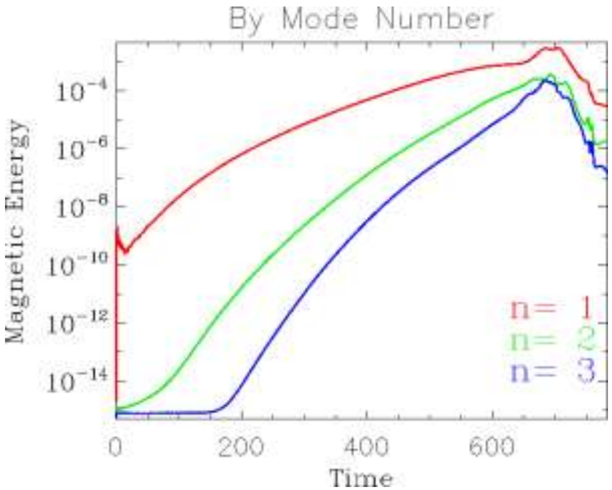



Confinement is lost, heat deposited in divertor region.

# Time History

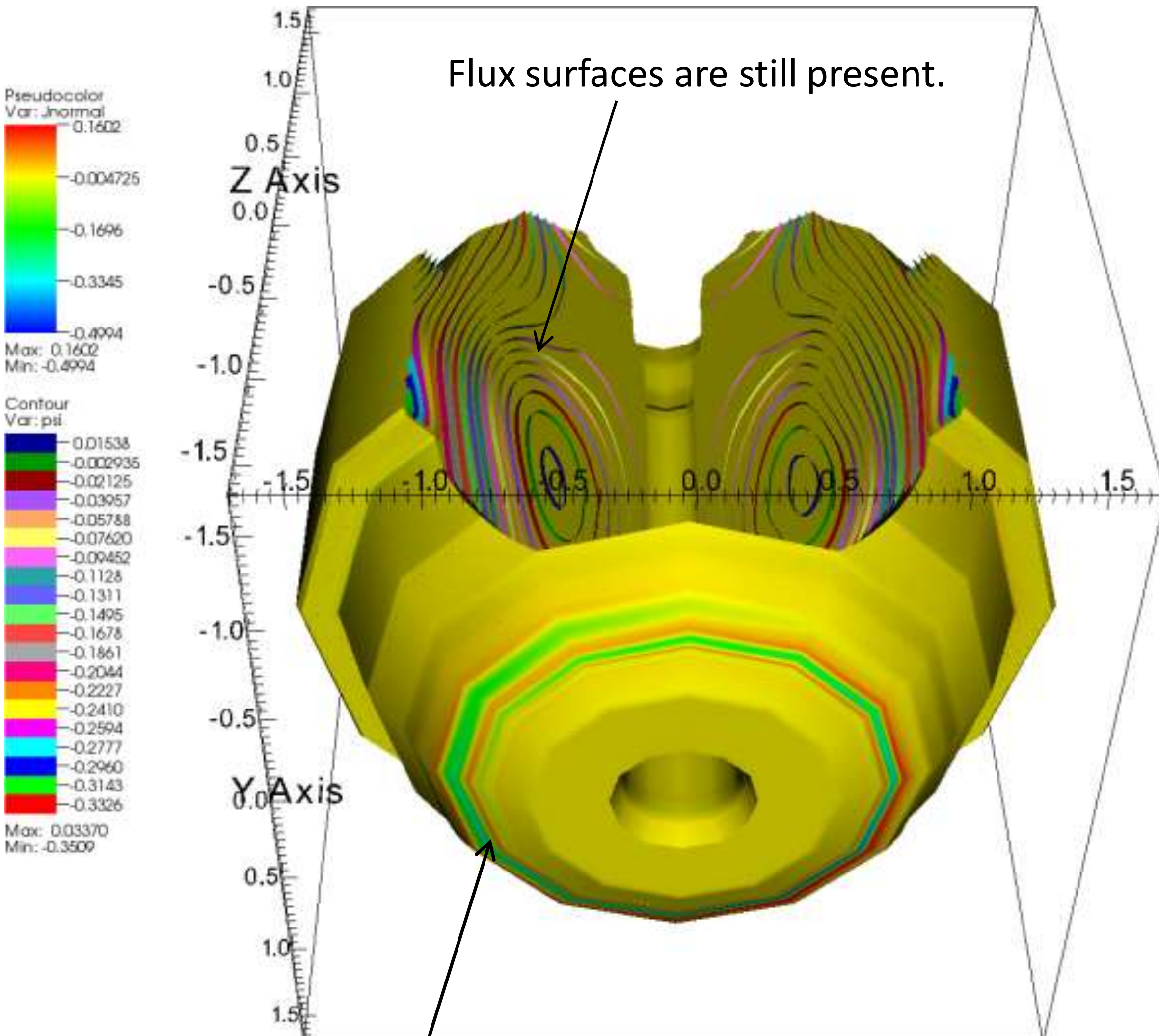


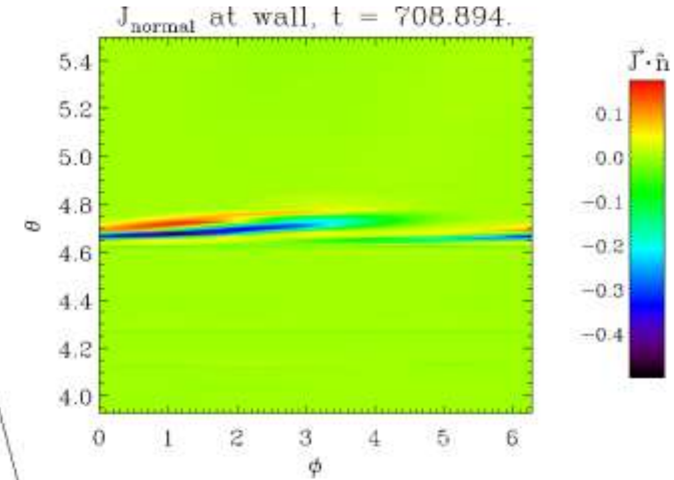



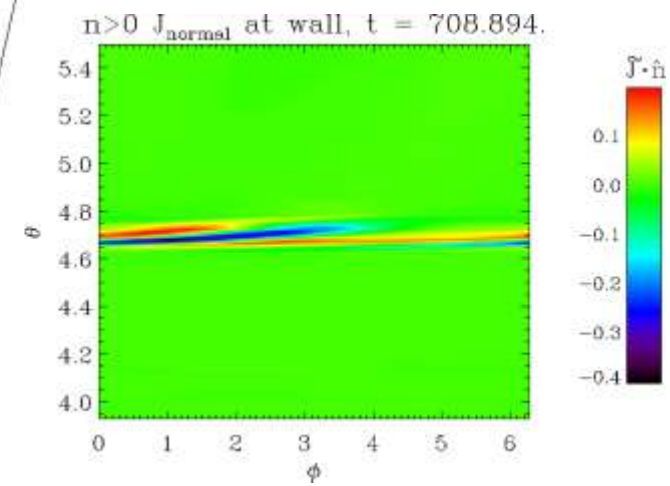
# Halo Current Distribution at Peak

$t$ = 708.89



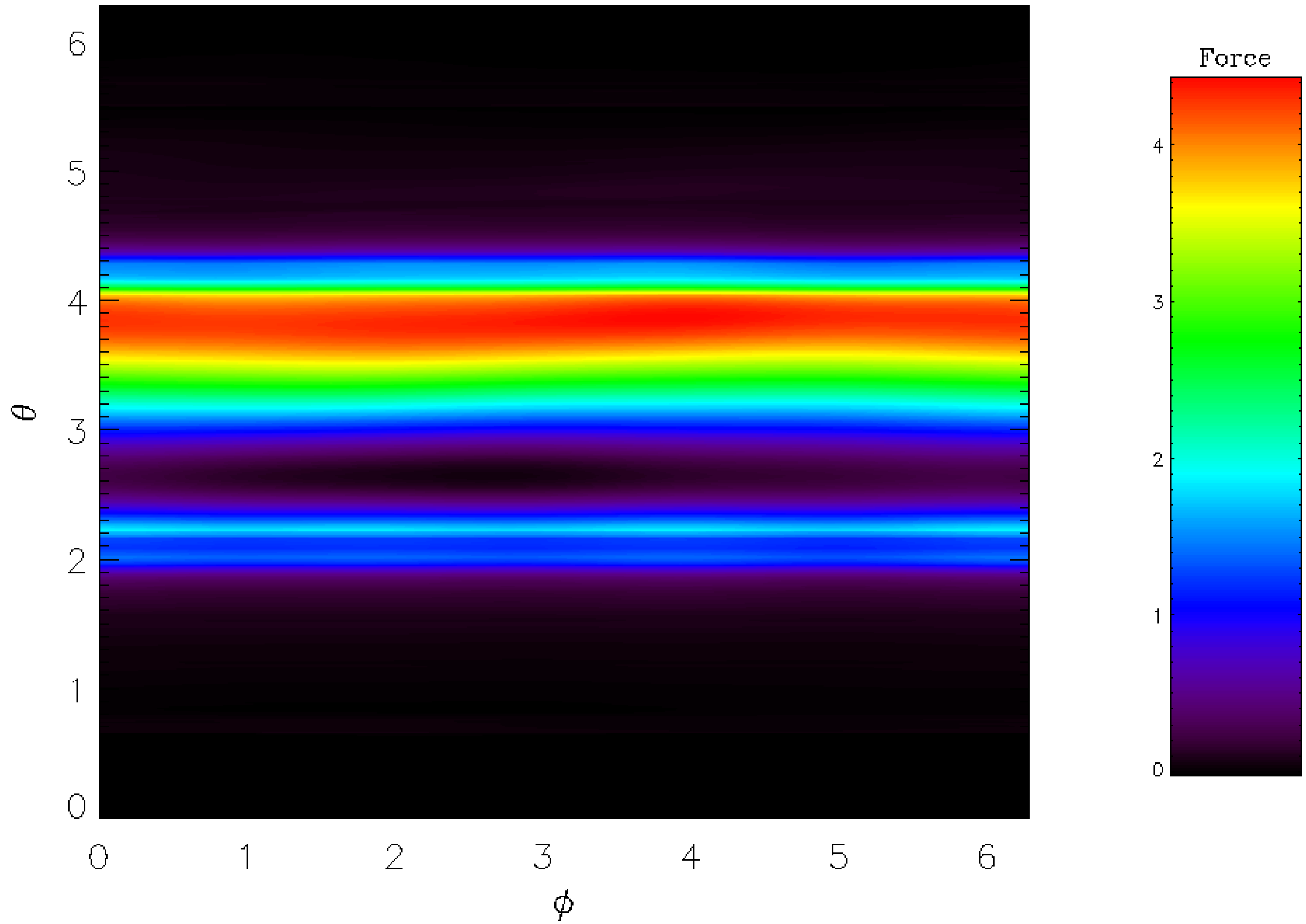

Current peaks on lower Group 12 plate.




*n*=1 component is again comparable to *n*=0.

# Non-equilibrium Wall Force Distribution, $t$=708.89




- Net horizontal force = 0.0232, in direction $\varphi$ = 4.969.
- Net vertical force = -0.563.

# Conclusions and Future Work

- M3D is capable of reproducing the qualitative characteristics of an NSTX disruption.
  - Wall-time dependence of current quench rate
  - Kink-like distribution of transient halo current

- Further work is needed to make quantitative contact with the NSTX shot database.
  - Compare with magnetics and SXR data.
  - Validate against a wider range of shots.

# Sign up for copies