M3D Simulation of Axisymmetric Sawteeth in JET

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Motivation

- Recent experiments in JET[1] and JT-60 with fast current ramp-up and external current drive exhibit a central region with zero current density.
- 1D transport timescale simulations predict that these discharges should have developed regions of *negative* current density.

Q: What prevents the current density from going negative?

A: Equilibria with sufficiently negative core current density do not exist in a torus. The plasma undergoes axisymmetric reconnection when the current begins to go negative, effectively clamping it at zero.

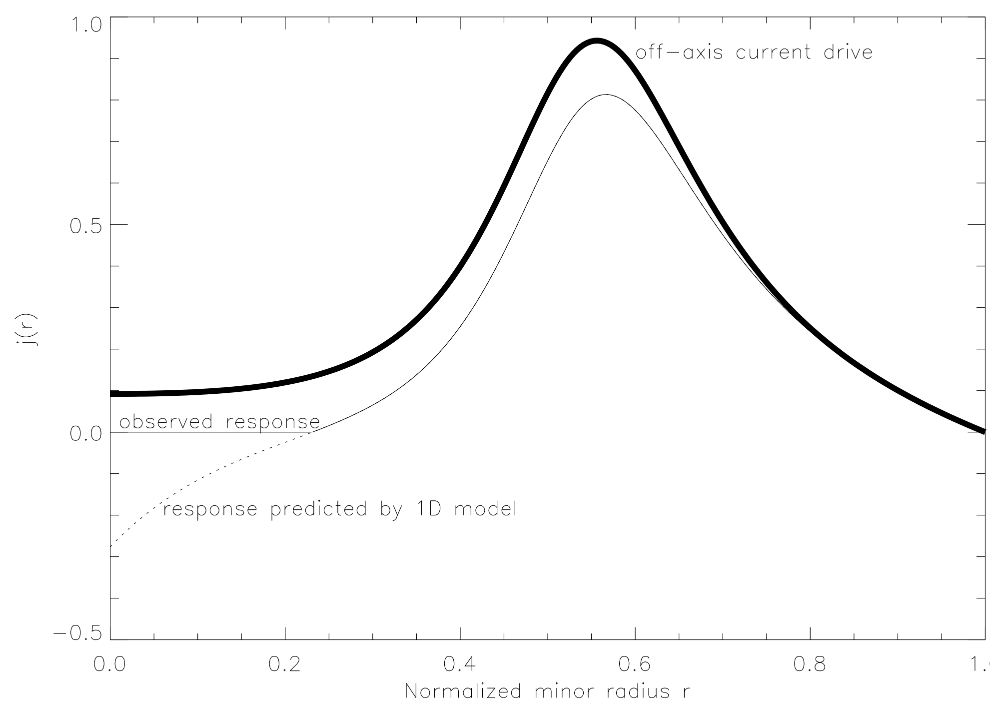
[1] See B. C. Stratton, et. al.'s poster, "Stability of JET Discharges with Zero Core Current Density" at the Tuesday afternoon poster session of this meeting for experimental details.

Modeling the Response to LHCD

- How negative *should* the current density go?
- Tokamak equilibrium codes such as TSC/LSC cannot make a prediction; no toroidal equilibrium exists with internal $\iota = 0$ surfaces.
- Therefore solve

$$\frac{\partial \psi}{\partial t} = \eta_{||} \left(\nabla^2 \psi - j_{CD} \right)$$

with a 1D code starting from initial equilibrium:



- For realistic $\eta_{||}$ and $j_{CD}(r)$, the code predicts significantly negative core current density.

- Negative core current implies existence of $\iota = 0$ surface at finite minor radius.
- Ideal linear stability analysis of straight-cylinder equilibria with such surfaces shows[2] that for small displacements $\xi(r)\cos(m\theta + k_z z)$
$$W = \frac{1}{8}\int_0^b \left[f\left(\frac{d\xi}{dr}\right)^2 + g\xi^2 \right] dr \qquad (1)$$
where
$$f = r^3(\mathbf{k}\cdot\mathbf{B})^2/(m^2 + k_z^2 r^2) \qquad (2)$$
and
$$g = \frac{(m^2-1)r(\mathbf{k}\cdot\mathbf{B})^2}{m^2 + k_z^2 r^2}$$
$$+ \frac{k_z^2 r^2}{m^2 + k_z^2 r^2}\left(8\pi p' + r(\mathbf{k}\cdot\mathbf{B})^2 + \frac{2}{r}\frac{k_z^2 r^2 B_z^2 - m^2 B_\theta^2}{m^2 + k_z^2 r^2}\right) \qquad (3)$$
- For uniform displacements of the cylinder within the $\iota = 0$ surface, $m = 1, k_z = 0$ (corresponding to $m = 1, n = 0$ in a torus), $g \to 0$, f vanishes at the only point where $d\xi/dr$ is nonzero, and the equilibrium is neutrally stable.
- However, it is unstable to resistive modes.
- For the toroidal case, no equilibrium exists, but the response to LHCD can be modeled with a resistive MHD code.

[2] Rosenbluth, et. al., *Phys. Fluids* **16**, 1894 (1973).

The M3D Code[3]

- <u>M</u>ulti-level <u>3D</u>
- Contains multiple levels of physics, geometry, and grid models in one code package.
- Capable of fundamentally nonaxisymmetric studies.
- Features of version used for this study:
  - ◇ Resistive MHD physics model
  - ◇ 2D axisymmetric geometry at JET aspect ratio.
  - ◇ Unstructured triangular mesh.
  - ◇ Explicit time-dependence.
  - ◇ Fully parallel.
  - ◇ Toroidal current drive model:

$$\mathrm{E}_\phi + (\mathrm{v} \times \mathrm{B})_\phi = \eta(j_\phi - j_{CD})$$

where

$$j_{CD}(r) = j_0 \left\{ c + \frac{a^2 r^2 (1 - br^2)}{d^2[a^2 + (r-d)^2]} \right\},$$

$j_0 = 1.3, a = 0.15, b = 1.214924, c = 7.084 \times 10^{-2}$, and $d = 0.54$.

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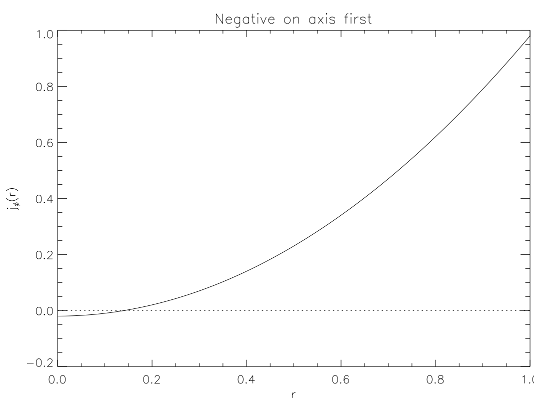
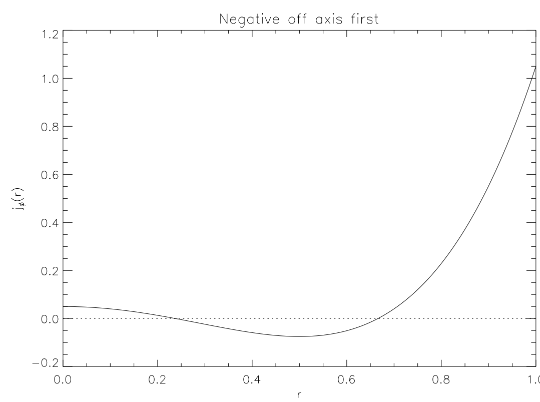
[3]Park, et. al., *Phys. Plasmas* **6**, 1796 (1999).

Initial Conditions

- Begin with a hollow (but not inverted) current equilibrium computed by VMEC.
- Current drive as above; $\eta = \mu = 10^{-2}$ initially for rapid current inversion.
- Just before central current goes negative, $\eta \to 10^{-3}$, $\mu \to 10^{-3}$
- Two possibilities exist: the current may go negative on the axis first, or off-axis first:

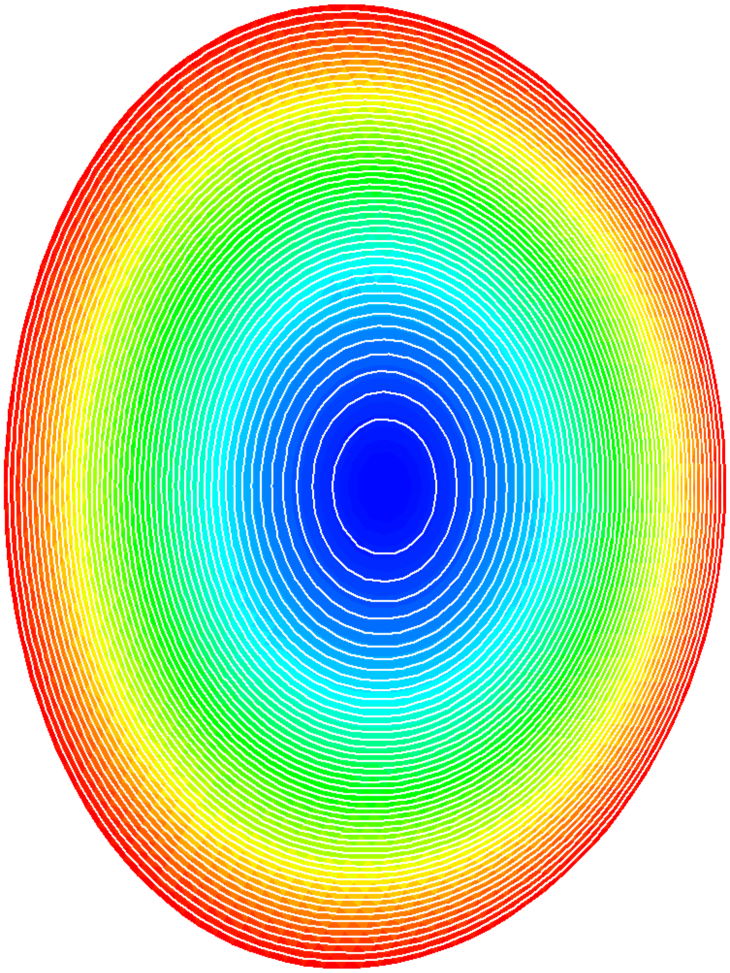




In case 1, the $\iota = 0$ surface appears immediately, and reconnection in a microscopic region around the origin should clamp the current at zero.

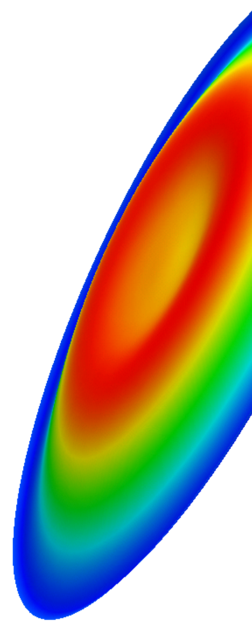
In case 2, the current may take on a finite negative value before the singular surface appears, and an axisymmetric sawtooth should be apparent.

Poloidal flux



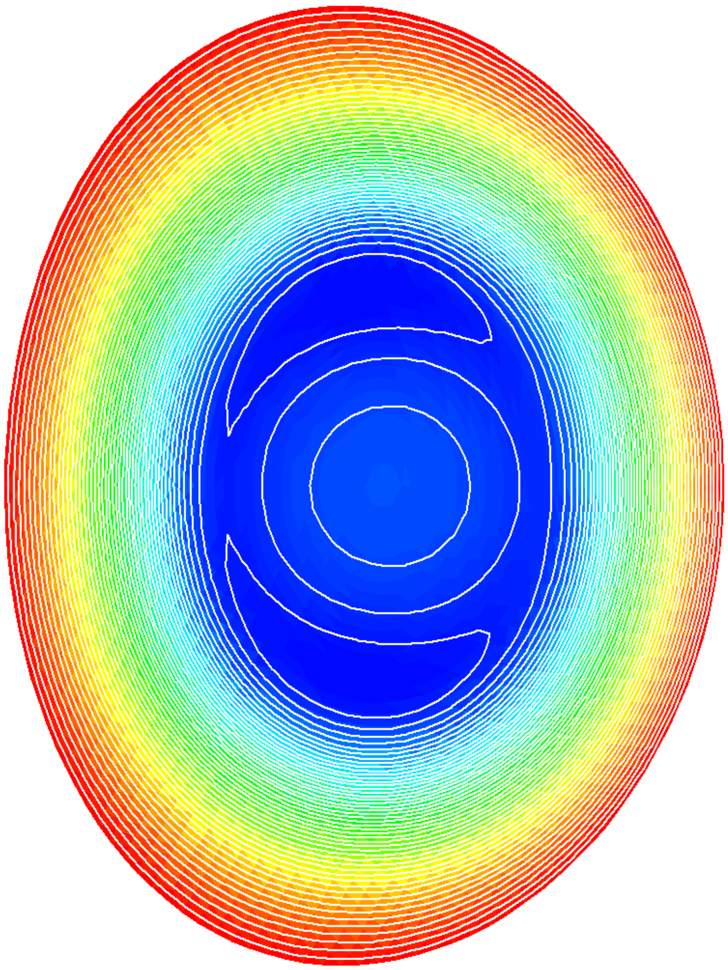
$t = 0.0\tau_A$
Initial state

Toroidal current density



$t = 0.0\tau_A$
Initial state has slightly hollow current profile

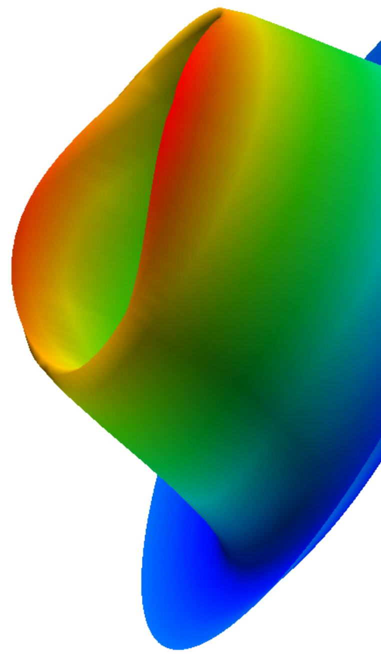
Poloidal flux



$t = 10.5\tau_A$

Islands form when current reverses

Toroidal current density

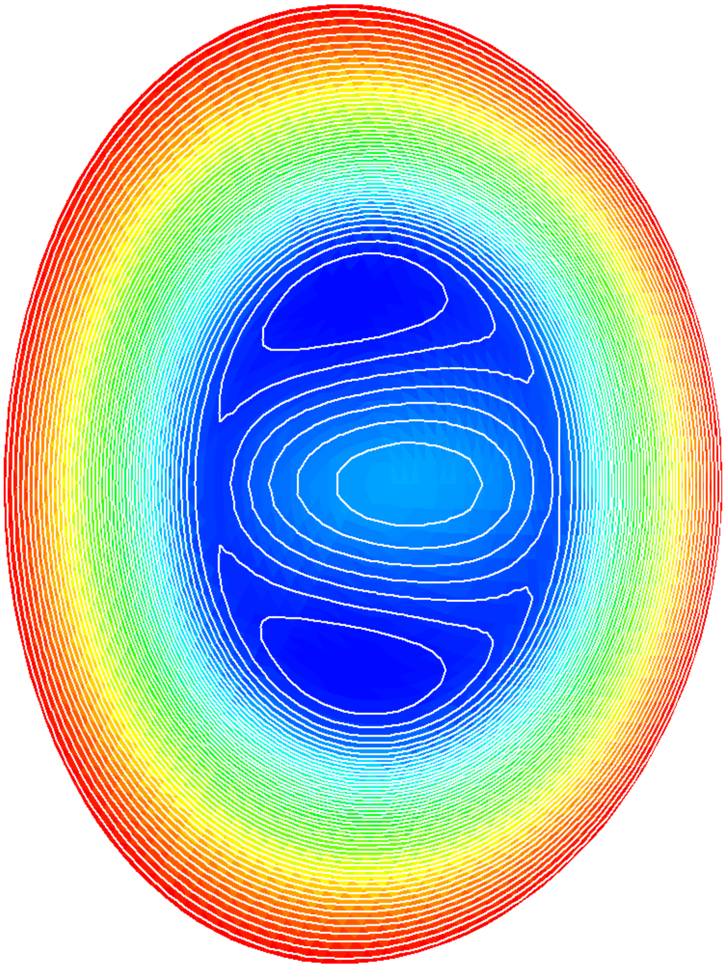


$t = 10.5\tau_A$

Current density peaks sharp

at singular surface

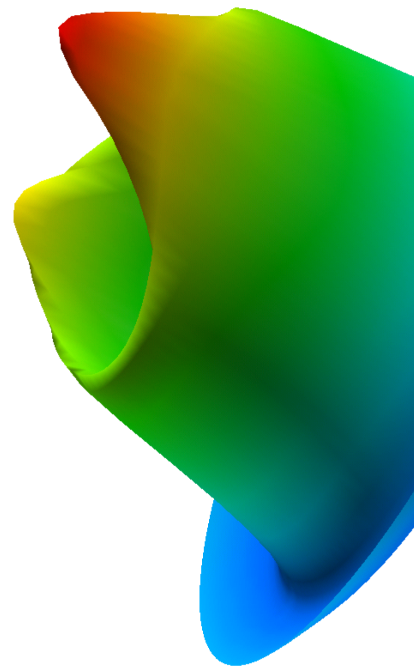
Poloidal flux



$t = 17.5\tau_A$

Central island reconnects at outboard current sheet

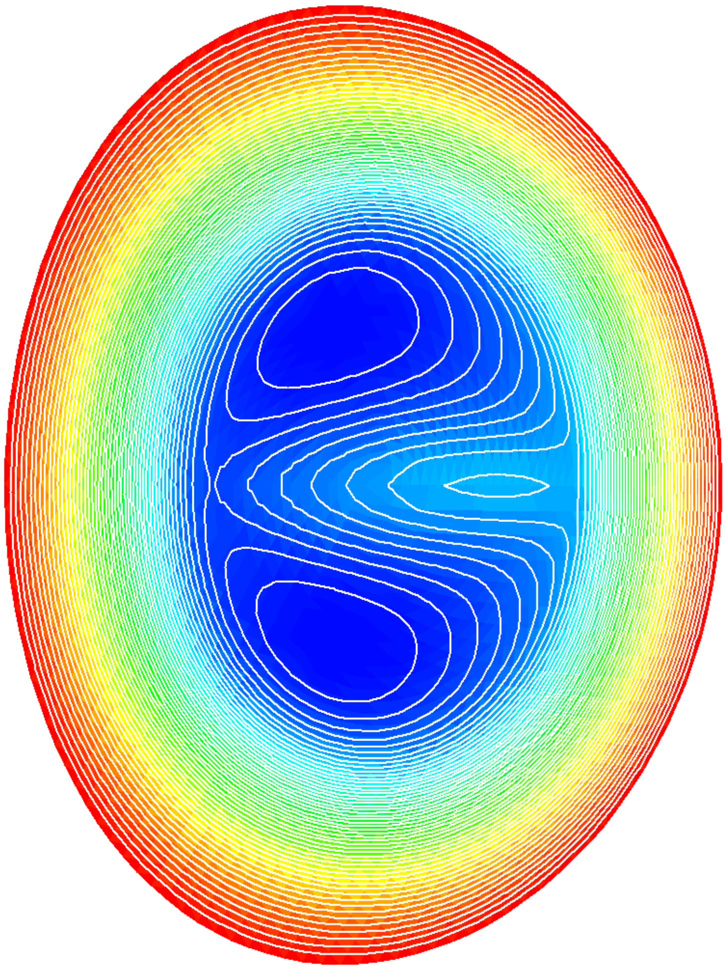
Toroidal current densit



$t = 17.5\tau_A$

Finite negative current ap
around (not at) the ax

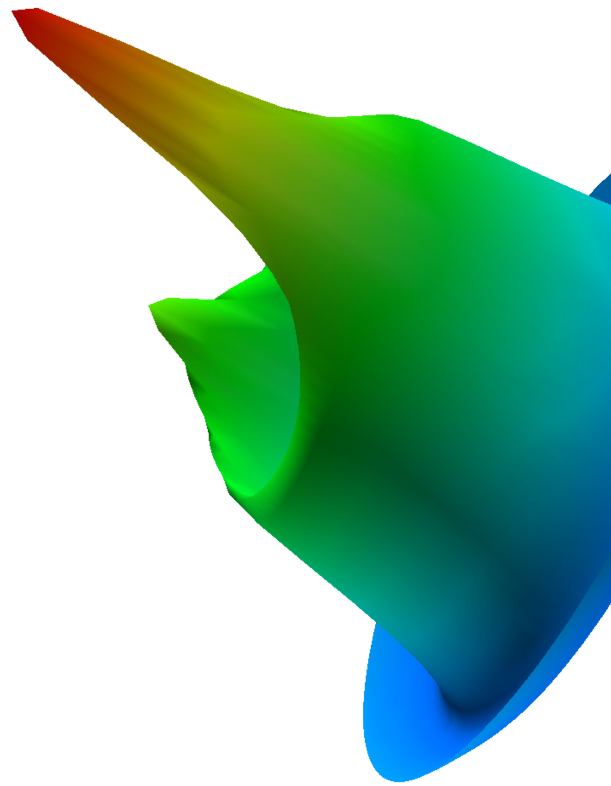
Poloidal flux



$t = 22.5\tau_A$

$m = 2$ islands begin to merge on inboard side

Toroidal current density

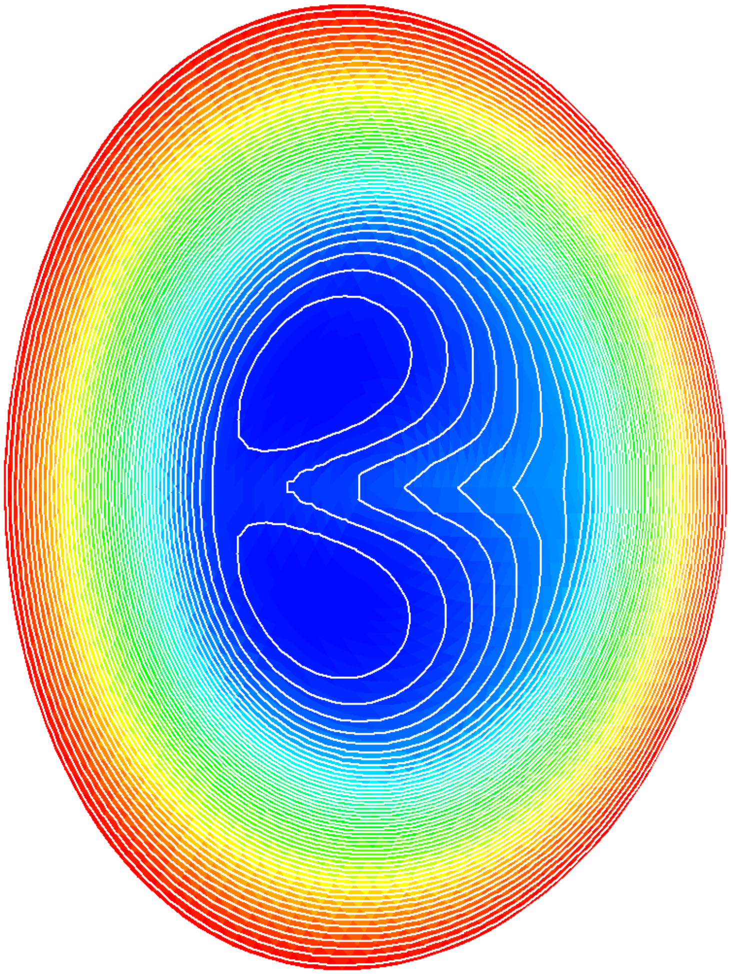


$t = 22.5\tau_A$

Current peaks at reconnecti

X-points

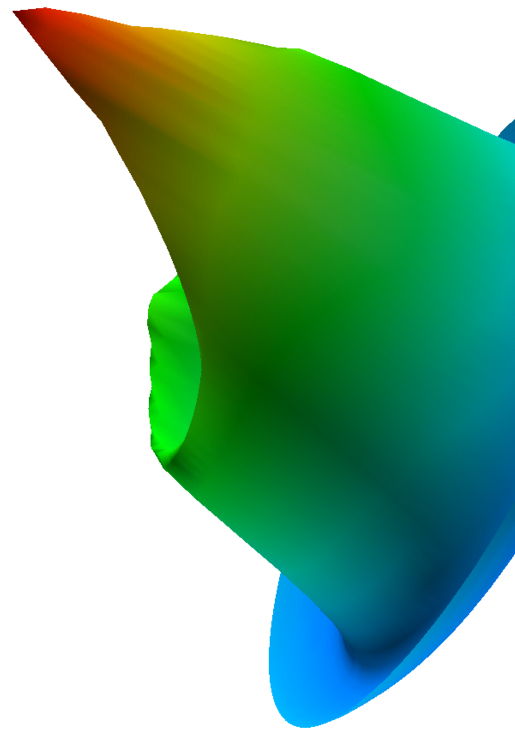
Poloidal flux



$t = 28.125\tau_A$

Initial island is gone;
others continue merging

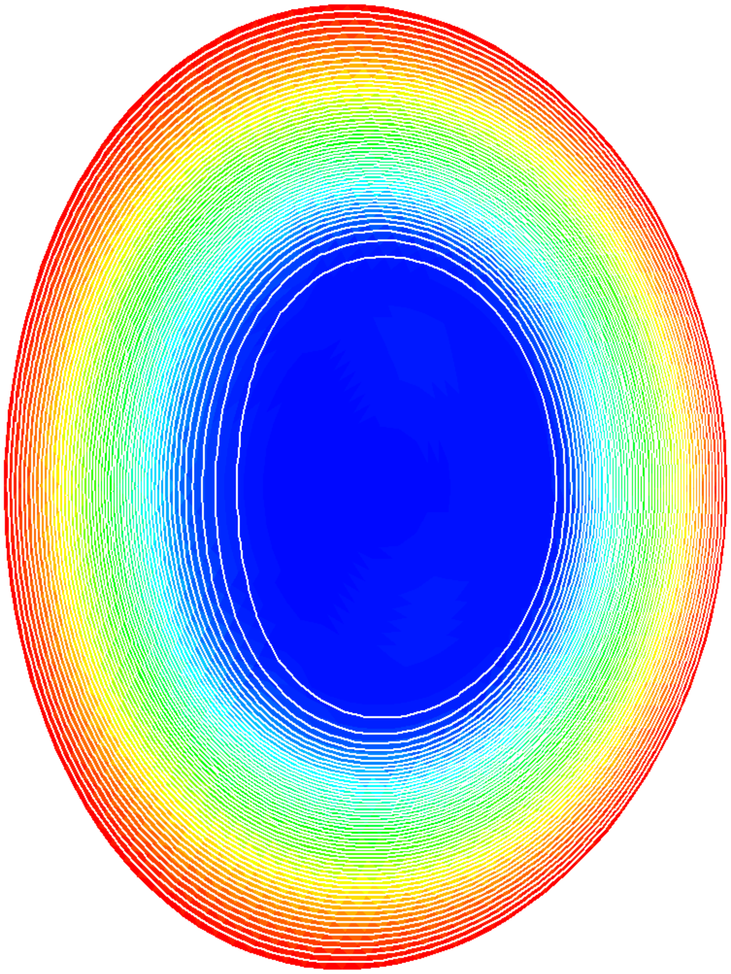
Toroidal current density



$t = 28.125\tau_A$

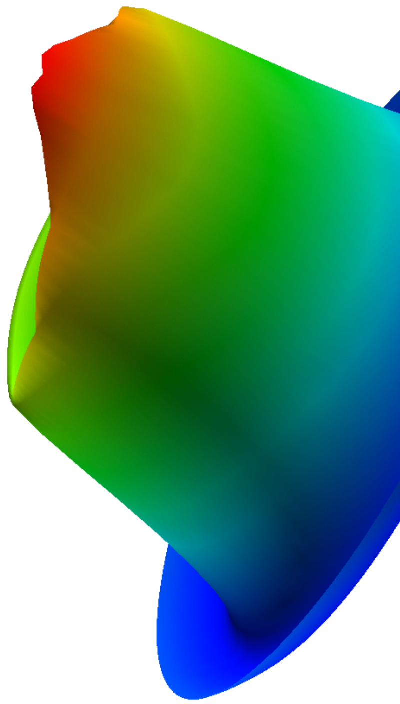
Reconnection redistributes cu
density, keeping it non-nega

Poloidal flux



$t = 34.0\tau_A$
One axisymmetric sawtooth period is complete

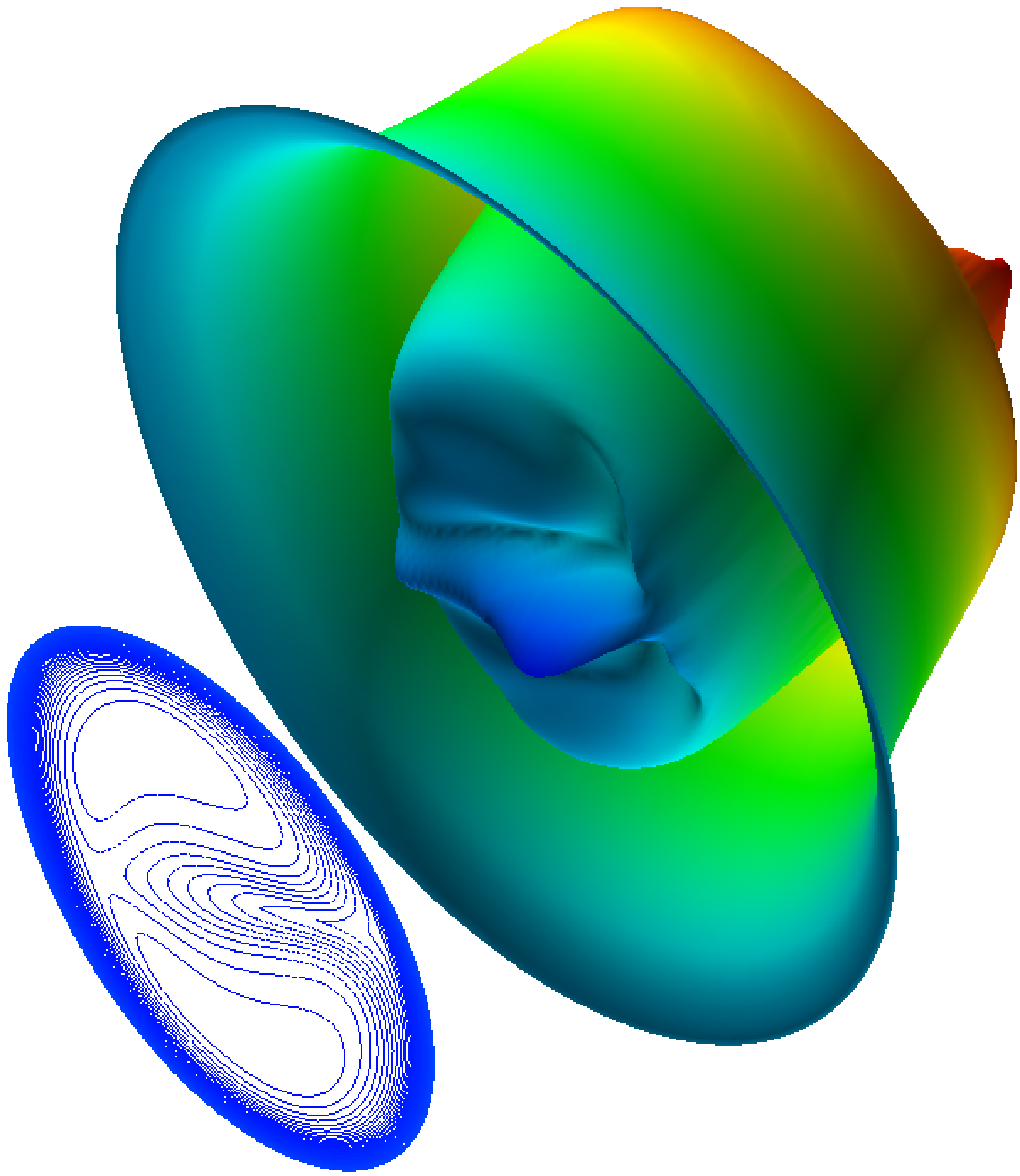
Toroidal current density



$t = 34.0\tau_A$
Current begins to flatten as sawtooth ends

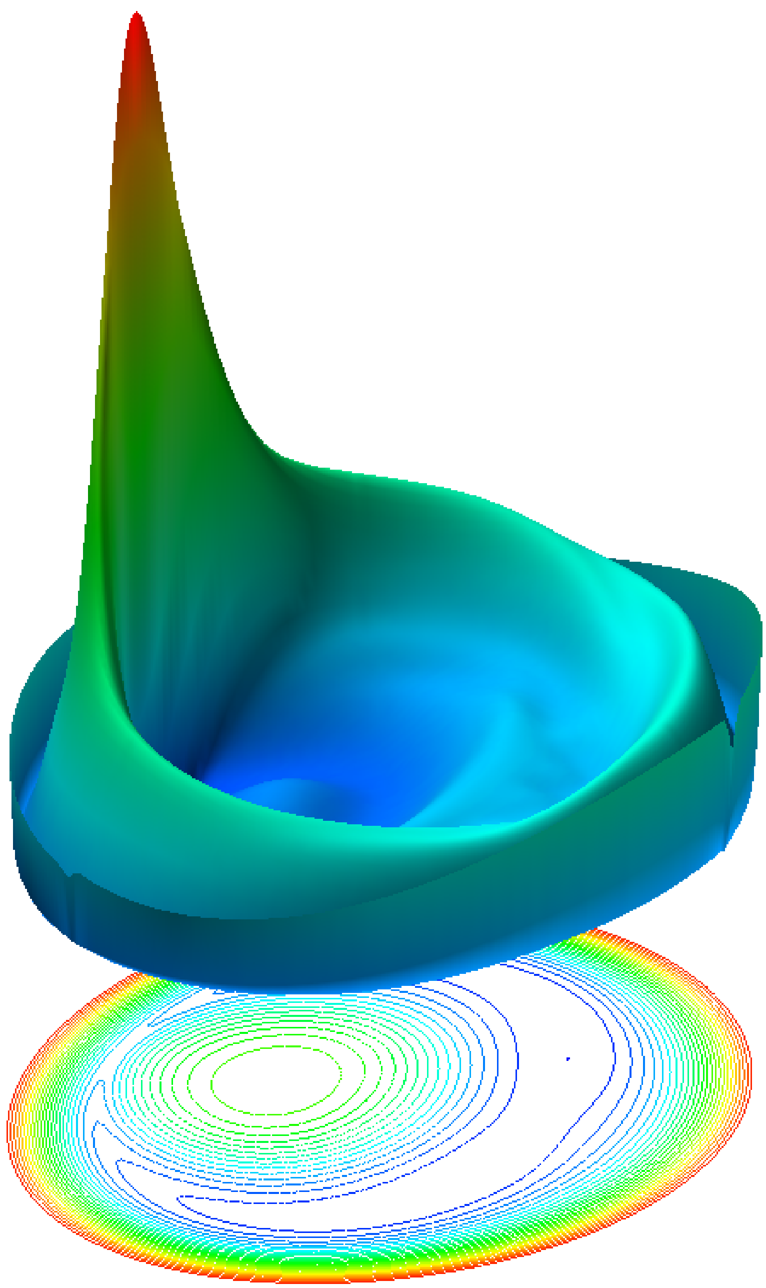
$\eta = 10^{-4}$ is Similar to $\eta = 10^{-3}$

Toroidal current surface and poloidal flux contours:



Strong Pressure Gradients Favor $m = 1$ Modes

Toroidal current surface and poloidal flux contours:



Conclusions

- Off-axis co-current drive causes transient current inversion in tokamak core, producing a non-equilibrium state.
- This leads to $n = 0, m = 1, 2, \ldots$ modes.
  - ◇ Ideally, these form singular current sheets.
  - ◇ In resistive plasmas, they cause reconnection and redistribution of current.
- If the current goes negative on-axis first, clamping at zero will be instantaneous.
- If the current goes negative off-axis first, zero-current condition will be maintained by finite-amplitude and finite-period axisymmetric sawteeth.
- Where the current goes negative first depends on the details of the current drive profile.

Future Plans

- Extend to $S > 10^4$ (JET value is $\sim 10^8$).
- Investigate $n > 0$ using full 3D runs.
- Investigate two-fluid effects on current distribution, reconnection rates with upcoming parallel two-fluid code version.