Nonlinear Calculations of Soft and Hard Beta Limits in NSTX

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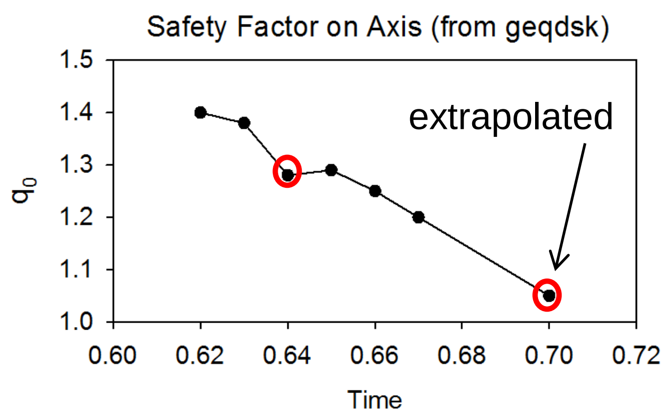
B. Lyons and J. Ramos are incorporating neoclassical effects into M3D-*C[1]*

motivation

- What causes a plasma to disrupt?
- Linear stability to all global modes for all time will ensure disruption-free operation.
- However, the converse is not true.
  - Linear instability does not necessarily imply a disruption.
- Can we use a non-linear MHD code to identify nonlinear events that lead to a disruption (or not)?

NSTX pressure driven modes with $q_0 \geq 1$

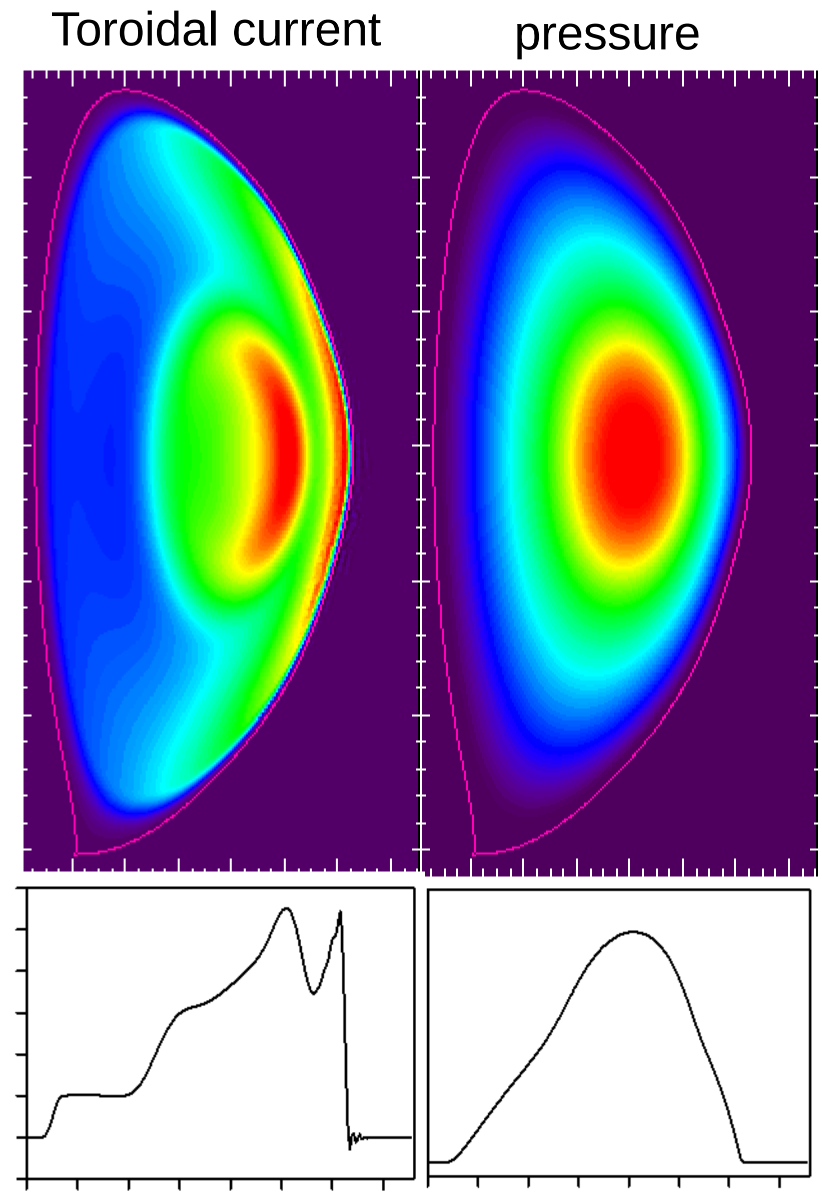
Series of geqdsk equilibrium for shot 124379 generated by S. Gerhardt for 2011 Breslau, et al NF paper.



$$\beta_P \simeq 0.8$$

$$\beta_T \simeq 7+\%$$

$$I_P \simeq 1\,MA$$



Midplane values →

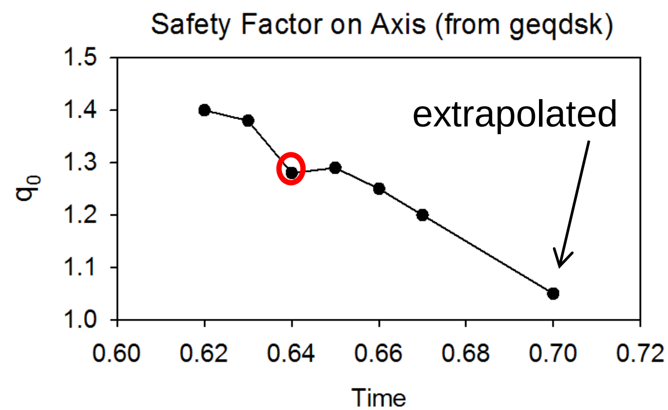
Possible mechanism for soft beta limit

Shot 124379

Time .640

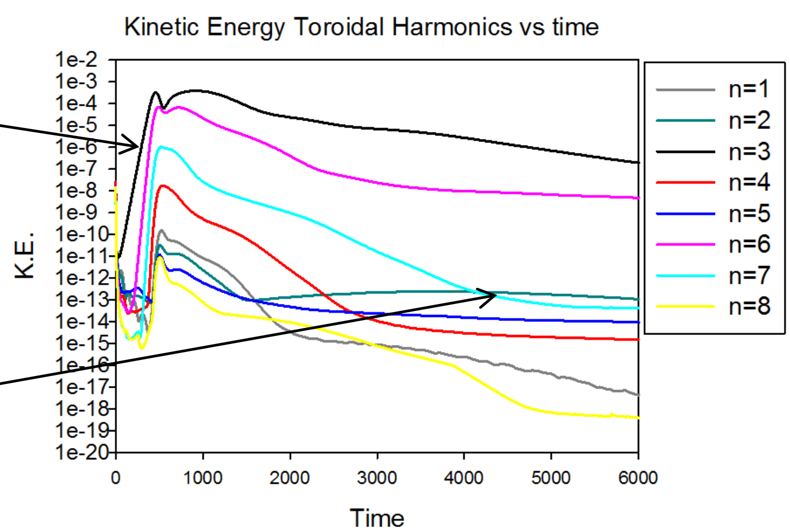
$q_0 = 1.28$

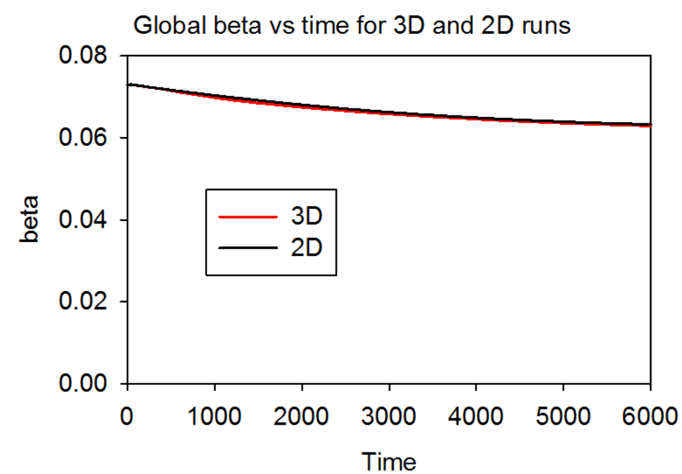
No toroidal rotation



Initially, only n=3 is unstable

All modes saturate with K.E. decreasing with time





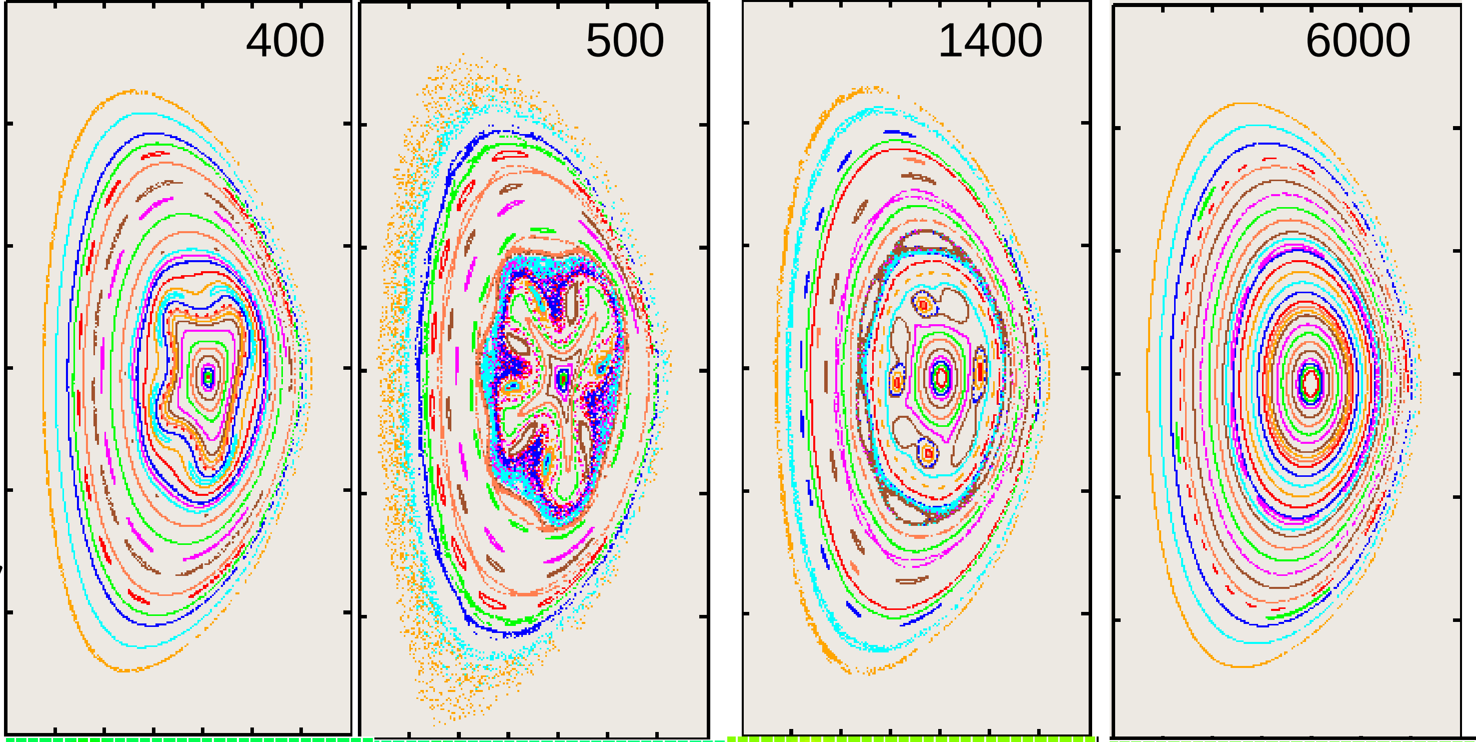
β decreases slightly in time, but no more than in an 2D run with same transport model

Soft beta limit

$q_0 = 1.28$

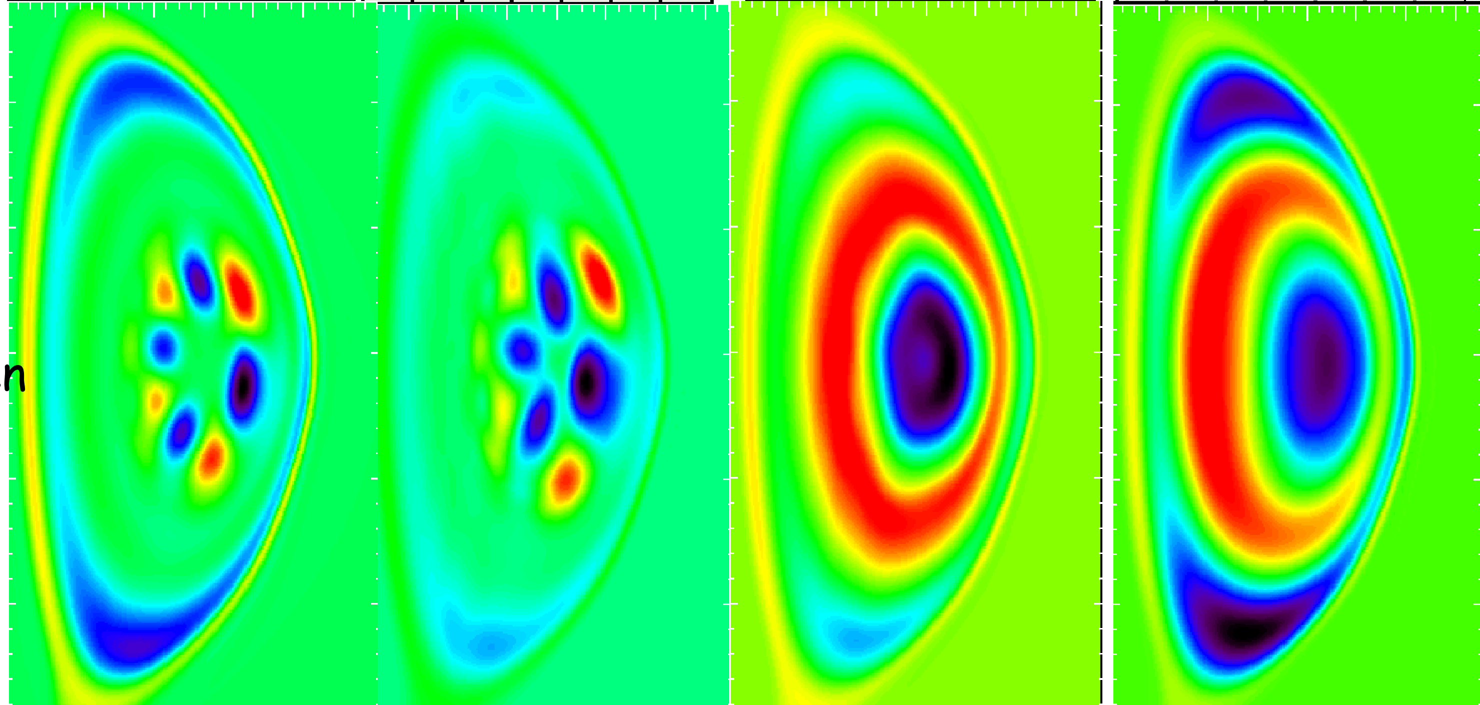
Poincare plots →

Surfaces deform, become stochastic, & completely heal.



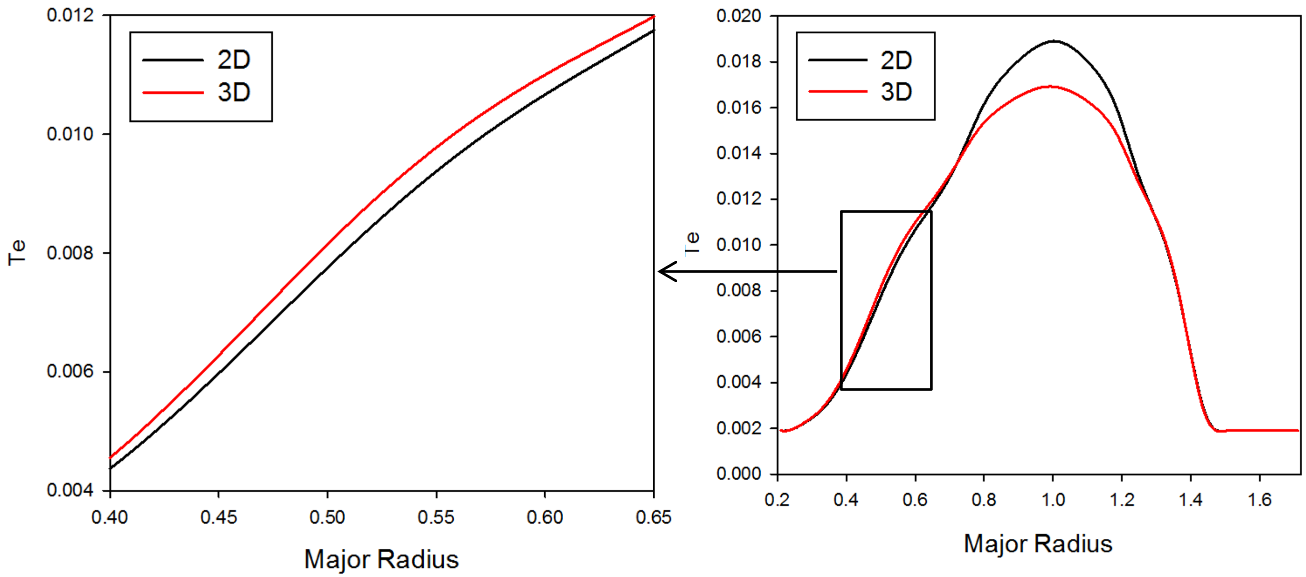
ΔTe →

First pure n=3, then nonlinear, finally axisymmetric annulus



Job33

soft beta limit -- continued



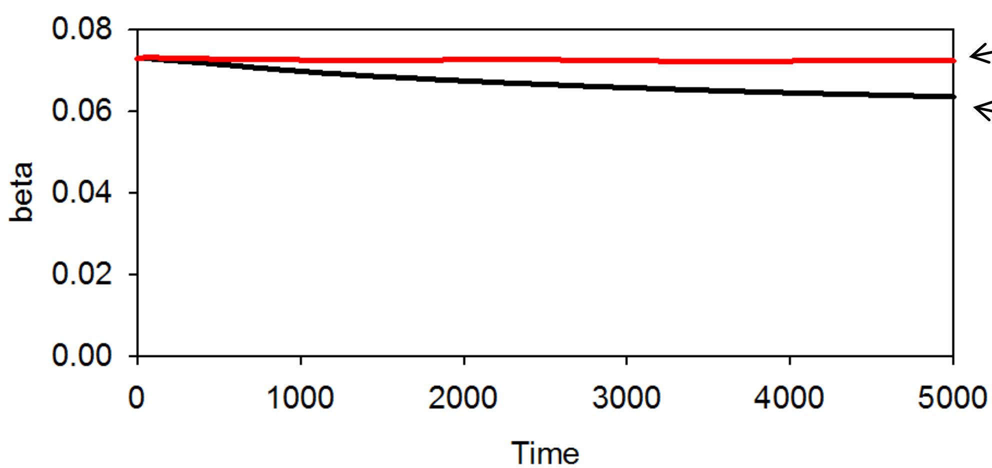
- Comparison of 3D run at t=6000 with 2D run with identical transport coeffs. shows thermal energy has been redistributed.

- Central Te differs by 10%, beta differs by only 0.6 %

dependence on heating source

- Previous run had beta decreasing in time, even in 2D case, because there was no heating source (except Ohmic).

- Now add *neutral beam source* to keep beta constant and to drive sheared toroidal rotation

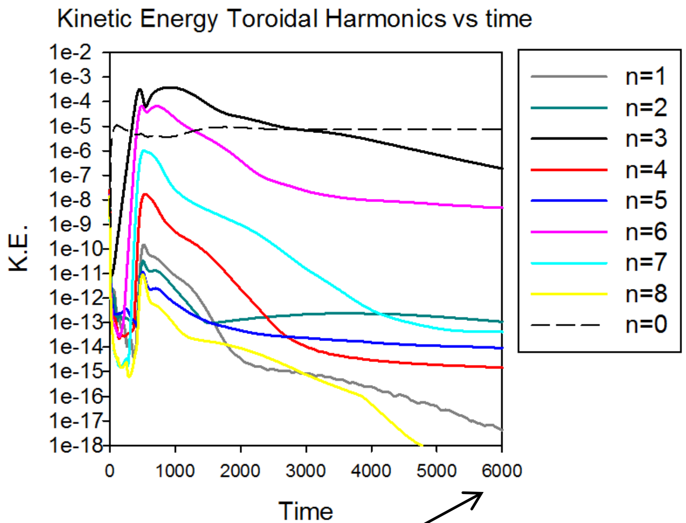


With neutral beam source

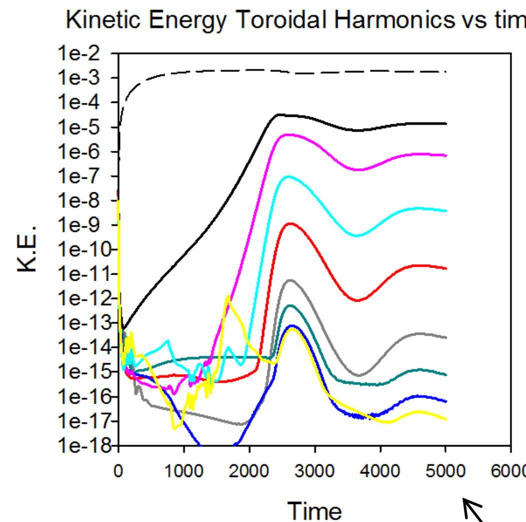
Previous run with Ohmic heating only

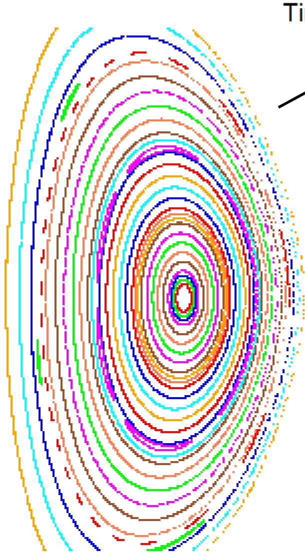
dependence on heating source–cont.

Ohmic heating only



With neutral beam source

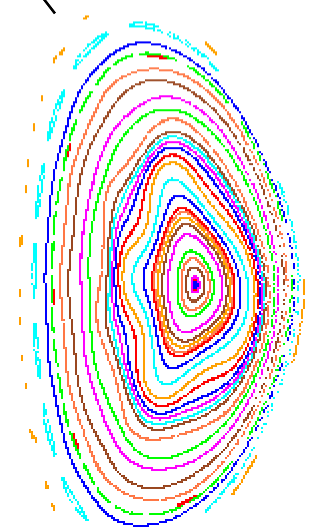




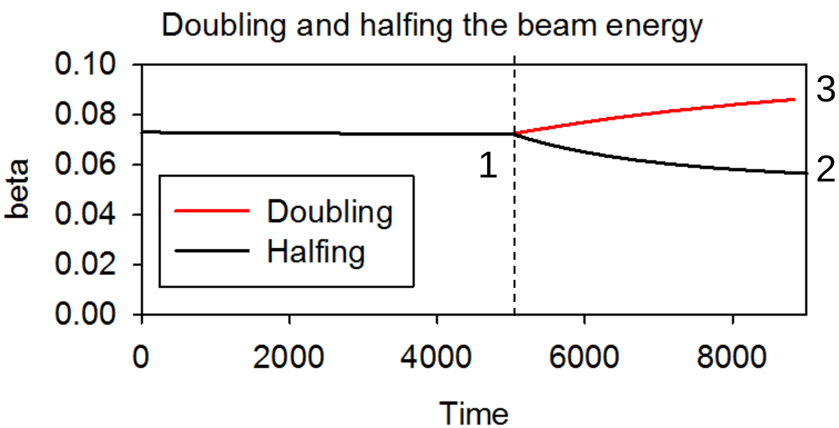
With heating and momentum source: (constant beta and sheared rotation)

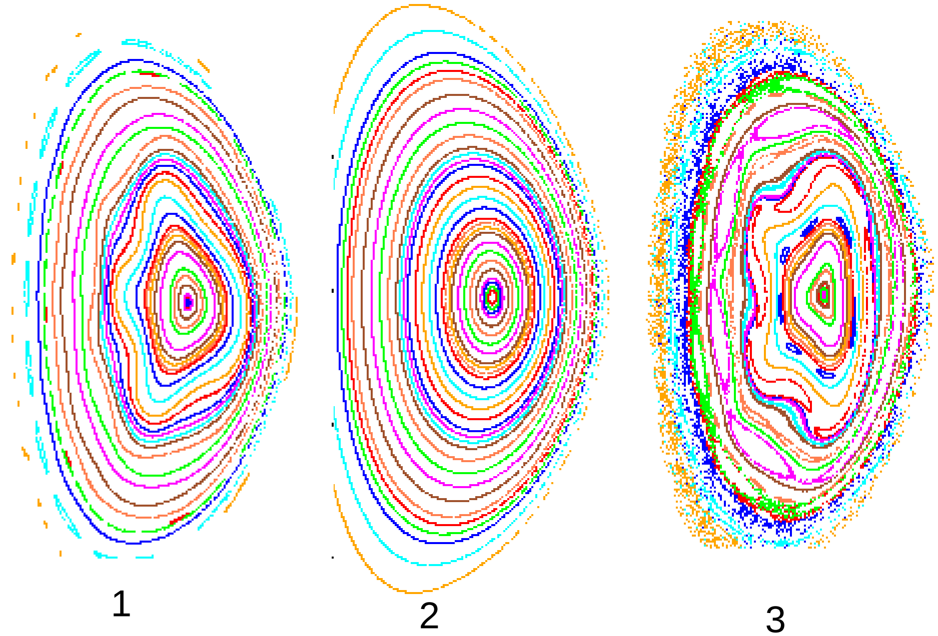
- Initial linear growth of n=3 mode much slower

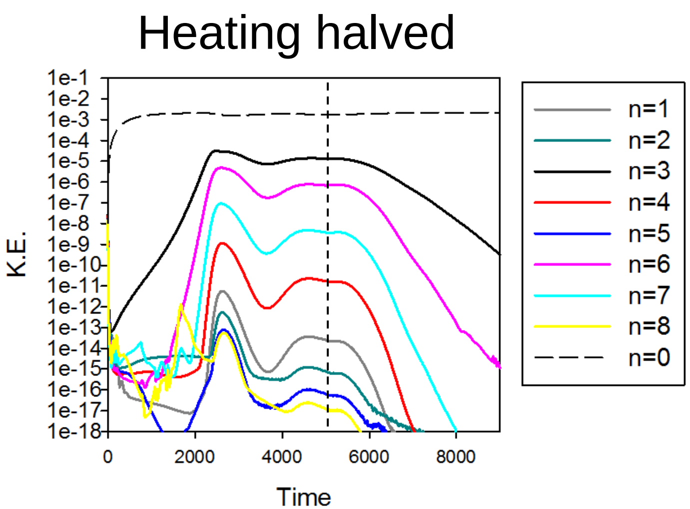
- n=3 and higher harmonics do not decay away: surfaces distort

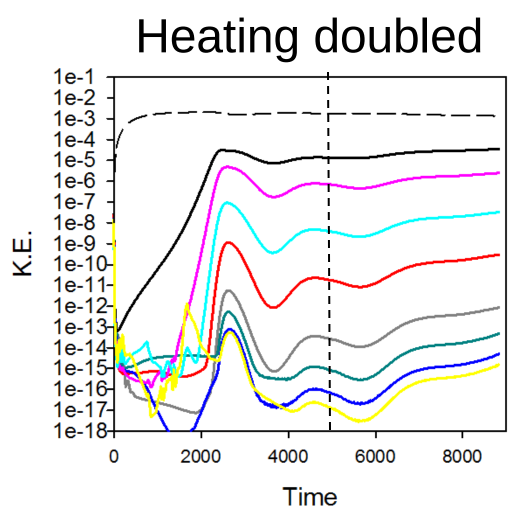


effect of increasing (decreasing) heating





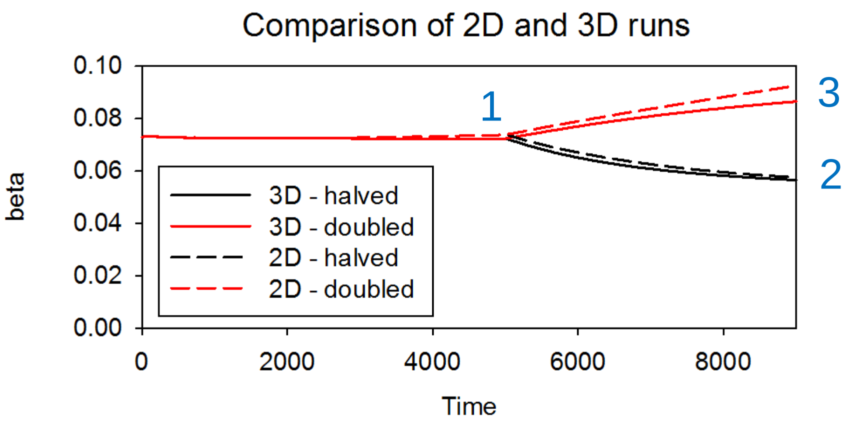




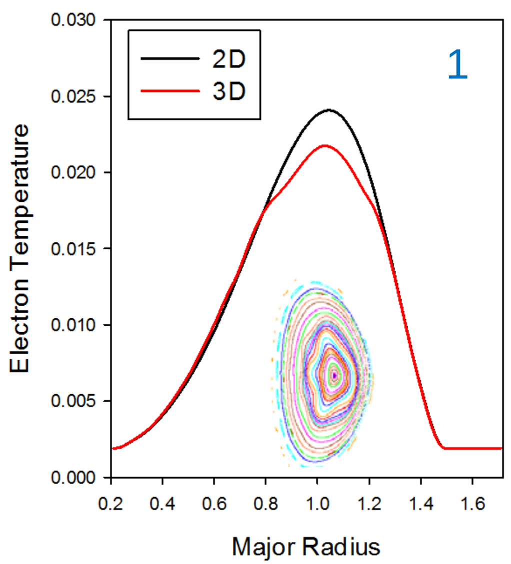
- With heating *reduced*, plasma returns to an axi-symmetric state (2)

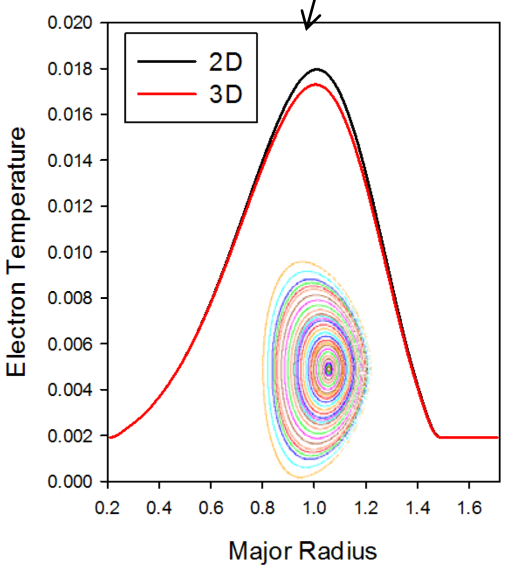
- With heating *increased*, surfaces become more distorted, but still exhibits confinement (3)

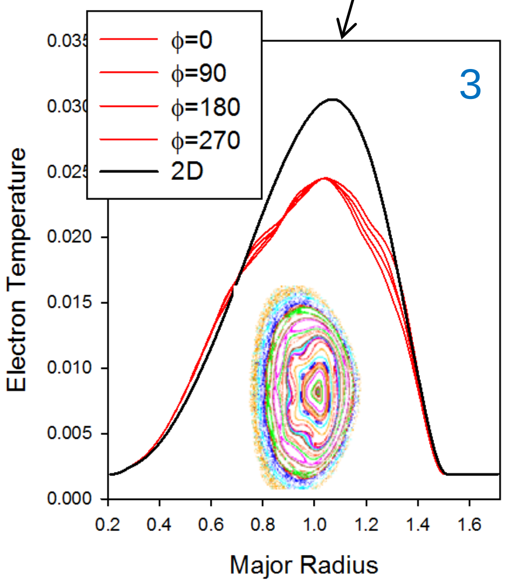
effect of increasing (decreasing) heating



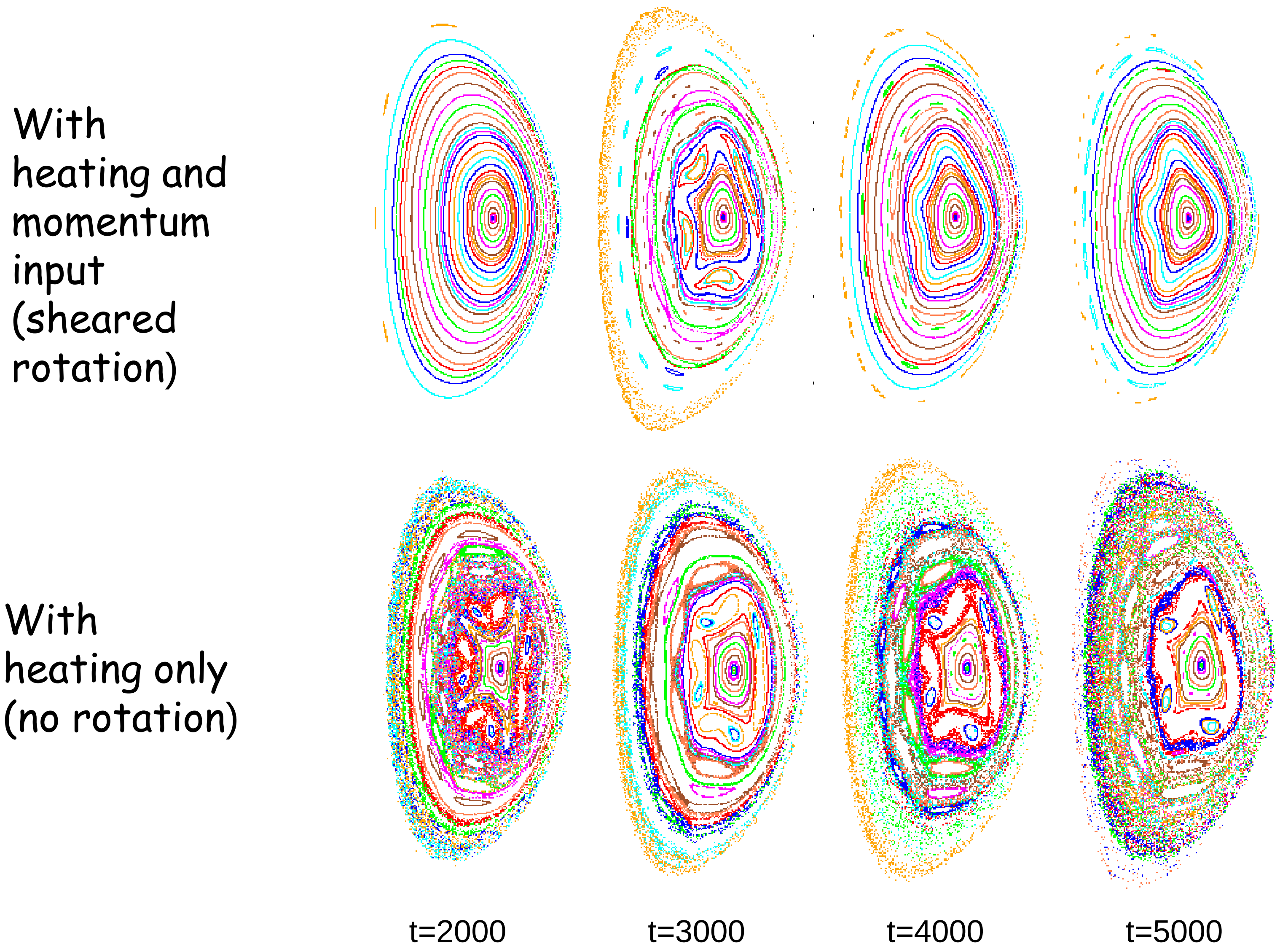
- at low heating power, Te profiles from 2D and 3D agree
- at higher heating powers, they differ considerably



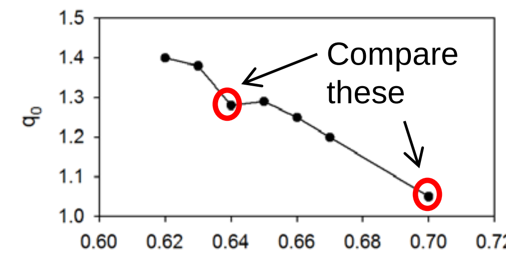


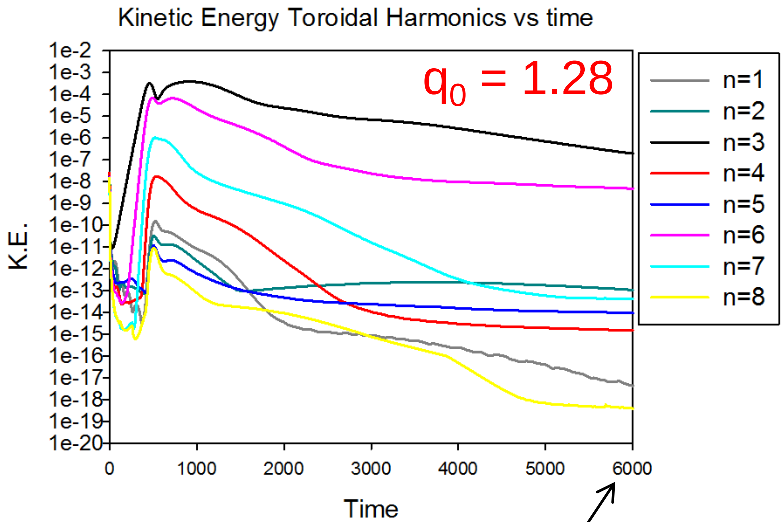


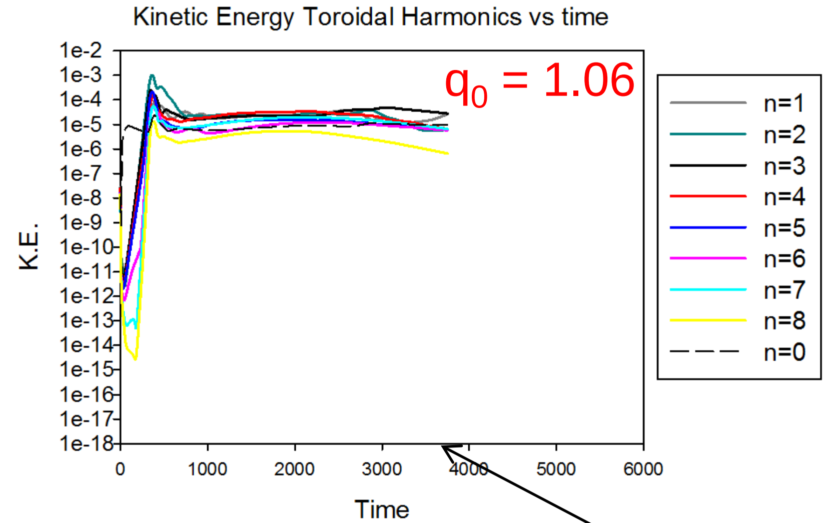
importance of sheared rotation

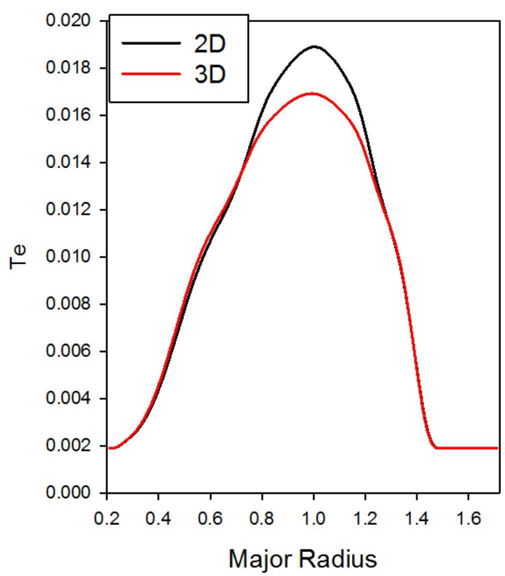


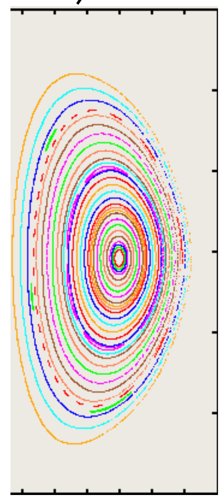
equilibrium with lower q_0 shows thermal collapse

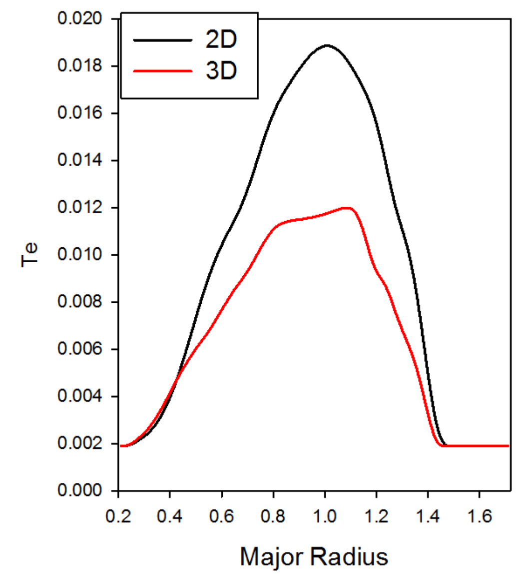


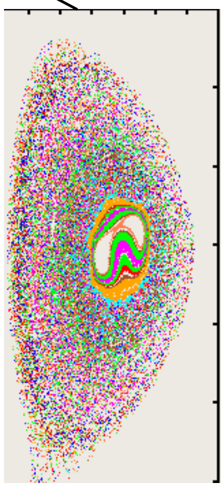






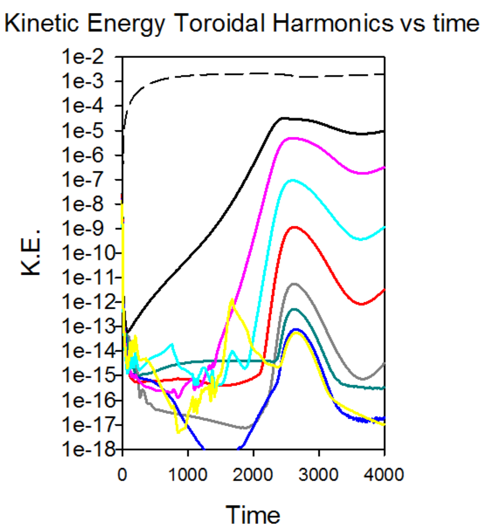




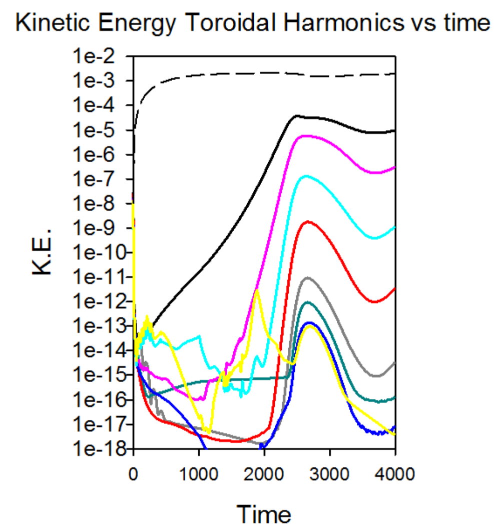


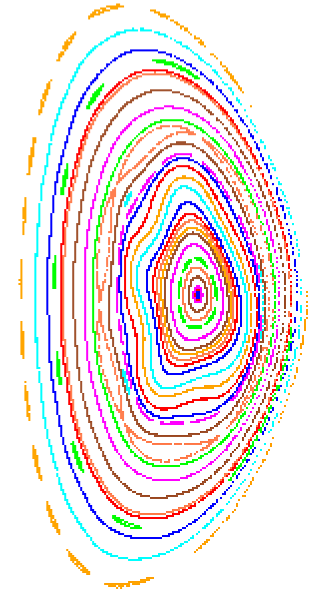
numerical convergence study

Original constant β run



With double the poloidal zones





summary

- M3D-C^1 working nonlinearly in production mode
- Studying nonlinear consequences of exceeding beta limits in NSTX for $q_0 > 1$.
- Mechanism for soft beta limit identified.
- Sheared rotation is stabilizing
- More violent behavior expected as $q_0 \rightarrow 1$
- Convergence studies underway

Exploratory Studies of Tokamak Sawteeth using M3D-C^1

Presented by S. C. Jardin

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Reconnection Workshop
Max-Plank/Princeton Center
Oct 28-29, 2013
Princeton NJ

Several types of long-time behavior have been found

We are using M3D-$\boldsymbol{C^1}$ to solve the MHD equations to compute the self-consistent long-time (transport timescale) behavior of a tokamak discharge subject to:

- loop voltage (I_P controller)
- density source (n_e controller)
- heating source (NB)
- momentum source (NB)
- shaping fields

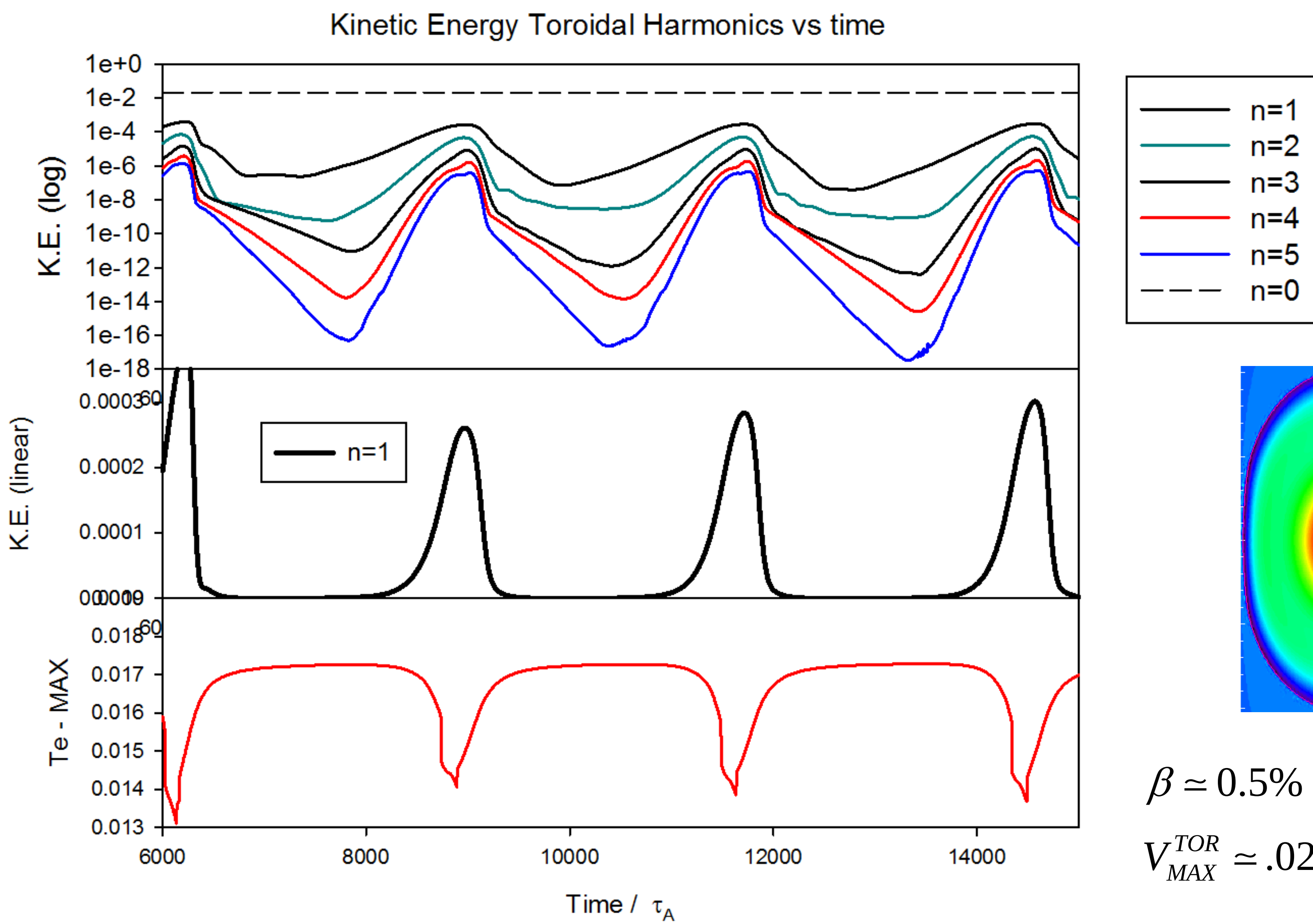
- resistivity
- viscosity
- thermal conductivity $\kappa_{\|}$ & $\kappa_{\perp}$
- particle diffusivity
- ion-skin depth c/ω_{pi}

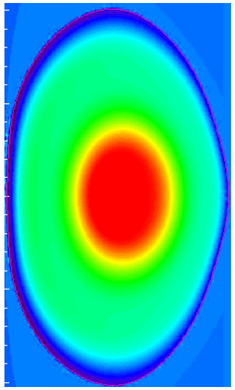
Depending on these physical parameters, we find two types of long-term behavior of the system:

- periodic oscillations (sawteeth)

- stationary helical states with flow

Canonical periodic oscillating discharge



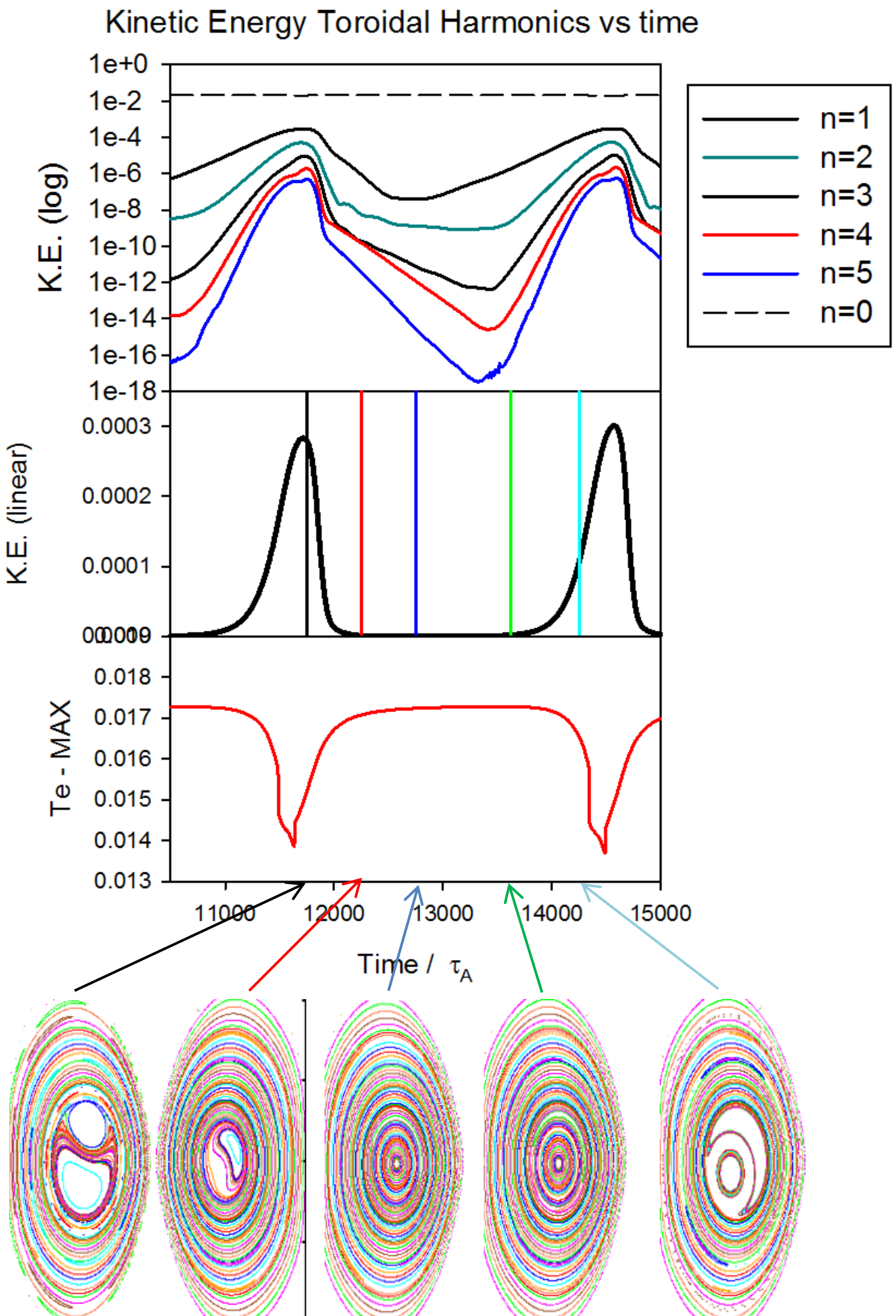


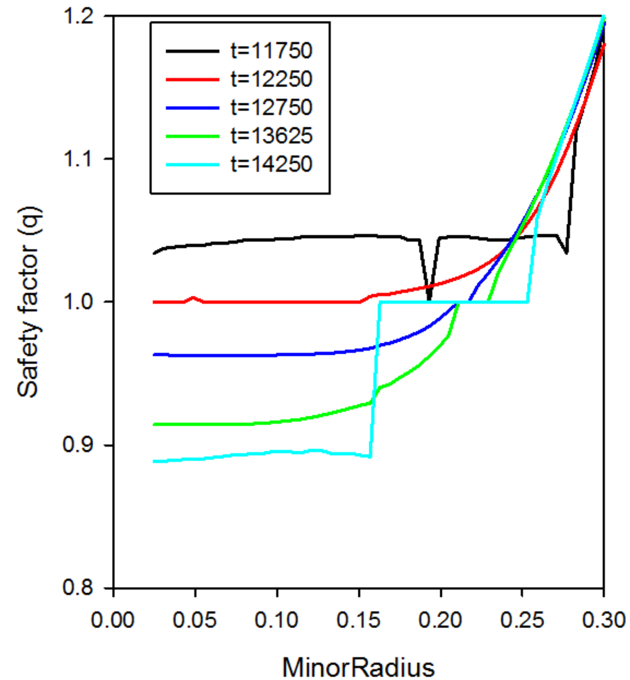
$\beta \simeq 0.5\%$ $q_{edge} \simeq 5.5$

$V_{MAX}^{TOR} \simeq .02 V_{Alfven}$ $S \simeq 10^6$

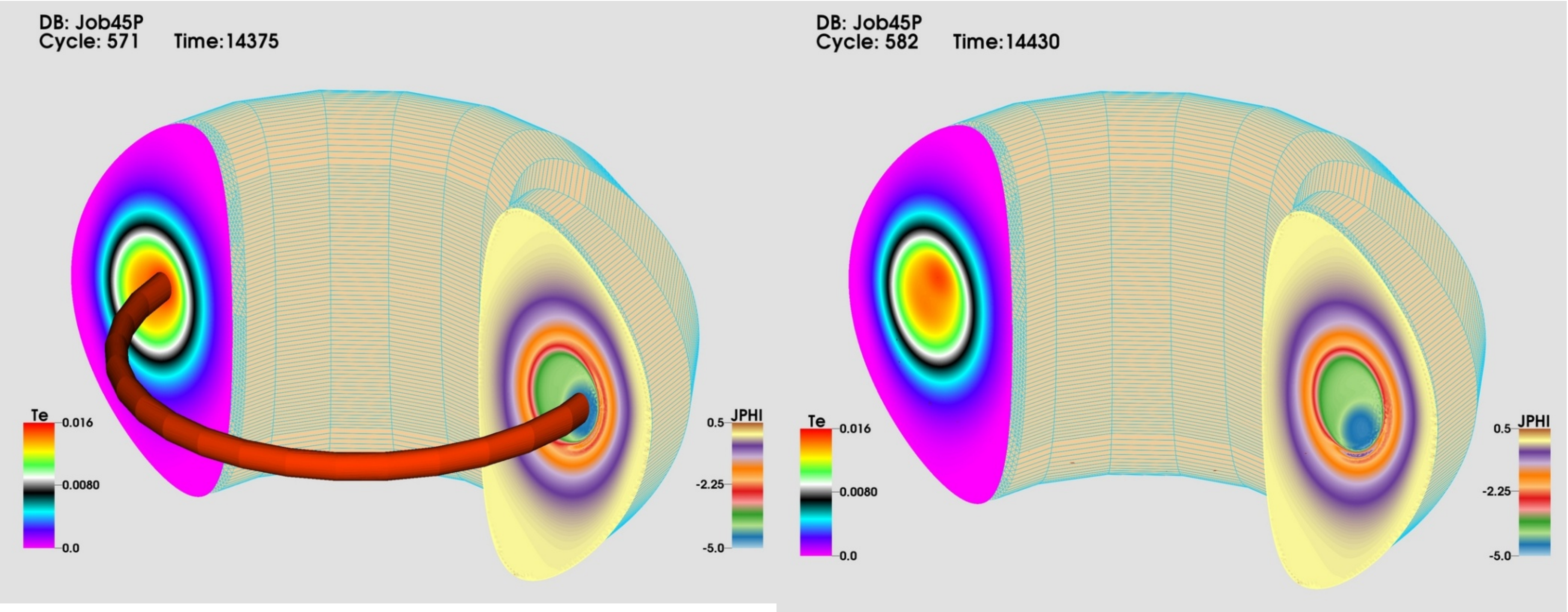
DIII-D 118164-J45

q-profile evolution during single sawtooth cycle

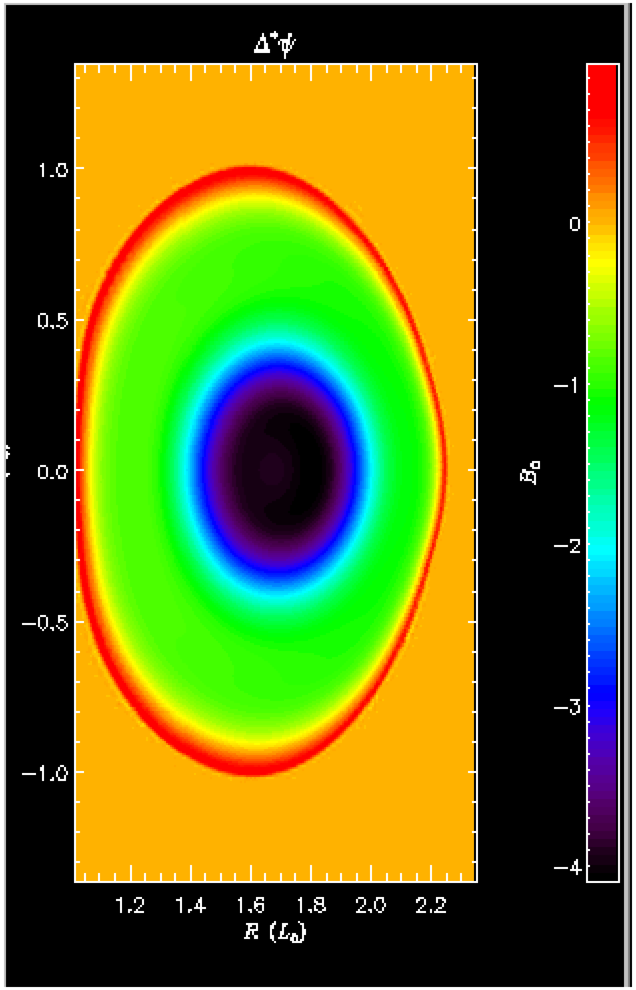




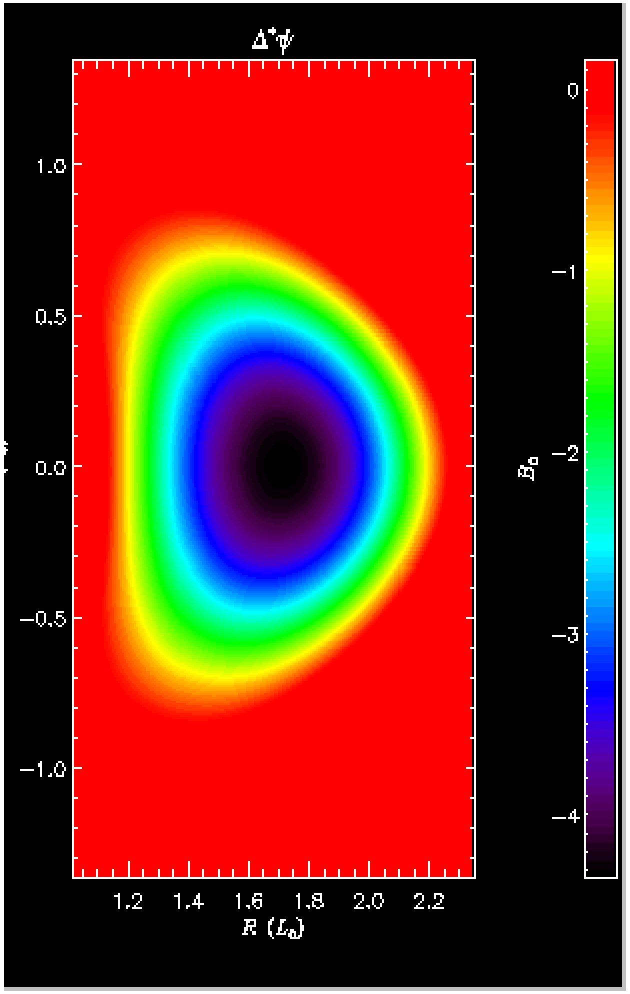
Sawtooth Movie



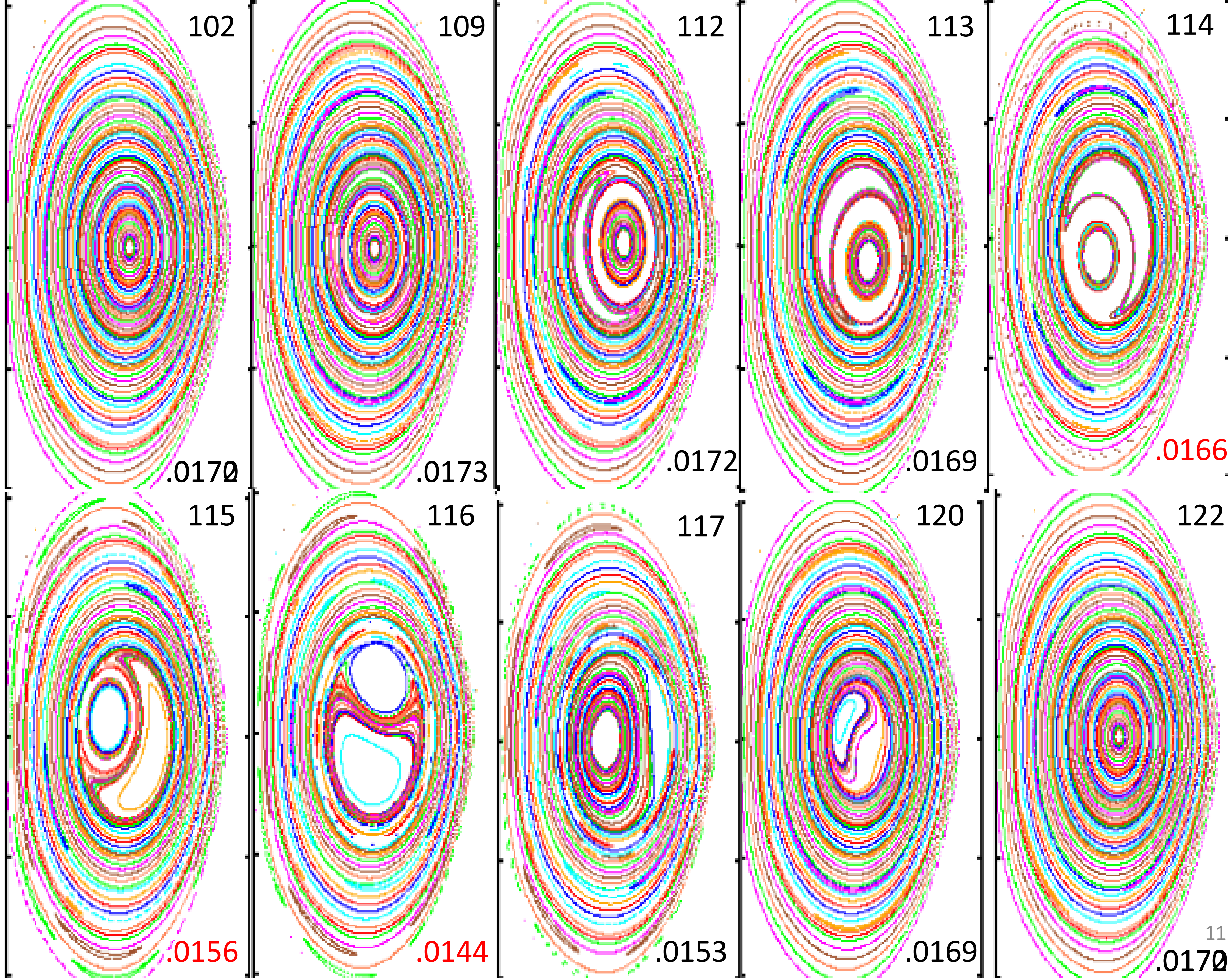
Differences in sawtooth behavior for bean-shaped and elliptical-shaped plasmas has been well documented experimentally (Lazarus, Tobias, …)



DIII-D shot 118164



DIII-D shot 118162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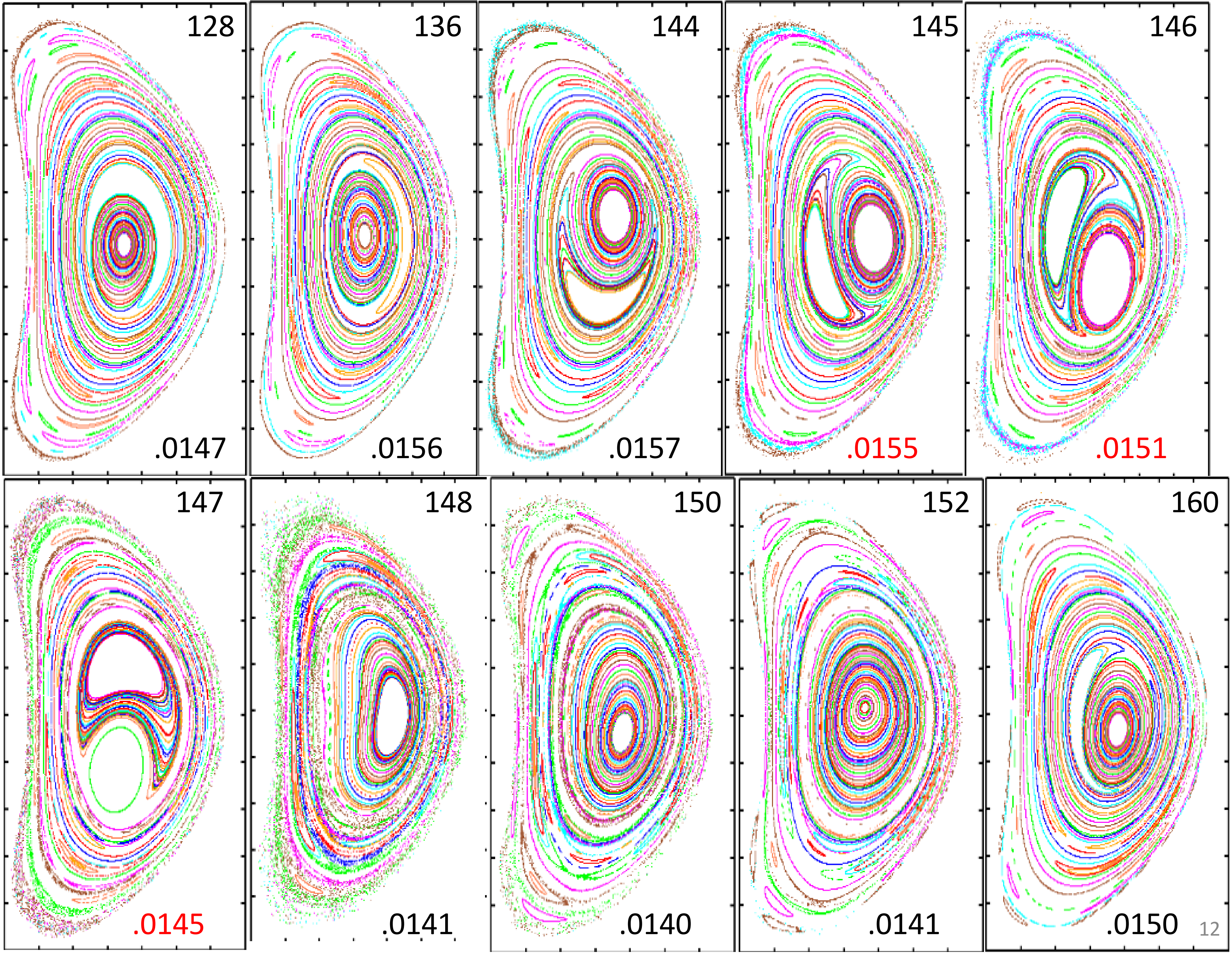
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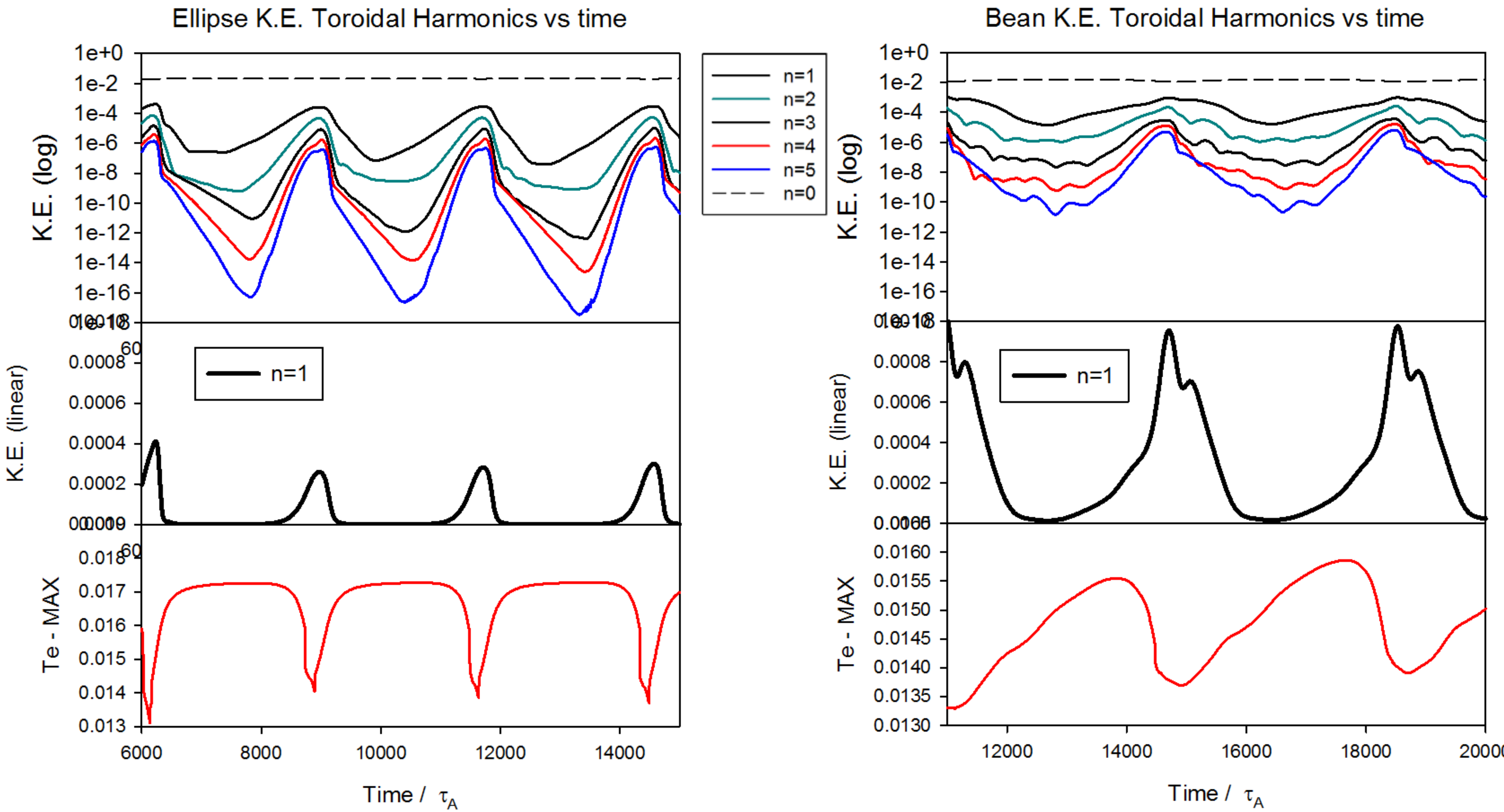
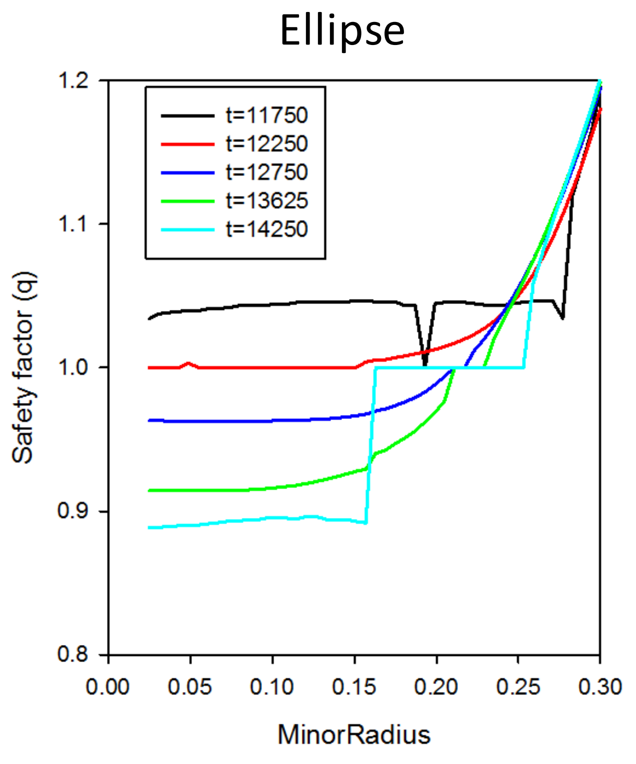
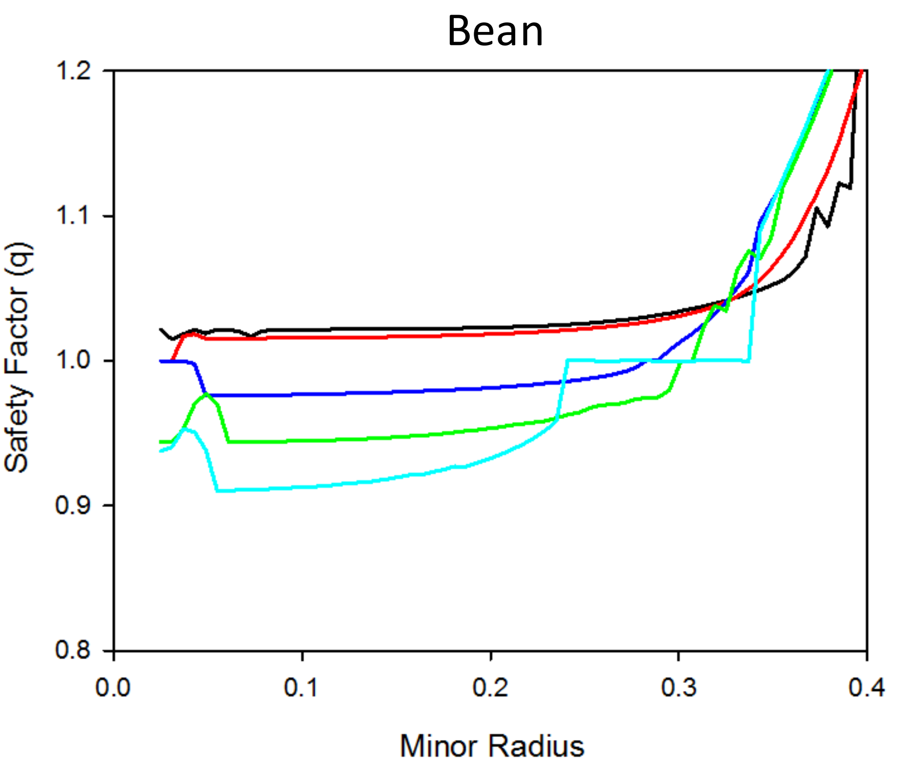
Comparison of Ellipse and Bean



Bean has shorter period, larger amplitude n=1, less decay in energy harmonics between ST.

Comparison of Ellipse and Bean



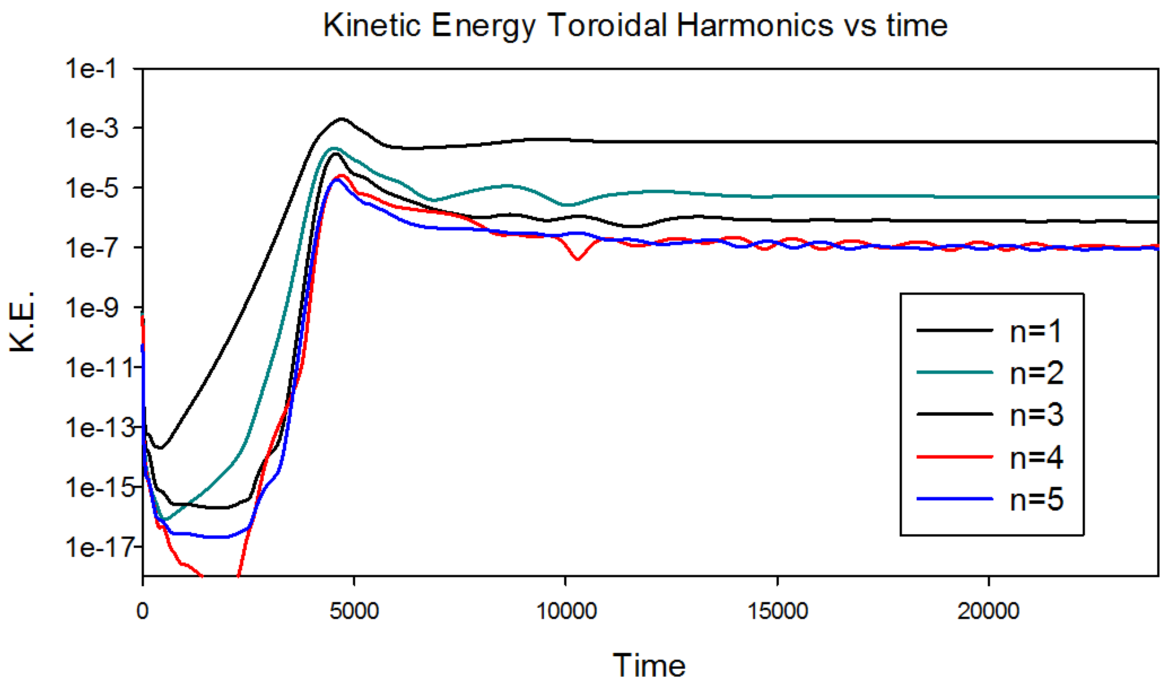


In Bean: -- q=1 surface extends to a larger radius

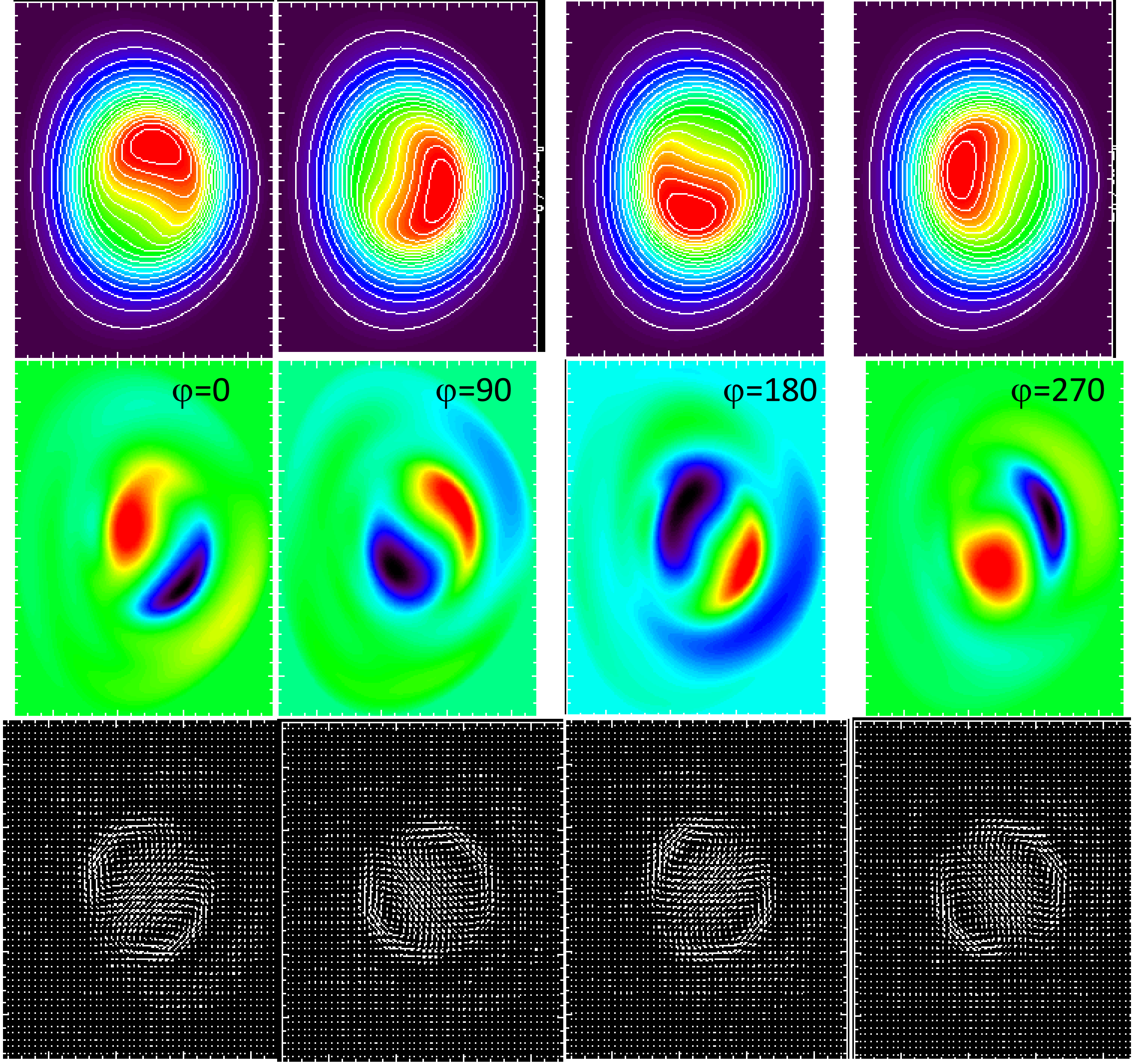
-- q(0) does not vary as much during sawtooth cycle

Stationary Helical State with Flow

In some cases, the sawteeth die out, and the system becomes stationary on all timescales.



T=24000



Electron Temperature

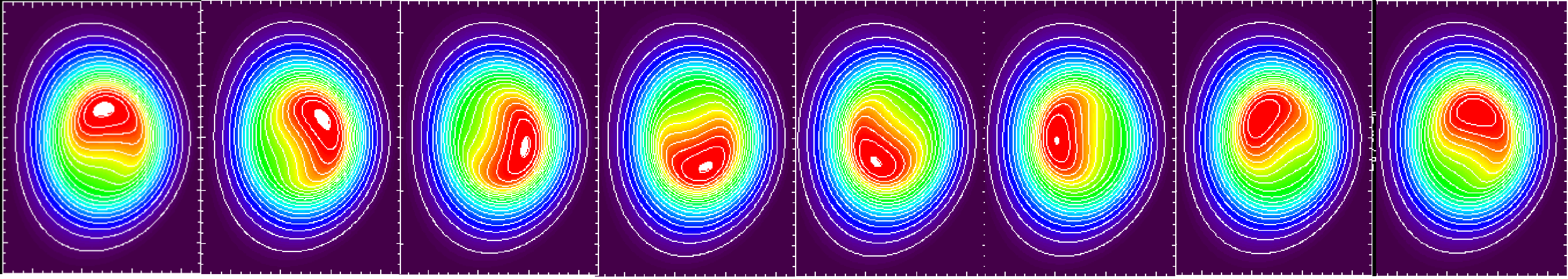
Toroidal Velocity

(Max= .004)

Poloidal Velocity

max=0.00064

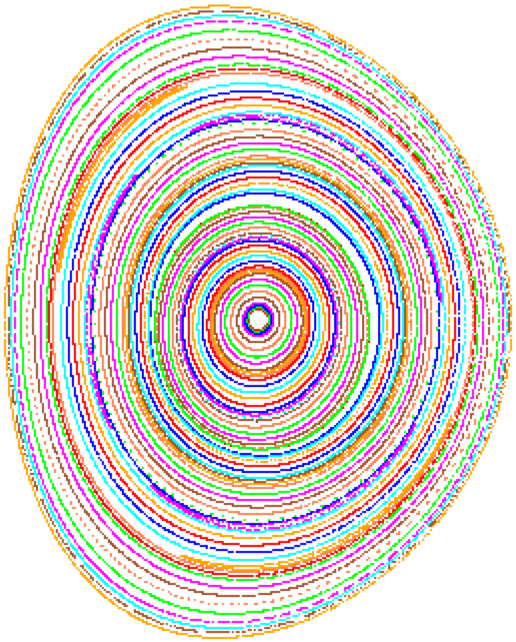
CMOD run25



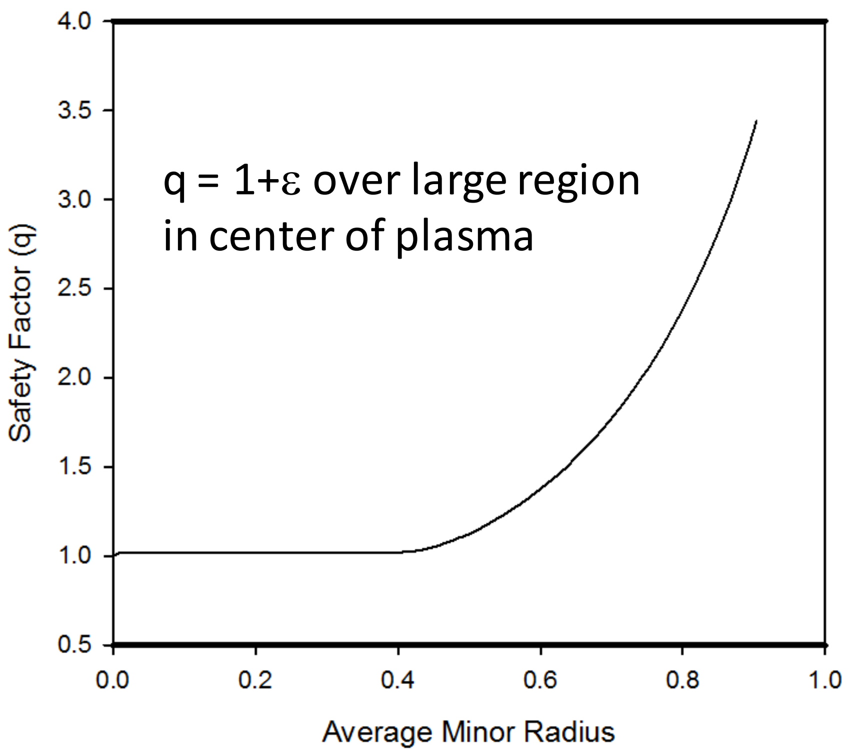
T=17000 T=20000 T=24000

Te at same poloidal location as time evolves -→

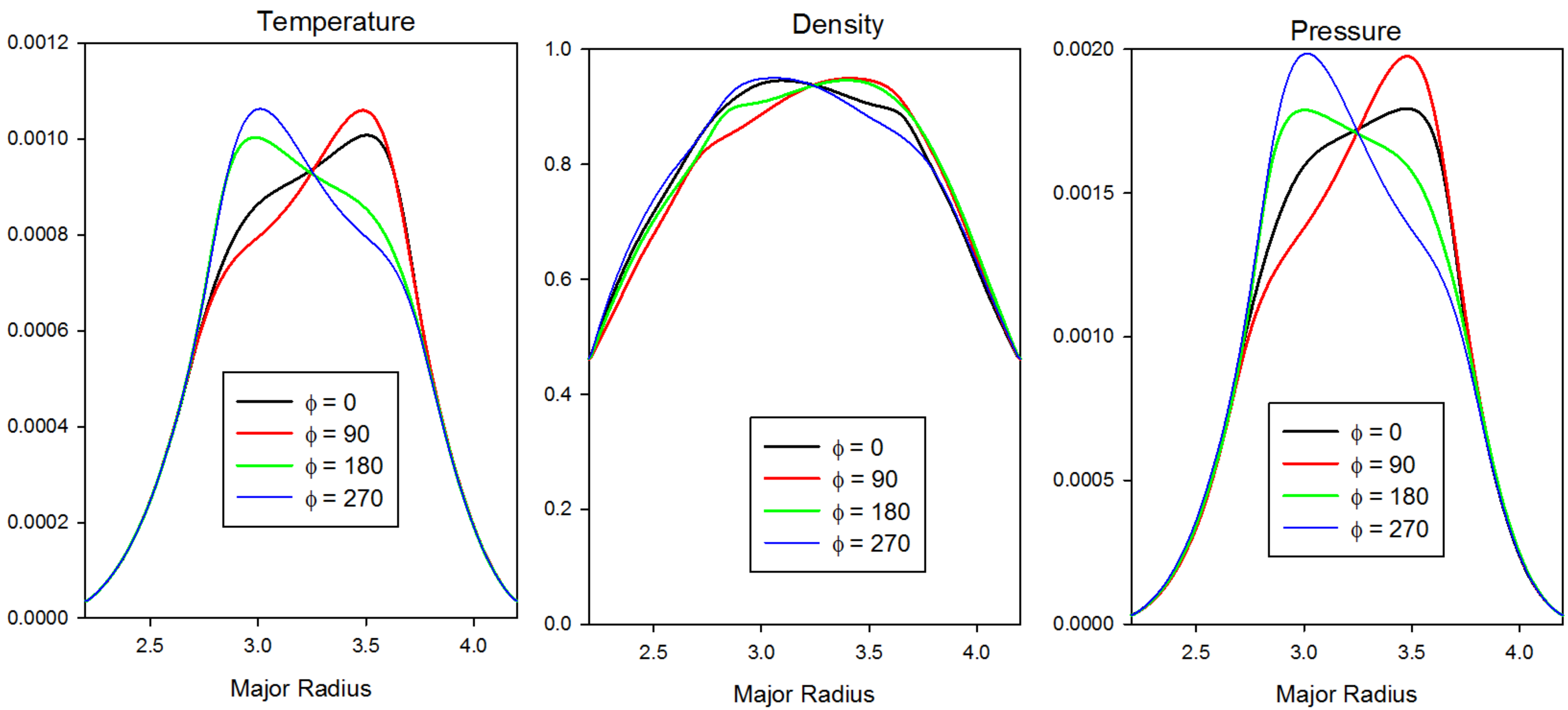
Mode is rotating every 7000 τ_A



Surfaces are almost axisymmetric with just a small m=1 island



CMOD run25



Interior to the region where $q=1+\varepsilon$, p, n, and T profiles are not constant on the magnetic surfaces. i.e., $p \neq p(\psi)$

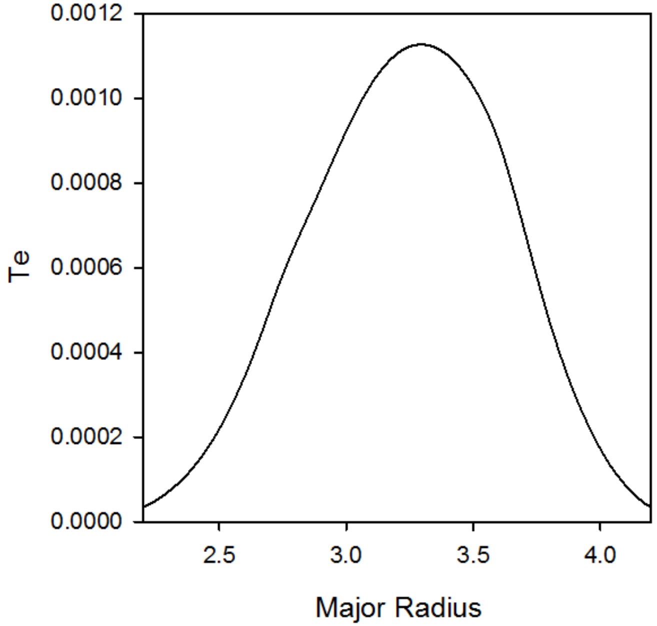
Exterior to the q=1 surface, they are constant on surfaces $p=p(\psi)$

CMOD run25

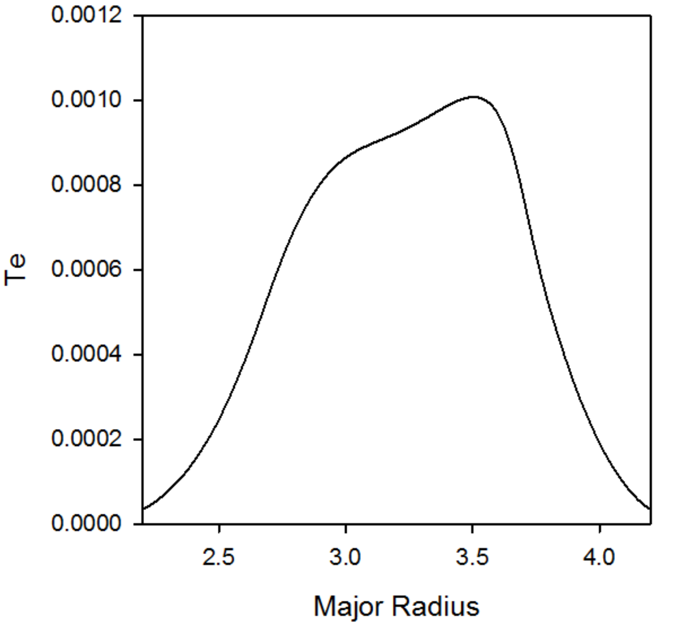
Terms in temperature equation

$$u \bullet \nabla T_e \quad = \quad \eta J^2 + \nabla \bullet \kappa_\perp \nabla T_e$$

Axisymmetric state (before)



Non-axisymmetric state (after)

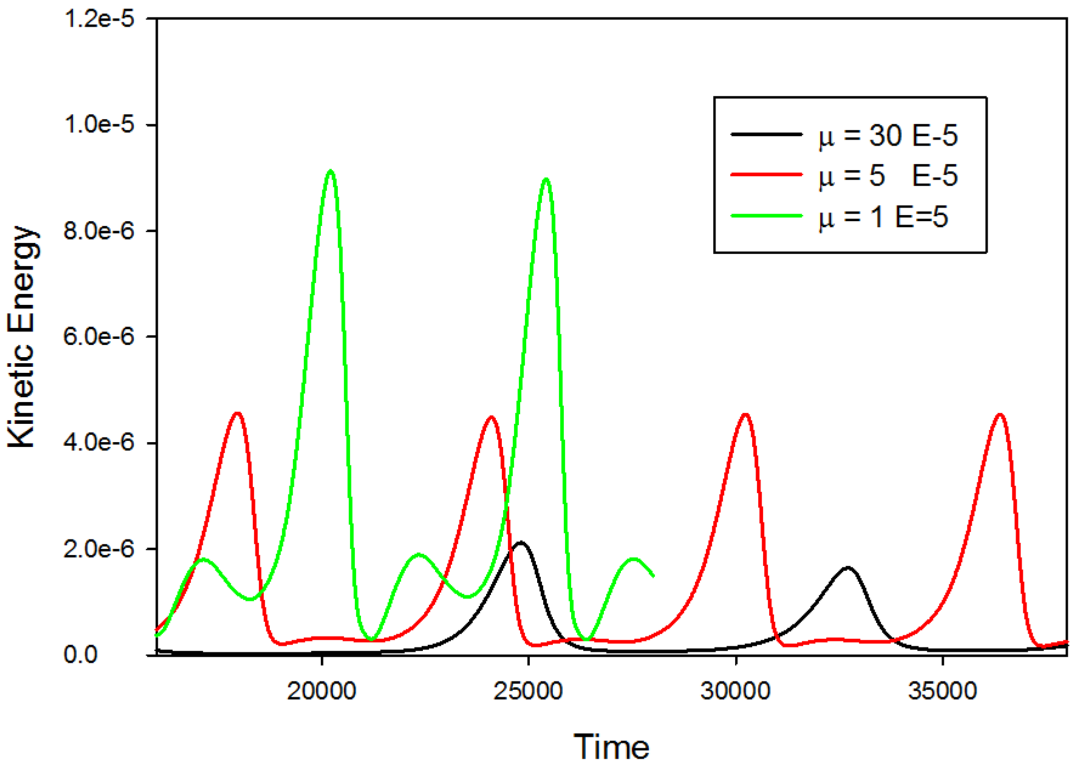


$$1.0\times10^{-8} \simeq 3.7\times10^{-7} - 3.7\times10^{-7}$$

$$3.4\times10^{-7} \simeq 3.7\times10^{-7} - 3.0\times10^{-8}$$

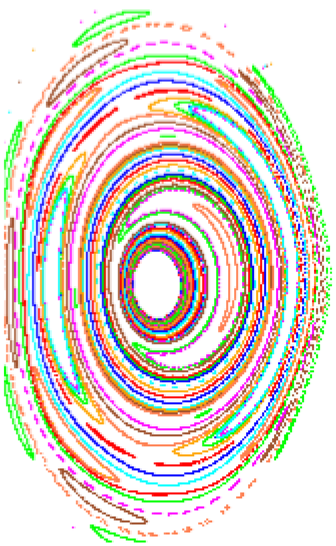
CMOD run25

Viscosity Scan

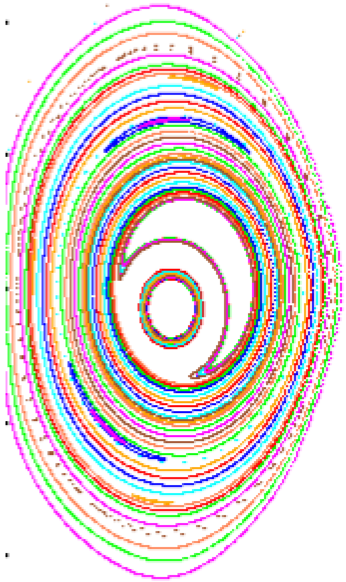


- Max KE amplitude increases with μ^{-1} (to a point)
- Period increases with μ
- Lowest μ can have more complex behavior

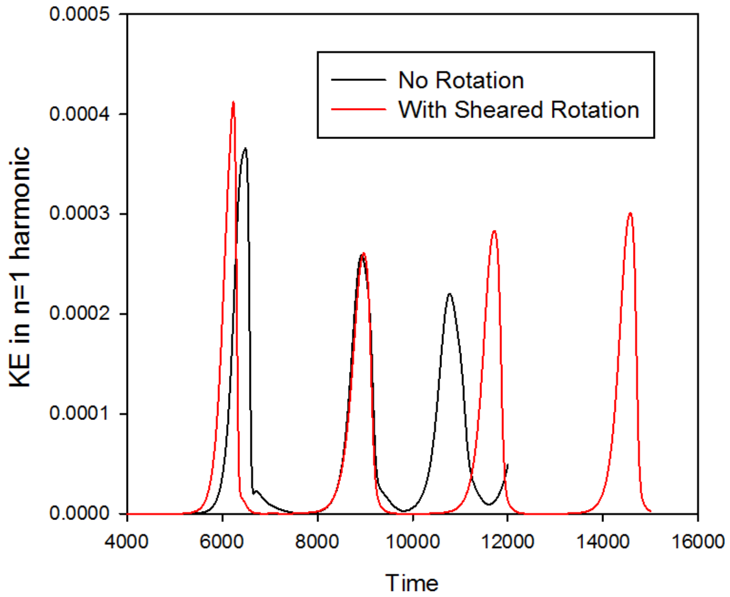
Effect of Sheared Rotation



Without rotation



With sheared rotation



Without sheared rotation in ellipse:
- sawteeth tend to die out
- large magnetic islands form

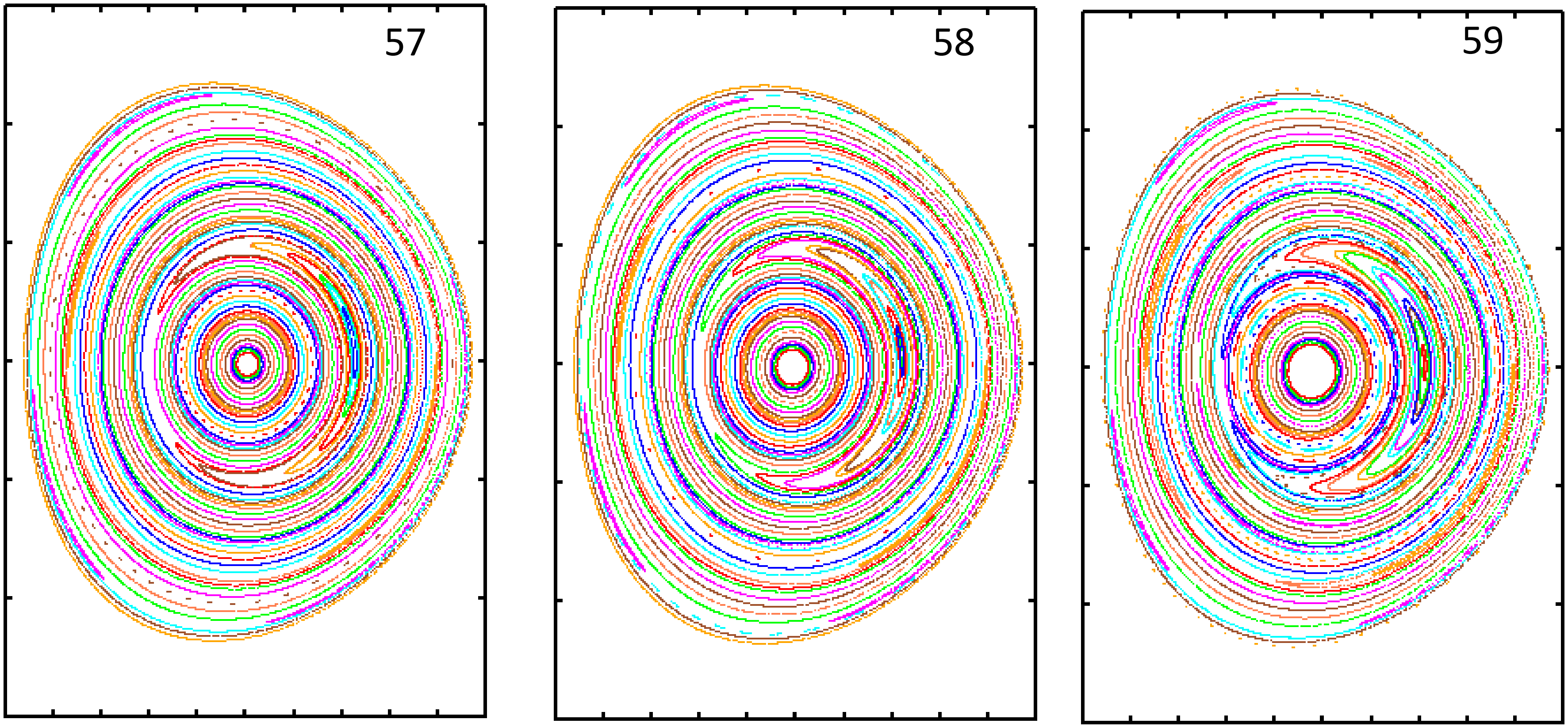
Two-Fluid Effects

$$n\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \bullet \nabla \mathbf{V}\right) + \nabla p = \mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{\Pi}_{GV} + \mu \nabla^2 \mathbf{V}$$

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} + d_i \left(\mathbf{J} \times \mathbf{B} - \nabla p_e \right)$$

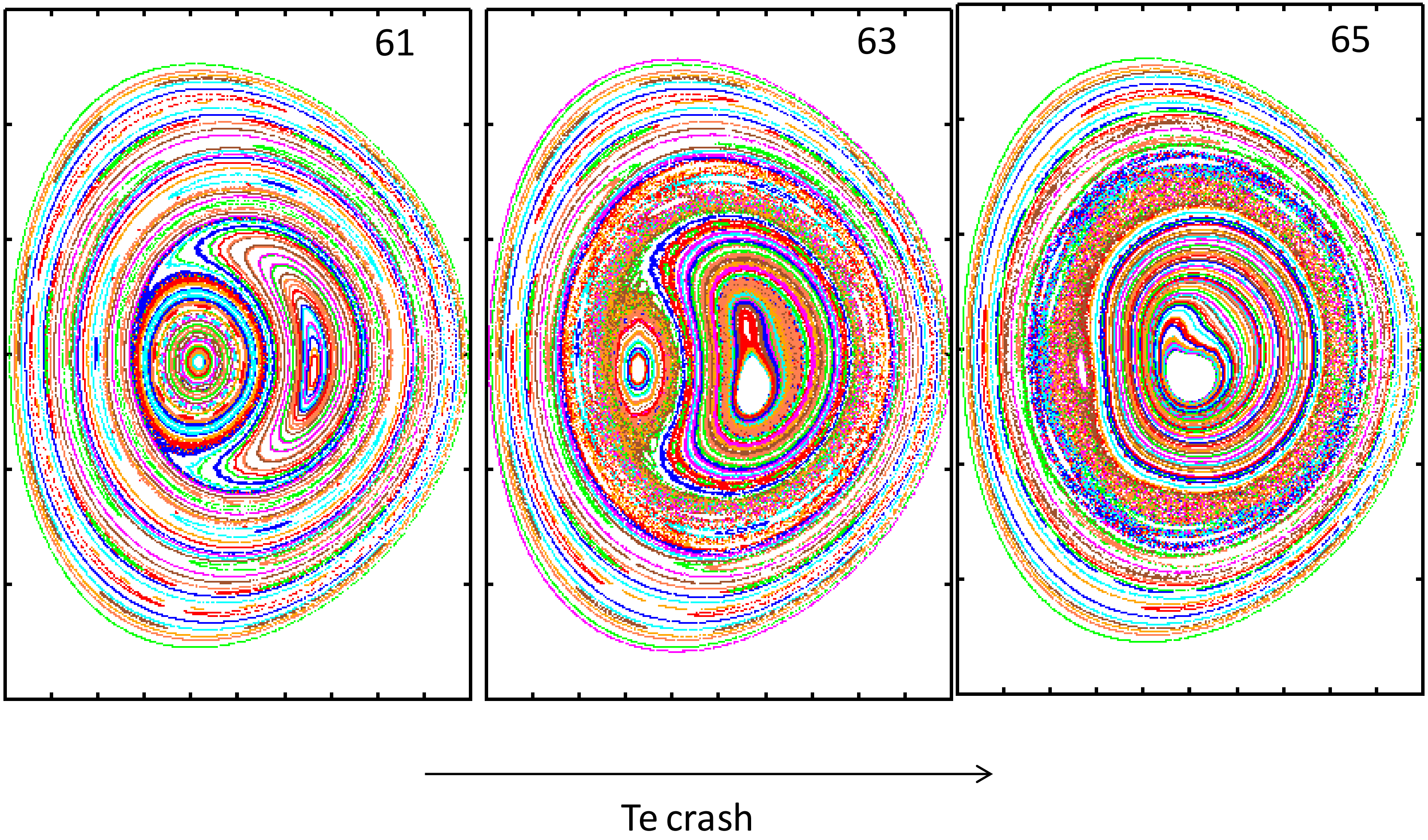
- Full Braginskii gyroviscus tensor
- Keep **J x B** term in Ohm's law
- 8 scalar variables advanced in time
- Ion skin depth: $d_i = \frac{1}{\ell_0}\left[\frac{M_i}{\mu_0 n_0 e^2}\right]^{1/2} = .0227\frac{1}{\ell_0[m]}\left[n_0[20]\right]^{-1/2}$

2F sawtooth shows distinctive shape



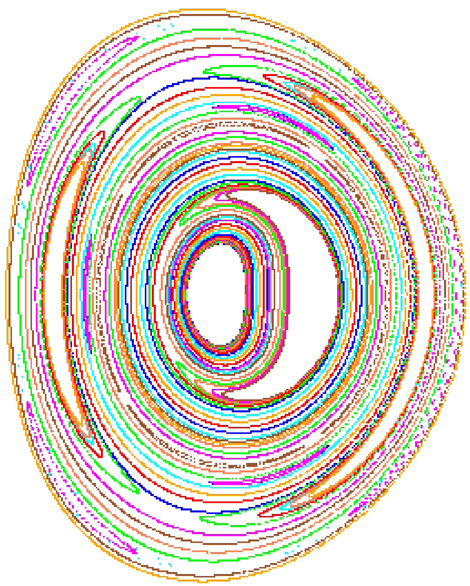
CMOD run25

Surfaces are destroyed in reconnection region during temperature crash

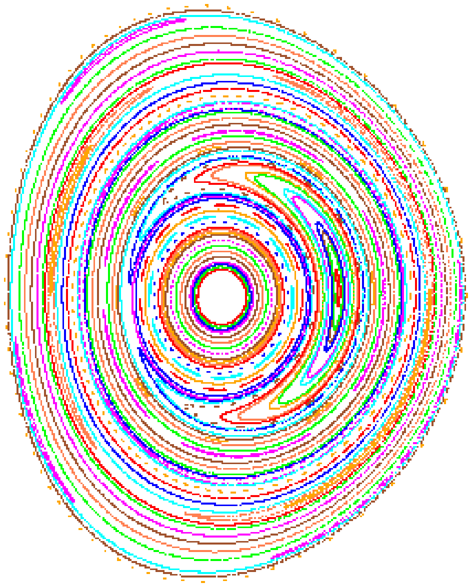


CMOD run25

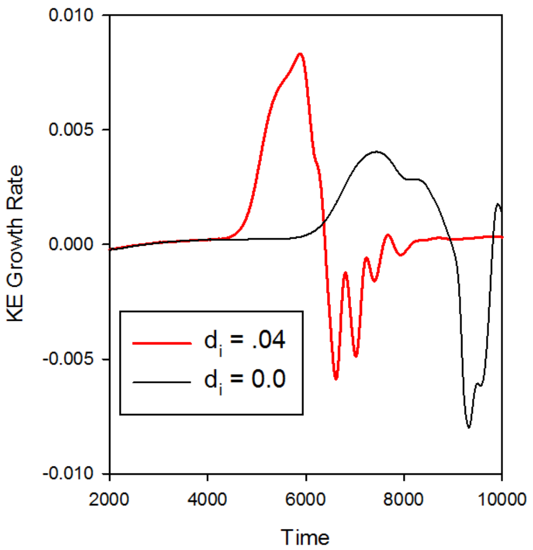
Comparison of surfaces for resistive and two-fluid MHD at similar stage in cycle shows reconnection layer is shorter in two-fluid. Rate increases by ~ 2



d_i=0



d_i= 0.04



Summary

- M3D-C1 has gone through many verification tests
- Two types of long time behavior: periodic or stationary states
- Comparison of ellipse and bean shaped X-section has begun
- Stationary states can have pressure and temperature variation within surfaces
- Growth rate almost independent of viscosity, but peak ke differs
- Sheared rotation promotes periodic behavior and good surfaces
- Two fluid terms lead to more circular interior surfaces, shorter reconnection layer, and faster reconnection times, however stochastic layer forms at late times