Disruption Modeling Status and Opportunities

S. C. Jardin

Princeton Plasma Physics Laboratory

Theory and Simulation of Disruptions Workshop

19 July 2013

PPPL

Areas where modeling is needed

- Causes of Disruptions
  - Density limit
  - Current and beta limits and regions of disruptivity
  - Overlapping islands, sawteeth, NTMs, ELMs, locked modes

- Effects of Disruptions
  - Forces from induced and conducted currents
  - Thermal loads
  - Runaway electrons

- Mitigation of Disruptions
  - Real time identification of impending disruptions
  - Massive Gas and/or Pellet Injection

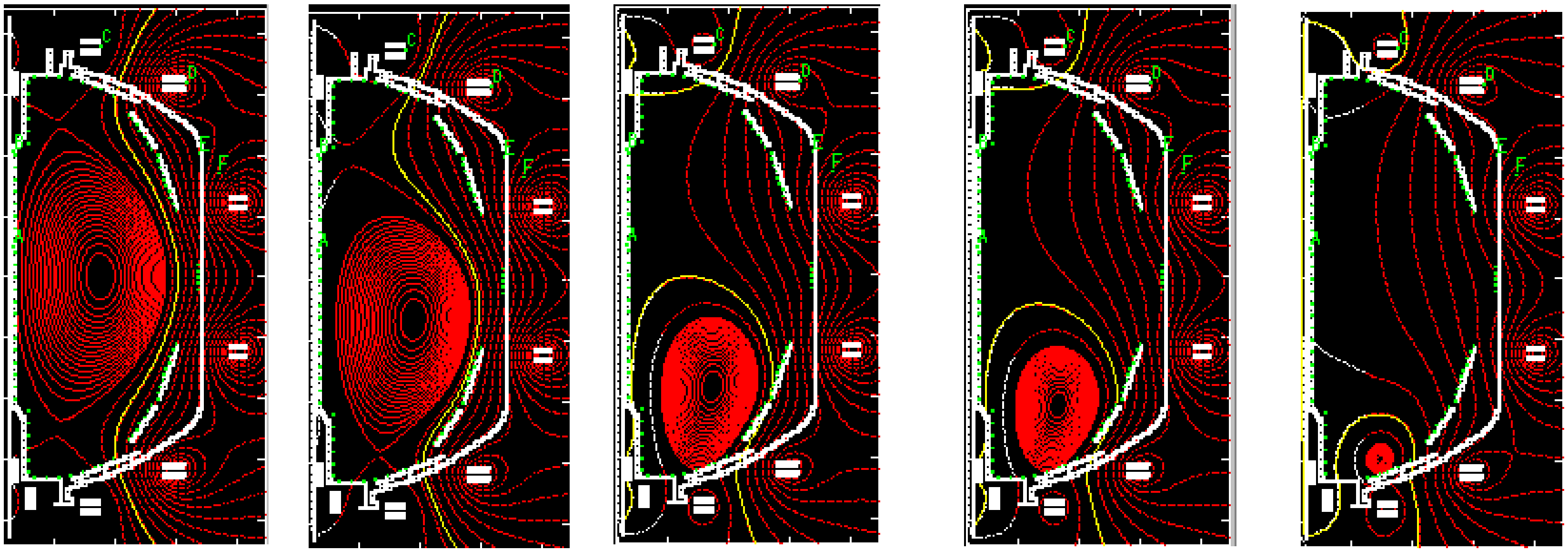
Outline

- Brief summary of 2D modeling of disruptions
- New capabilities in 3D modeling with M3D-*C*[1]
- Application to soft beta limit in NSTX

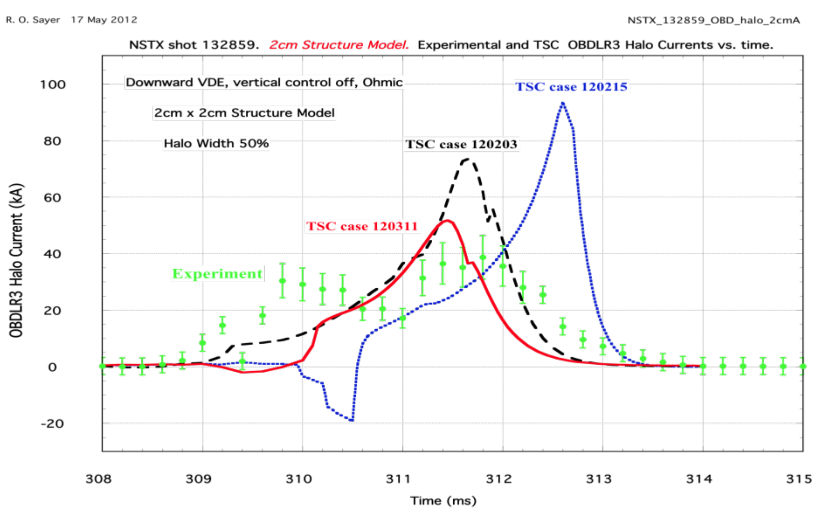
2D Integrated Modeling of Disruptions

Both the TSC and DINA 2D equilibrium evolution codes have been used extensively to model tokamak disruptions for over 20 years

- Developed 2D models of plasma+halo with a few adjustable parameters that were fit by detailed modeling of disruptions in existing experiments
  - DIII-D, ASDEX-U, JT-60, NSTX
- Detailed (2D) models of vacuum vessel and other conductors
- Runaway electron model (Rosenbluth/Putvinski)
- Calibrated pellet injection and impurity radiation models



259 ms   300 ms   310 ms   311 ms   312 ms



$q_{95} \sim 2$
$q_0 \sim 1.2$

Thermal quench & start of current quench

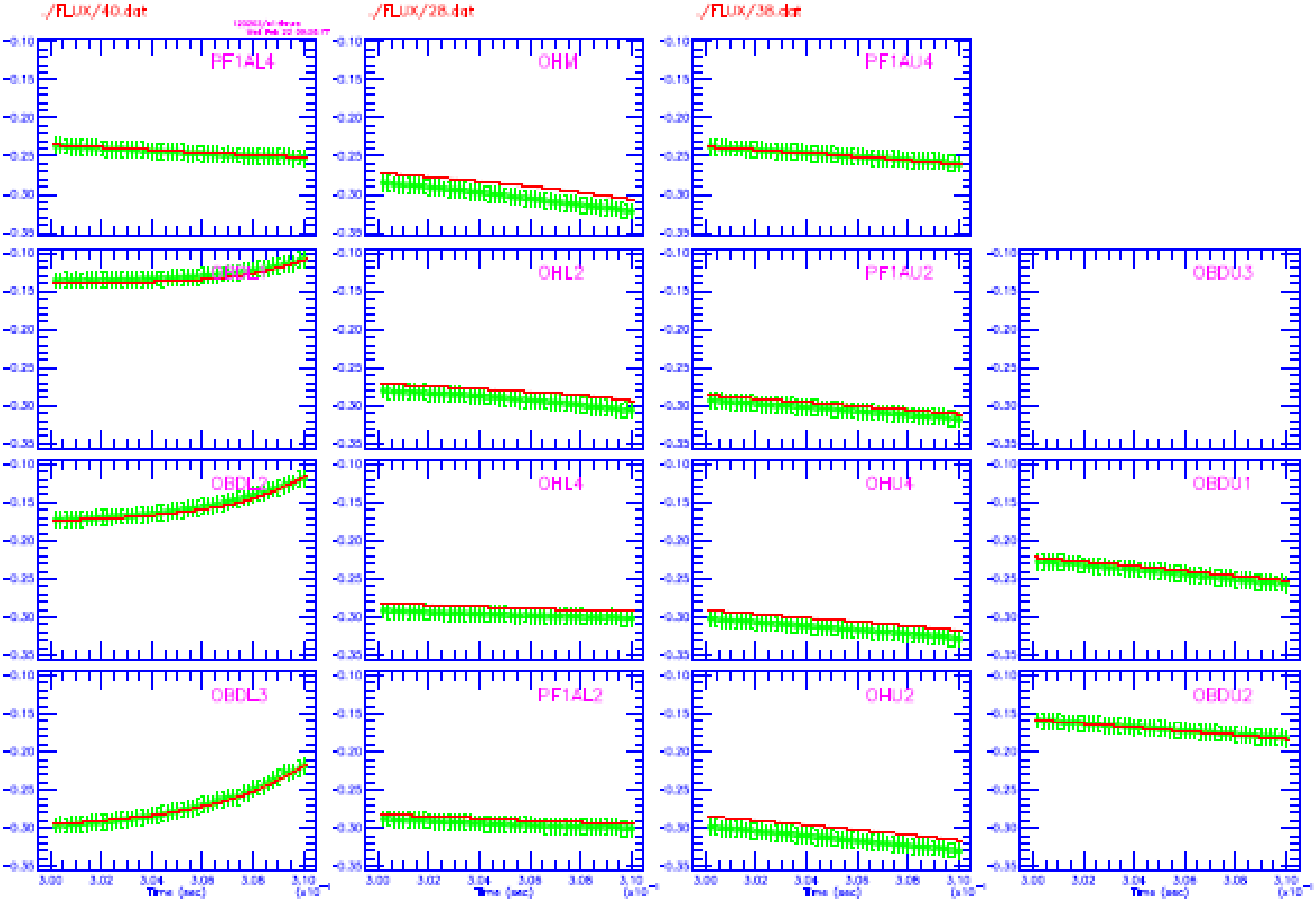
TQ: large $\chi_\perp$

Te: keV → 30ev in ~ < .1ms

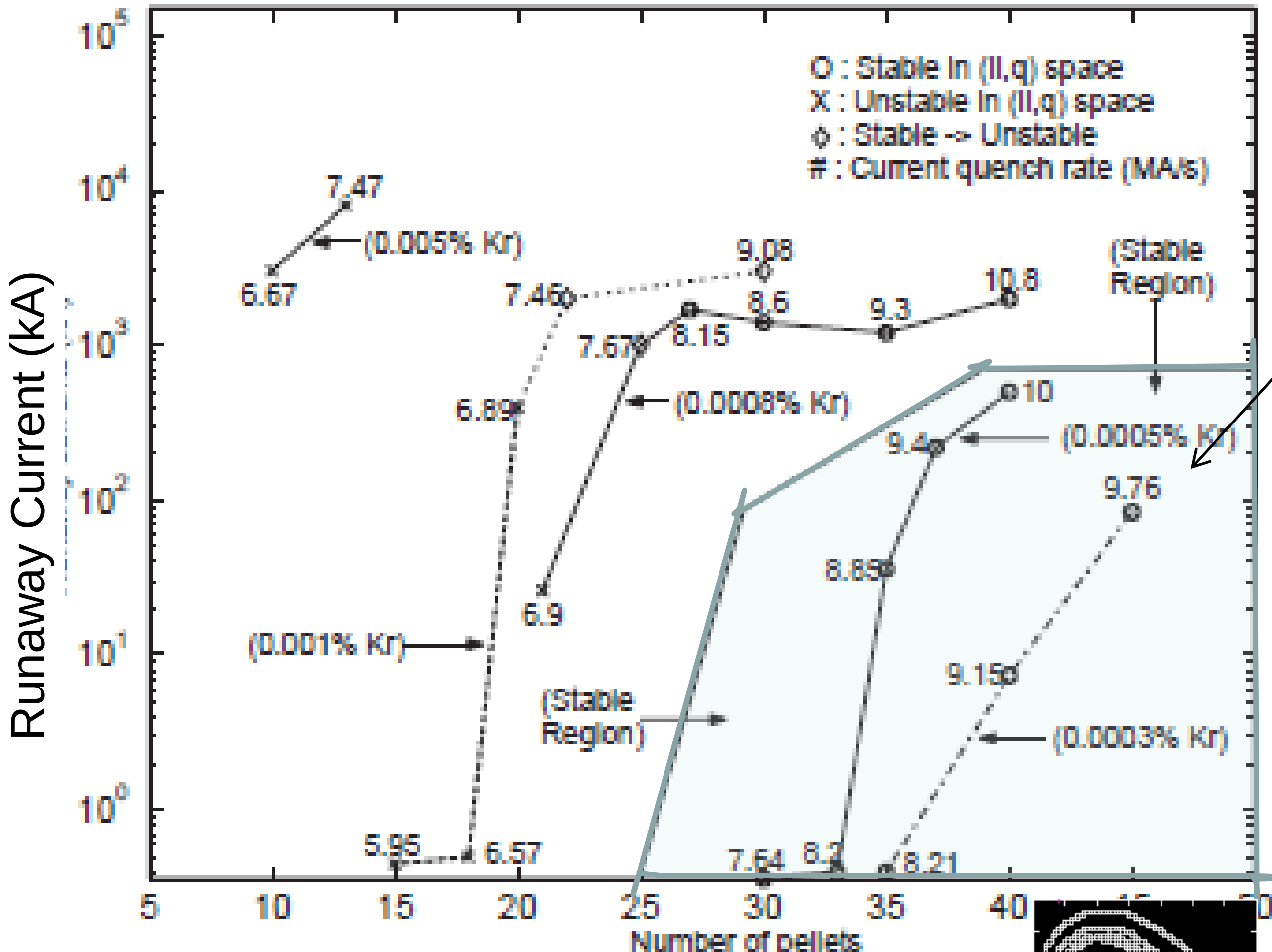
CQ: ~ 2-3 ms. Resistive decay in cold plasma

$T_{HALO} \sim$ 6-10 eV

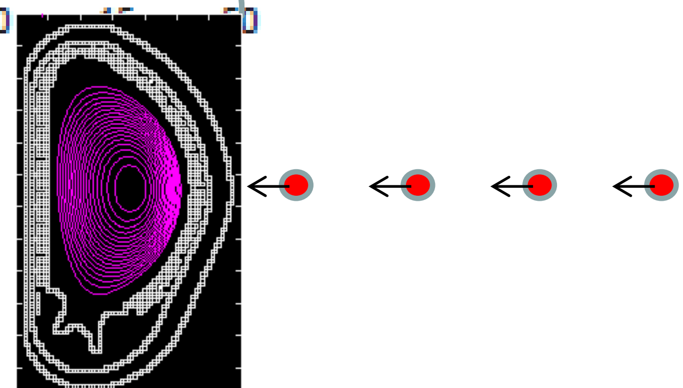
Comparison of exp and TSC flux loops during VDE drift phase



A fast shutdown technique for large tokamaks: NF 40 923 (2000)



A regime exists where the plasma remains MHD stable during 4-sec current rampdown with negligible runaway generation



- 4 sec current ramp-down using PF coils
- Sequence of Krypton doped hydrogen pellets
- Monitor MHD stability

Summary of 2D Modeling

- Can match typical current quench rate on today's tokamaks with Te ~ 30 eV
- Can reproduce axisymmetric halo currents with:
  - T_{HALO} ~ 6 ev
  - If sheath resistance included, larger T_{HALO} is used
- Semi-empirical pellet model with some validation (Schmidt, TFTR)
- Avalanche runaway electron model needs validation (Rosenbluth)

Outside the scope of 2D modeling

- Mechanism that leads to thermal quench
- 3D effects on runaway electrons
- toroidal peaking factor of induced and halo currents

3D Modeling needs

- Highly implicit 3D MHD code to treat multiple timescales
  - Accurate for highly anisotropic $\chi_{||} >> \chi_{\perp}$
  - with plasma, wall, vacuum regions
- 3D model of vessel (with ports, etc)
- Plasma-wall interaction and impurity generation, transport, radiation
- 3D runaway electron model
- Accurate modeling of thermal quench and associated physics (converged results)

3D Modeling needs

- Highly implicit 3D MHD code to treat multiple timescales
  - Accurate for highly anisotropic $\chi_{||} >> \chi_{\perp}$
  - with plasma, wall, vacuum regions
- 3D model of vessel (with ports, etc)
- Plasma-wall interaction and impurity generation, transport, radiation
- 3D runaway electron model
- Accurate modeling of thermal quench and associated physics (converged results)

Thermal quench

→Can we use a nonlinear 3D Extended MHD code to determine when exceeding a stability limit will lead to a thermal quench and subsequent disruption?

M3D-C^1 code

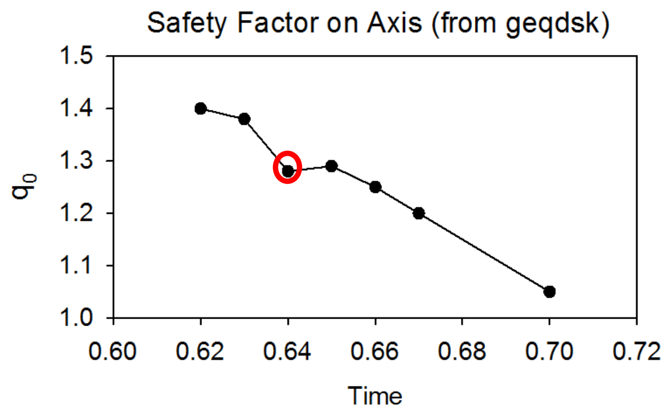
- High accuracy
  - High order finite elements in 3D with C^1 continuity
  - Optimal decomposition of vector fields into scalars $\nabla \bullet \mathbf{B} \equiv 0$
  - Full 2F MHD equations without common approximations
  - Accuracy of linear flux-coordinate (FC) codes without using FC

- Long-time simulations (large time steps)
  - Fully implicit algorithm
  - Unique preconditioning that remains effective nonlinearly
  - Pure Galerkin method converges from below on ideal MHD modes

- Geometrical flexibility
  - Unstructured mesh allows variable mesh size (mesh packing)
  - Does not use flux coordinates ➔ Plasma region with separatrix
  - Arbitrary shaped vacuum vessel and conductors

NSTX pressure driven modes with $q_0 \geq 1$

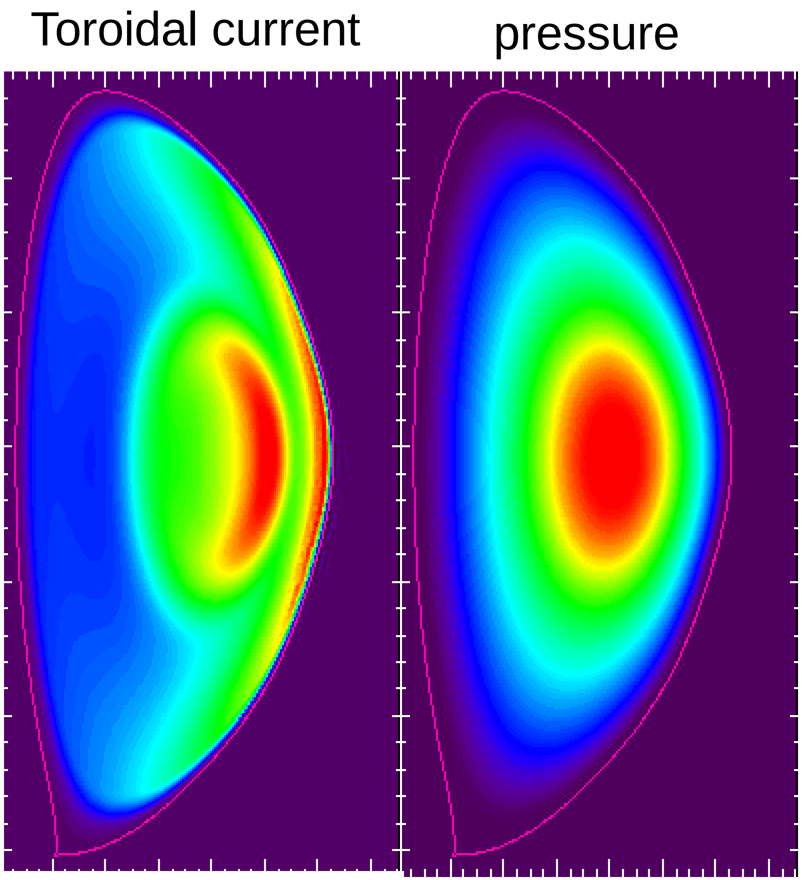
Series of geqdsk equilibrium for shot 124379 generated by S. Gerhardt for 2011 Breslau, et al NF paper.



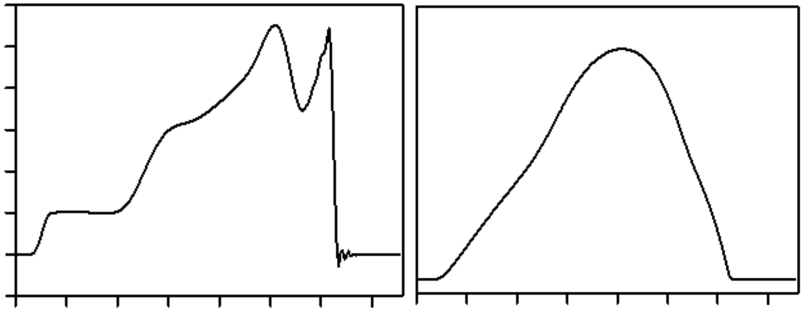
$$\beta_P \sim 0.8$$

$$\beta_T \sim 7+\%$$

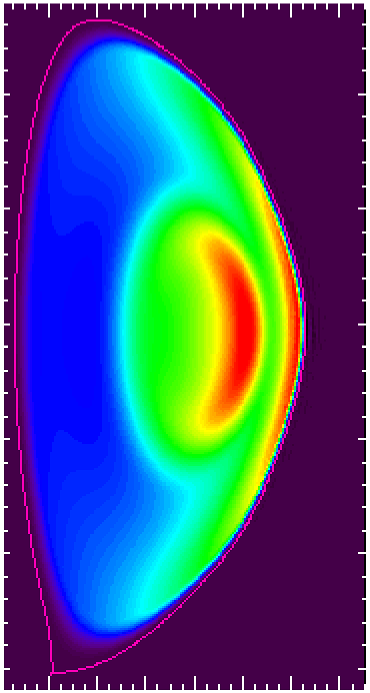
$$I_P \sim 1\,MA$$

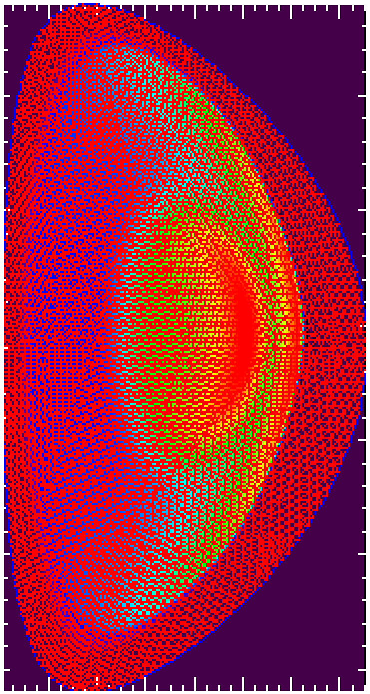


Midplane values →

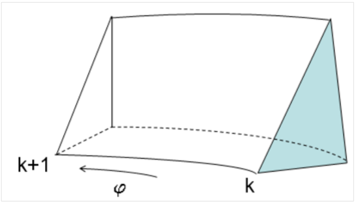


Triangular wedge finite elements





Each element has a polynomial in (R,φ,Z) for each scalar with 72 terms.   All first derivatives continuous between elements.



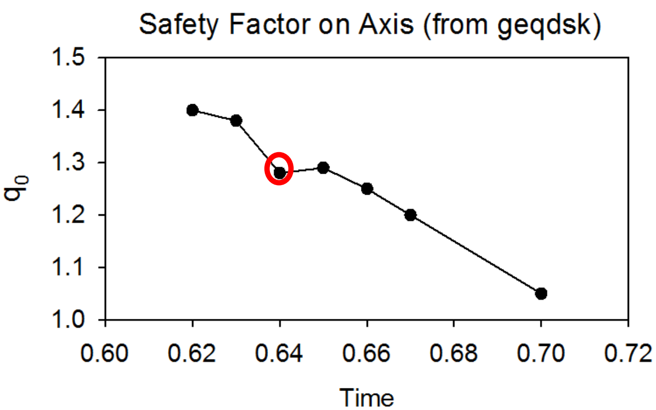
Possible mechanism for soft beta limit

Shot 124379

Time .640

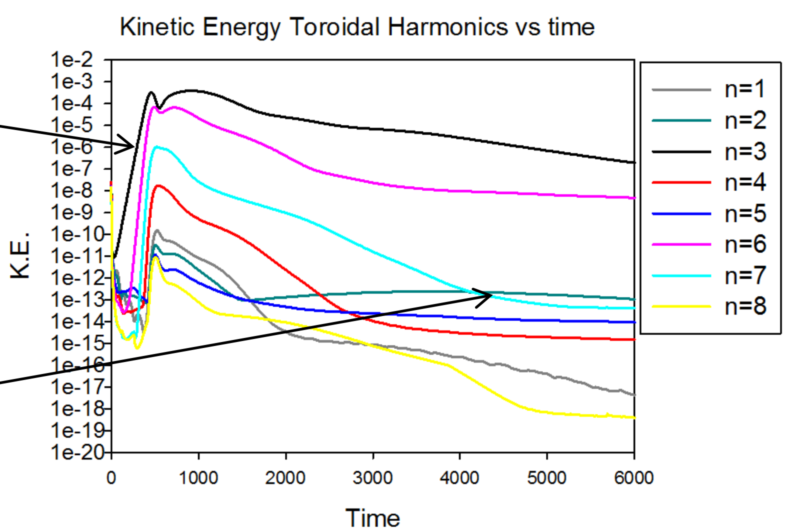
$q_0 = 1.28$

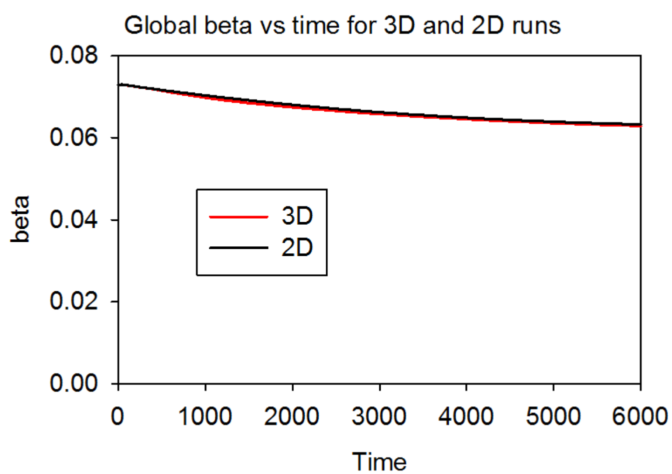
No toroidal rotation



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

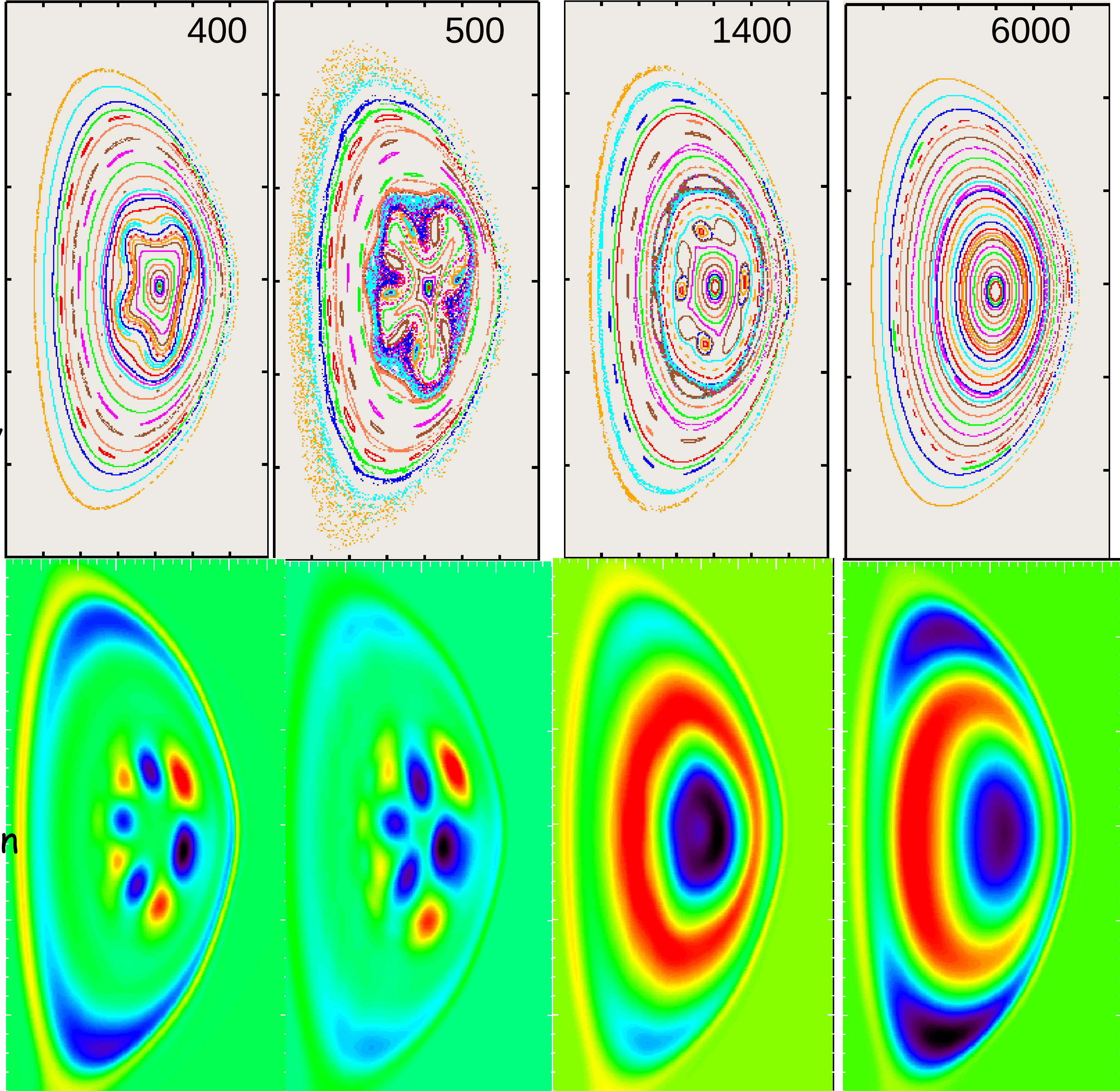
Soft beta limit
$q_0 = 1.28$

Poincare plots →

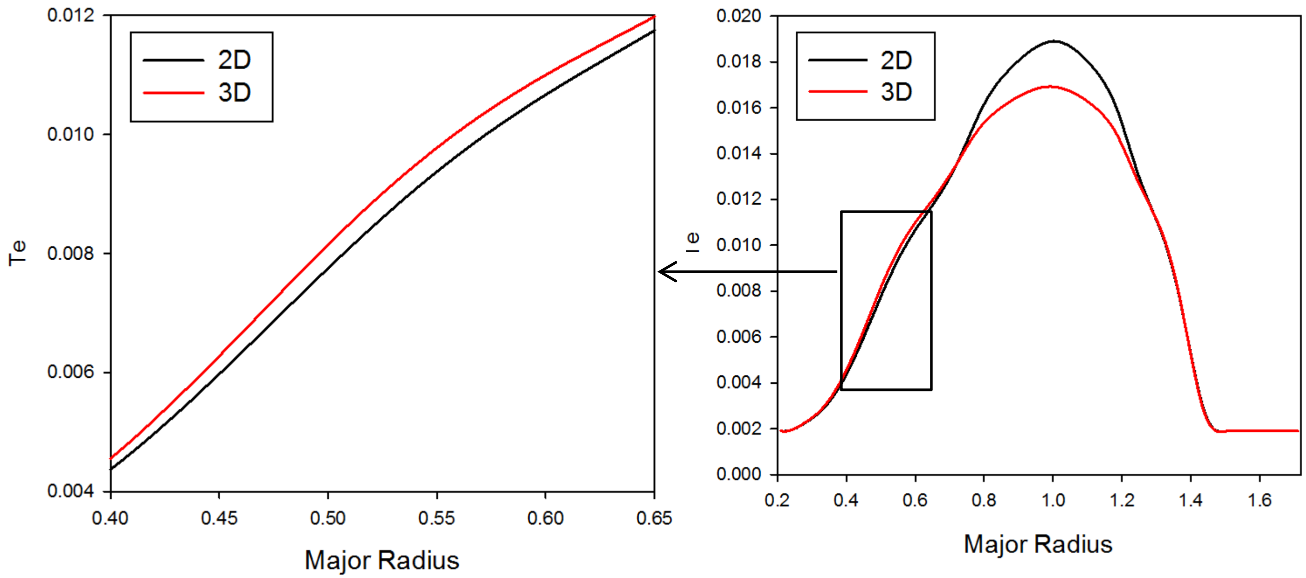
Surfaces deform, become stochastic, & completely heal.

ΔTe →

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



soft beta limit -- continued



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

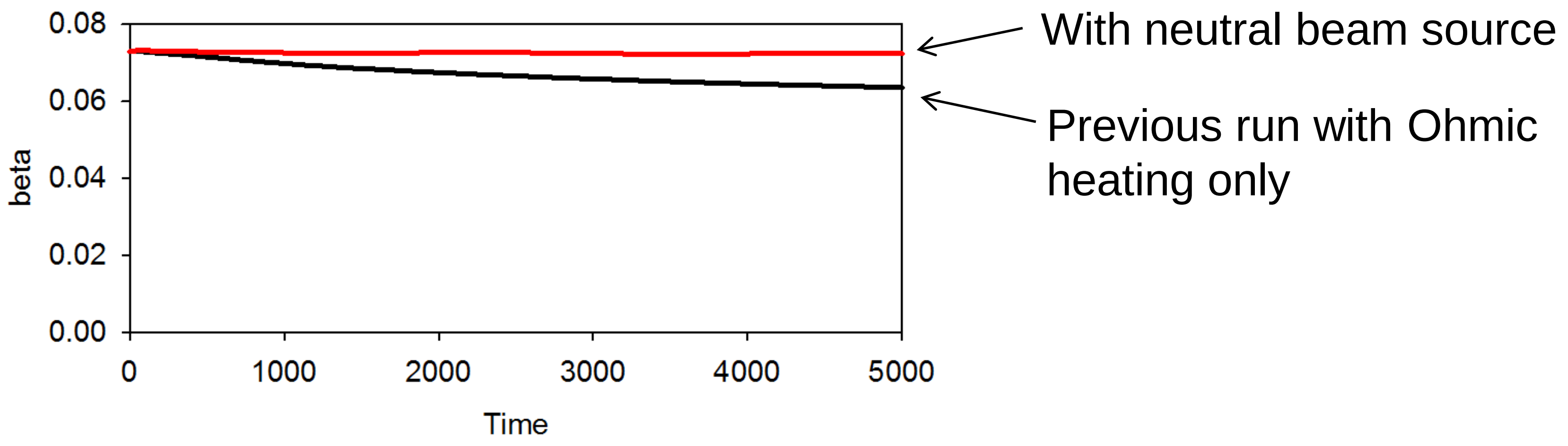
- Central Te differs by 10%, beta differs by only 0.6 %

- Increased transport in center (note: effect not in GK codes)

dependence on heating source

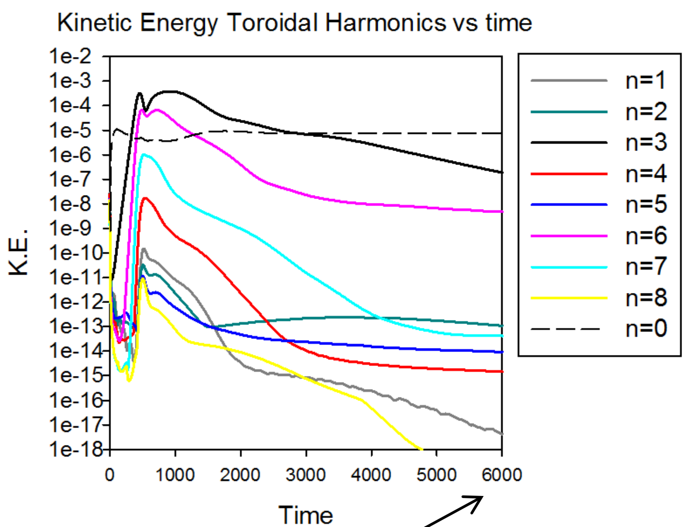
- Previous run had beta decreasing in time, even in 2D case, because there was no heating source (except Ohmic).

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

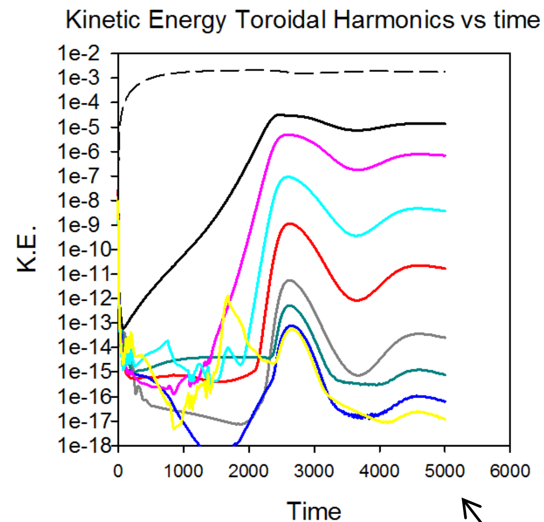


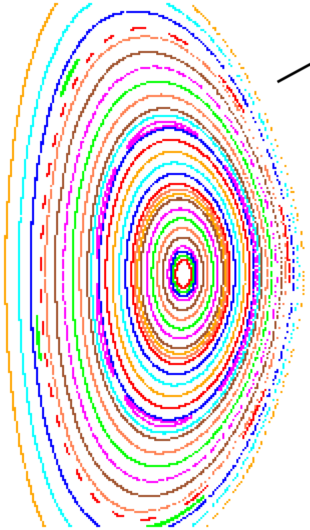
dependence on heating source-cont.

Ohmic heating only



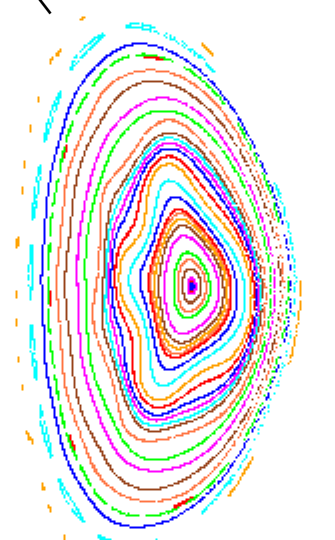
With neutral beam source



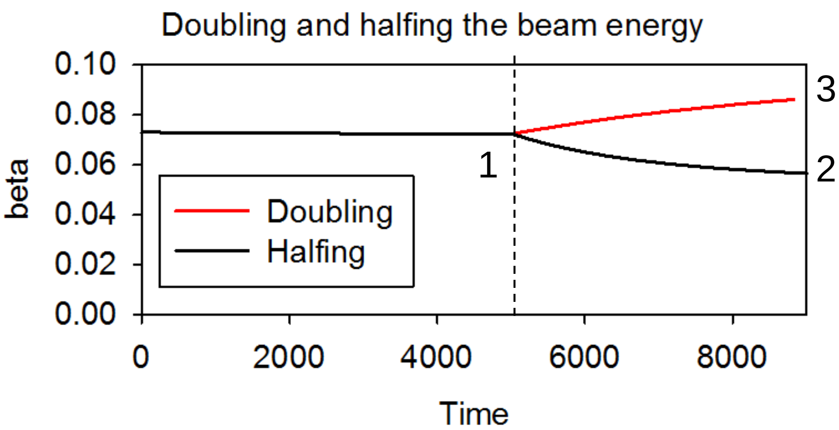


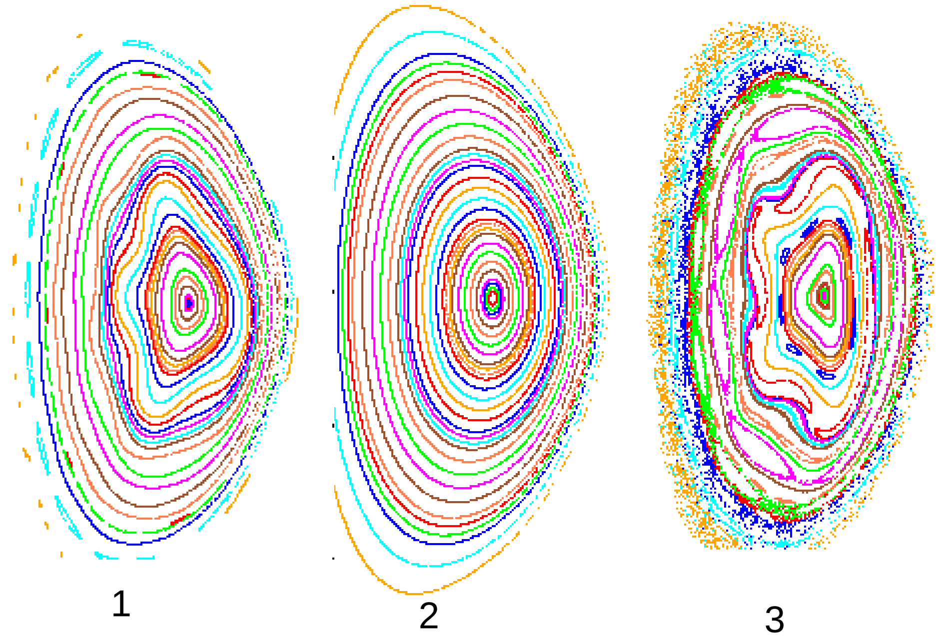
With heating and momentum source: (constant beta and sheared rotation)

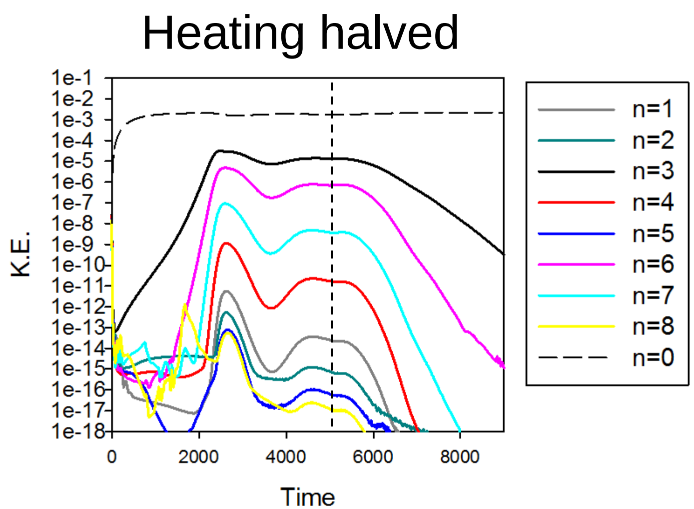
- Initial linear growth of n=3 mode much slower
- n=3 and higher harmonics do not decay away: surfaces distort, but non-disruptive

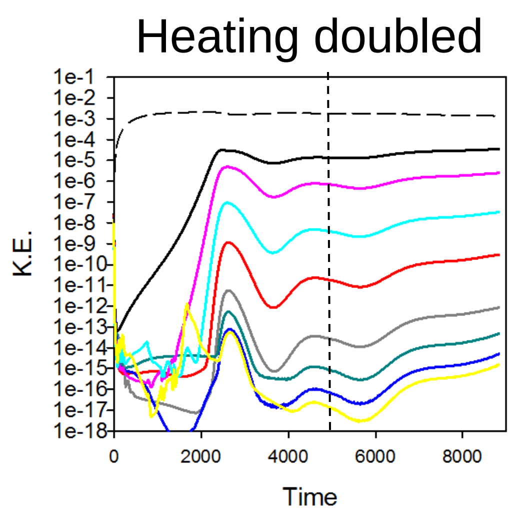


effect of increasing (decreasing) heating



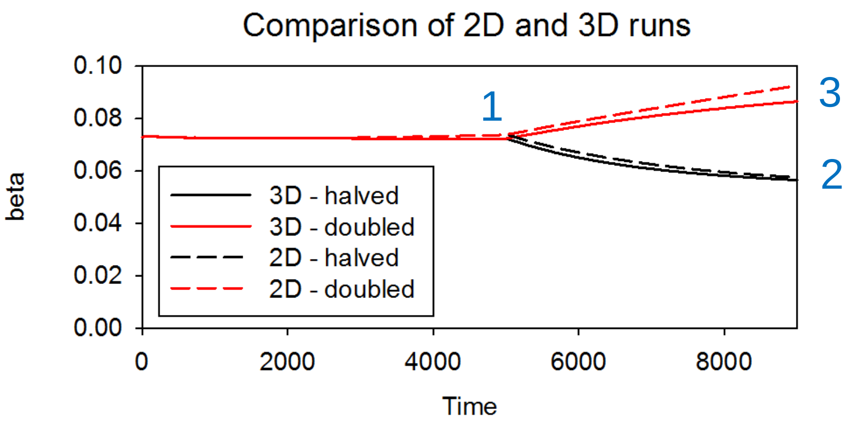




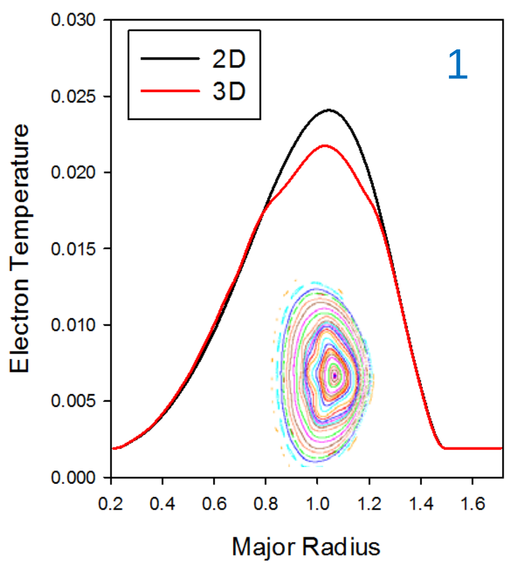


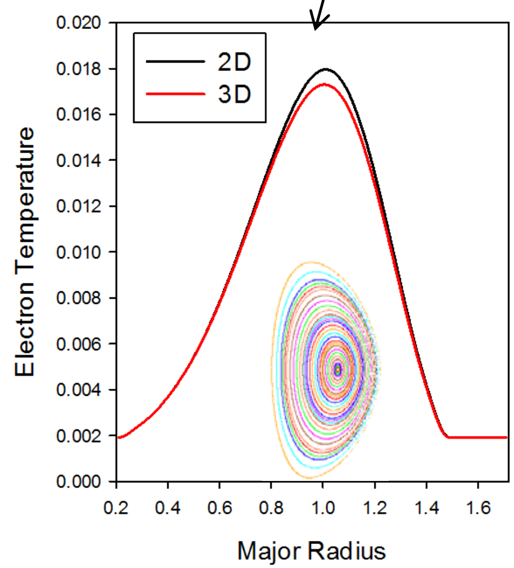
- With heating *reduced*, plasma returns to an axi-symmetric state (2)
- With heating *increased*, surfaces become more distorted, but still exhibits confinement (3)

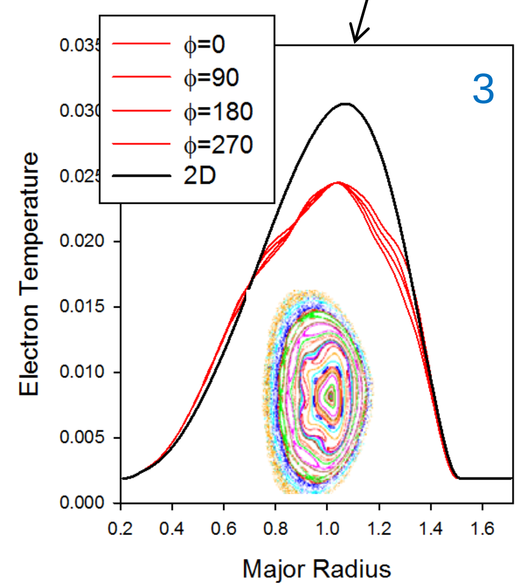
effect of increasing (decreasing) heating



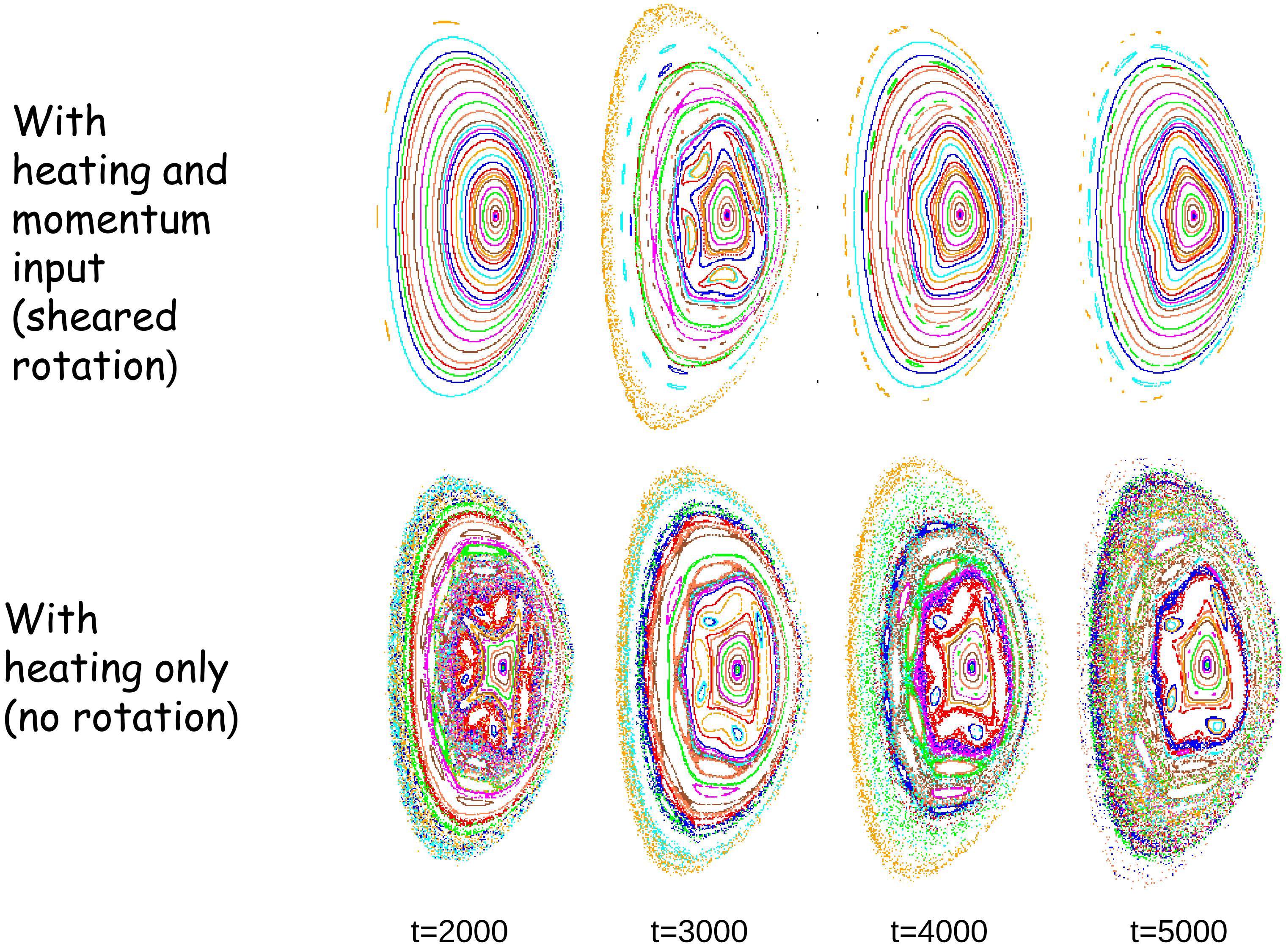
- at low heating power, Te profiles from 2D and 3D agree
- at higher heating powers, they differ considerably





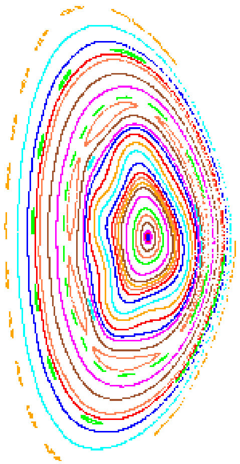


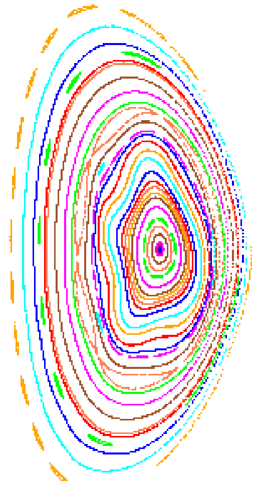
importance of sheared rotation

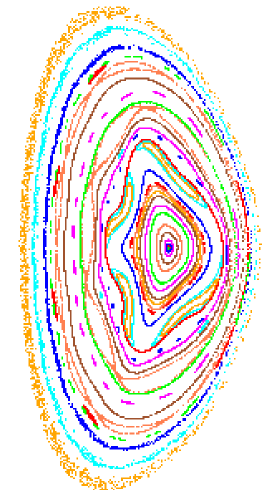


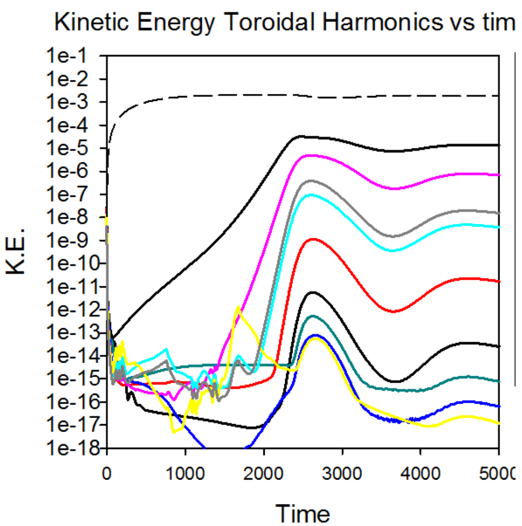
numerical convergence study

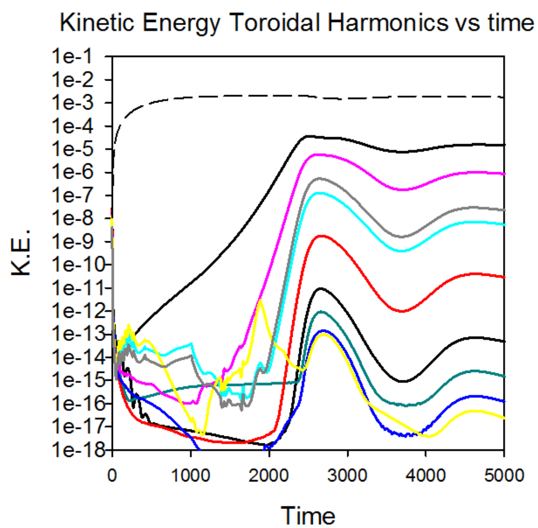
Original constant β run	w/double the poloidal zones	w/double the toroidal zones

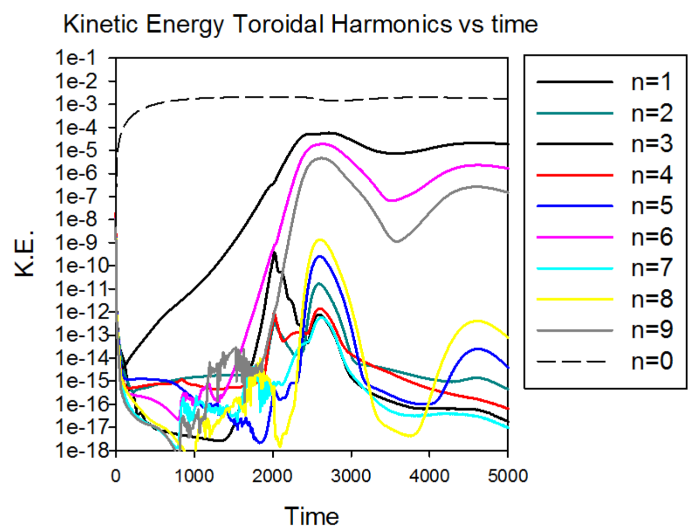






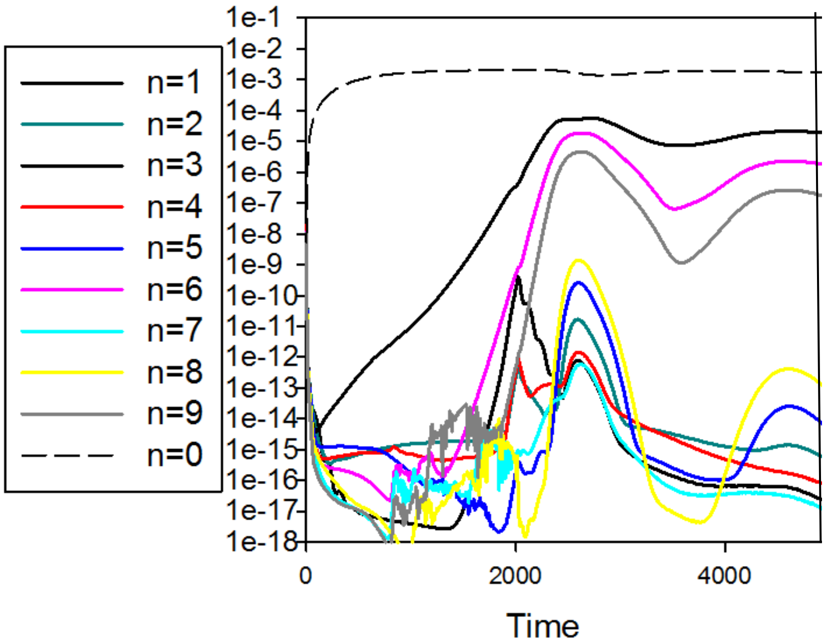


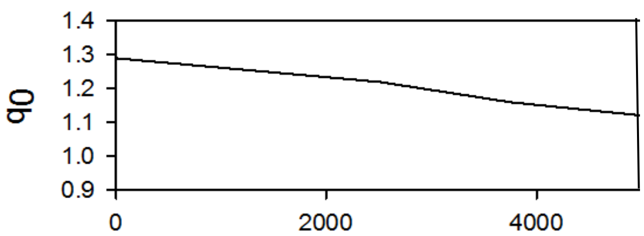




Longer times

Kinetic Energy Toroidal Harmonics vs time

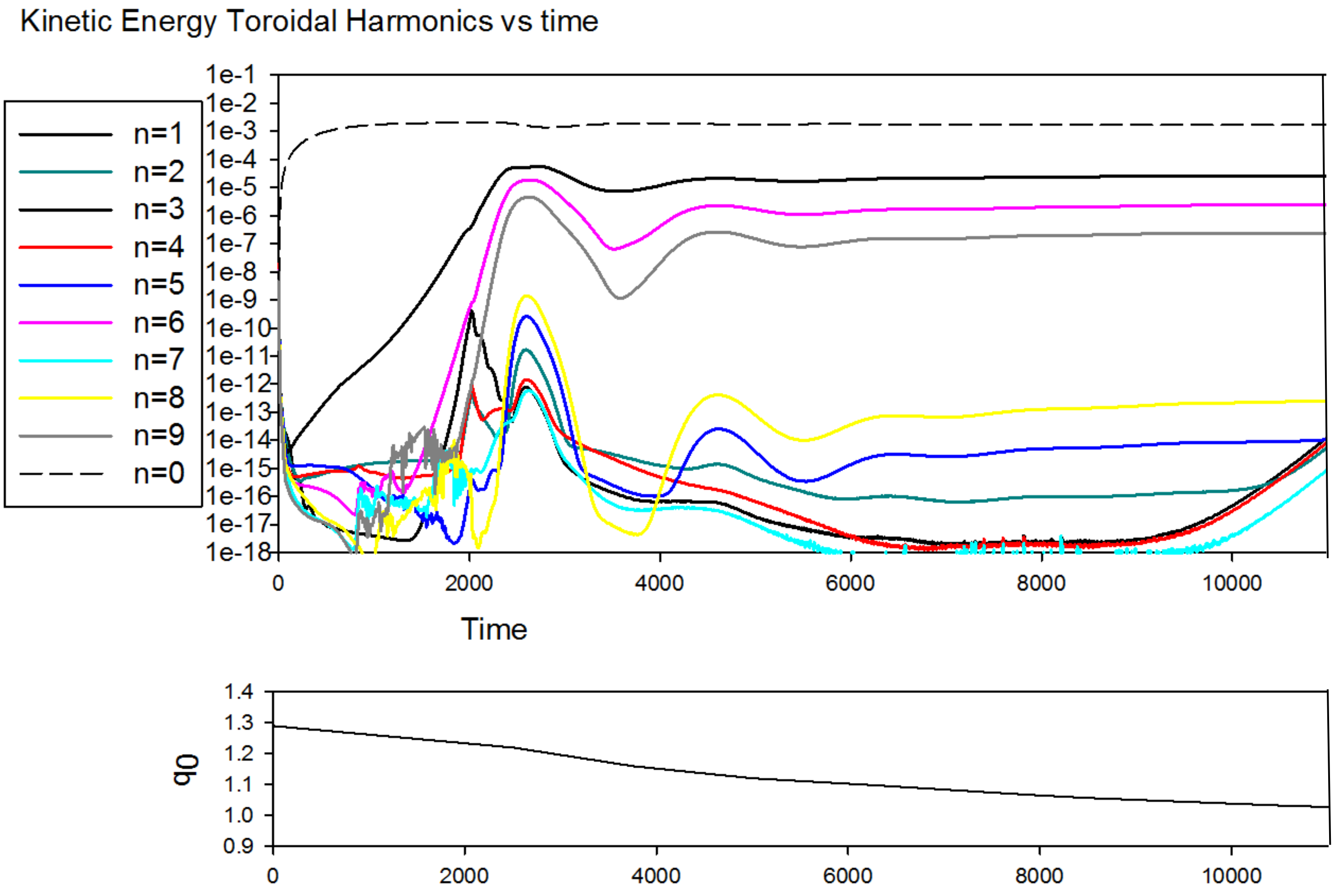




The current (and q) profiles are continuing to evolve.

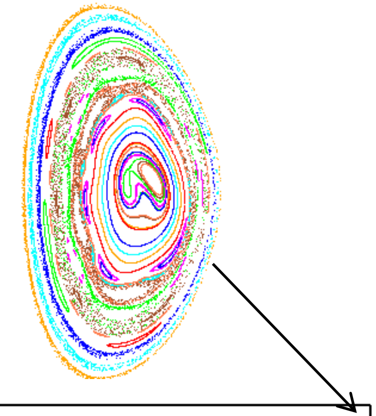
Does anything interesting happen at longer times?

Longer times



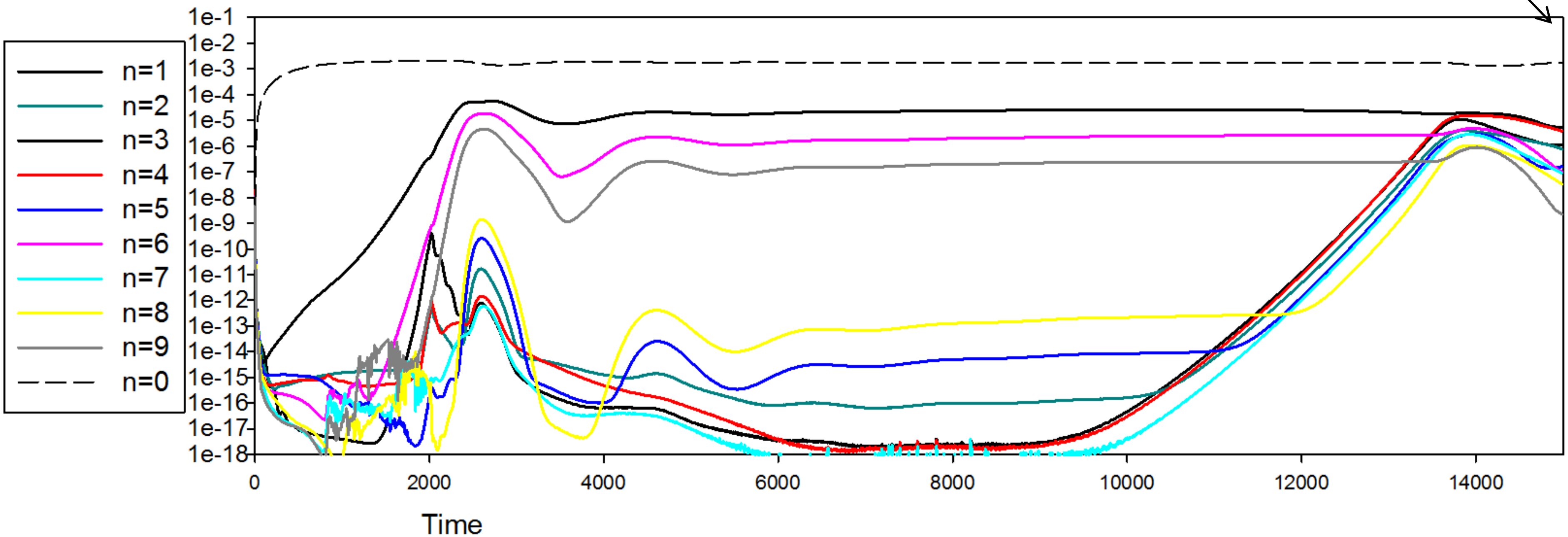
As q_0 falls to near 1, the n=1 mode starts to grow and drives harmonics n=2,4,7…

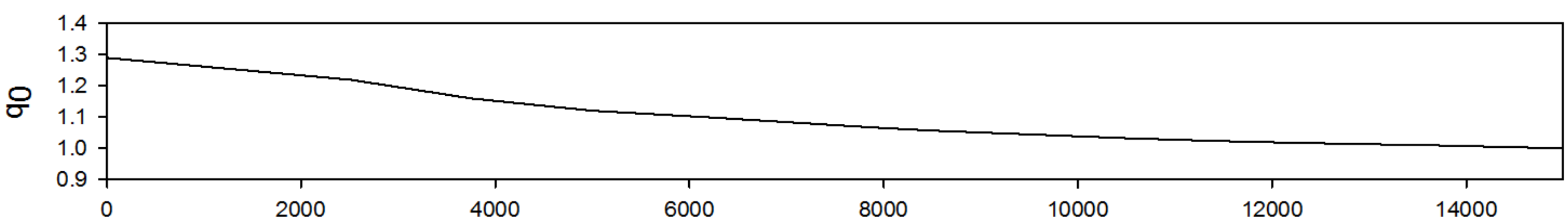
Longer times



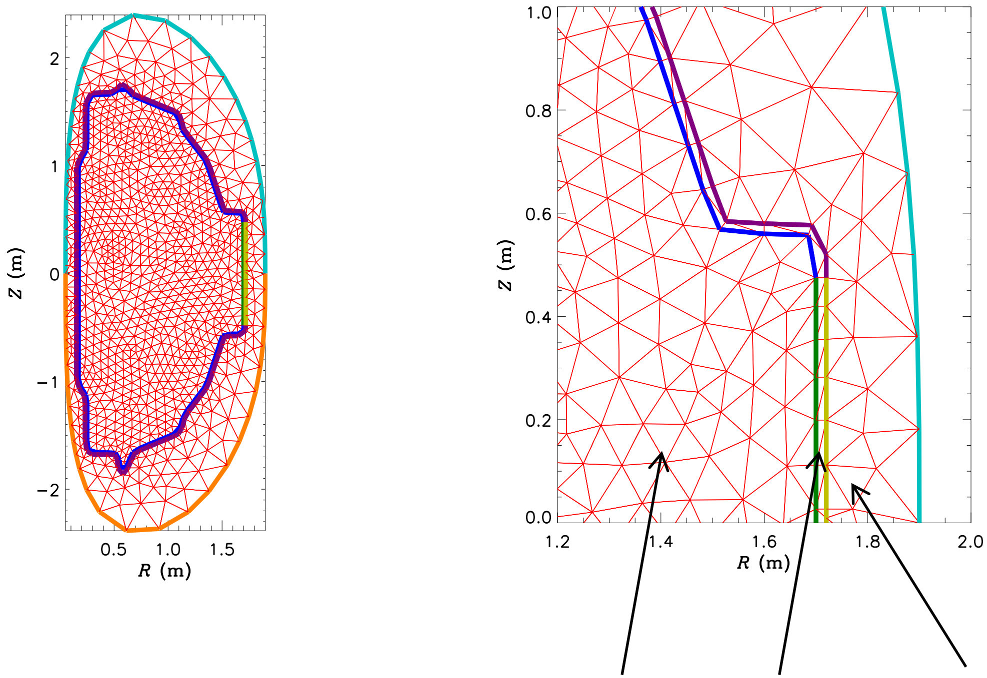
After some transient, surfaces appear to reform. Still healing!

Kinetic Energy Toroidal Harmonics vs time





“Thick wall” capability recently added to M3D-*C*[1]



Finite elements in 3 regions: plasma, wall, and vacuum

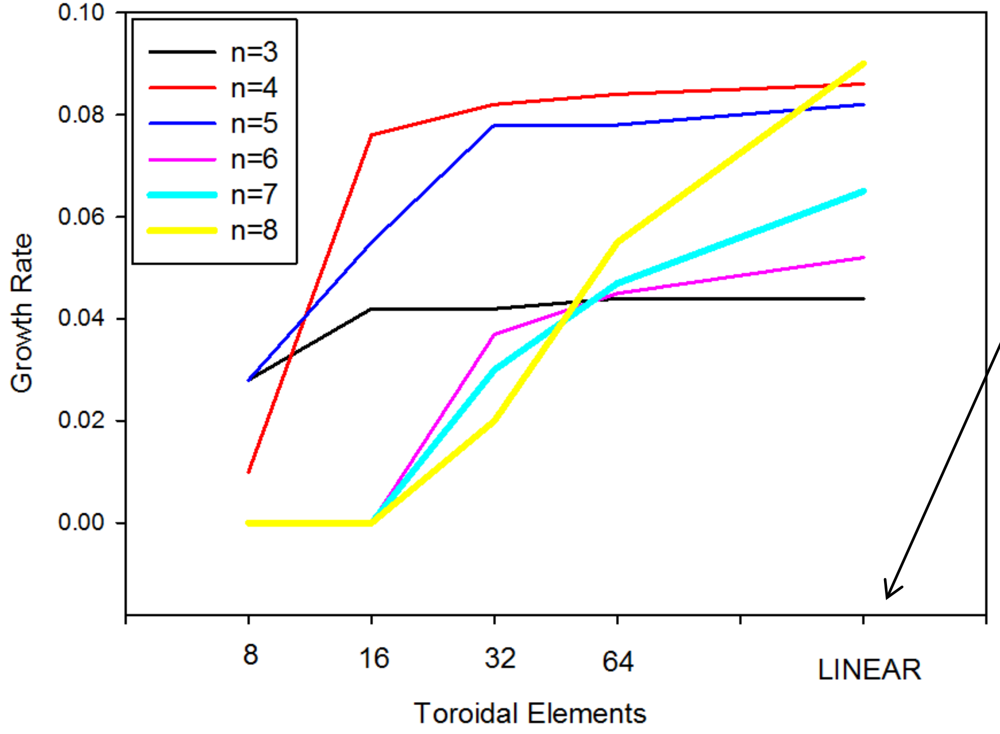
summary

- 2D and 3D models have and are contributing to understanding experimental results and extrapolating to ITER
- Opportunities exist for improving models to increase realism
- Example presented of modeling the nonlinear consequence of exceeding linear beta limit with M3D-C^1.
- Possible mechanism for soft beta limit identified.
- Sheared rotation shown to be stabilizing
- Need for more experimental validation of converged numerical modeling results

NSTX shot 124379 time 0.640
TF scaled by 0.9 so q_0=1.17

convergence studies for linear regime of nonlinear code

M3D-*C*[1] growth rate vs number of toroidal elements



LINEAR result uses same code, but assumes φ dependence *exp(inφ)*, everything is complex, non-linear terms are not included

This scaled equilibrium was above the beta limit and unstable to many linear (interchange) modes with n>1.

The nonlinear code is ***converging from below*** to the linear result, which is essential for numerical stability in these cases.