Nonlinear 3D M3D-C^1 Simulations of Tokamak Plasmas Crossing a MHD Linear Stability Boundary

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Abstract. Understanding the difference between hard and soft limits is crucial for effective disruption prediction and avoidance in tokamak plasmas. We present several computational examples of both hard and soft beta limits. In the examples presented here, we begin most simulations with the plasma stable to all modes. During the simulation the plasma crosses a stability boundary due to evolving profiles, loss of control, or injection of mass, energy, and or flux. This can lead to saturation or disruption. Effective real-time disruption prediction requires that we can distinguish between the two.

Introduction and Outline

- The goal of the present work is to give an overview of the work our group is doing in the area of nonlinear disruption prediction using the nonlinear 3D implicit MHD code **M3D-*C*[1]**.

- We seek to better understand and develop a predictive capability for when approaching and crossing a MHD linear instability boundary leads to a thermal quench and subsequent disruption (**hard limit**), and when it just leads to increased transport or small amplitude oscillations (**soft limit**).

- Consider the following examples of each:

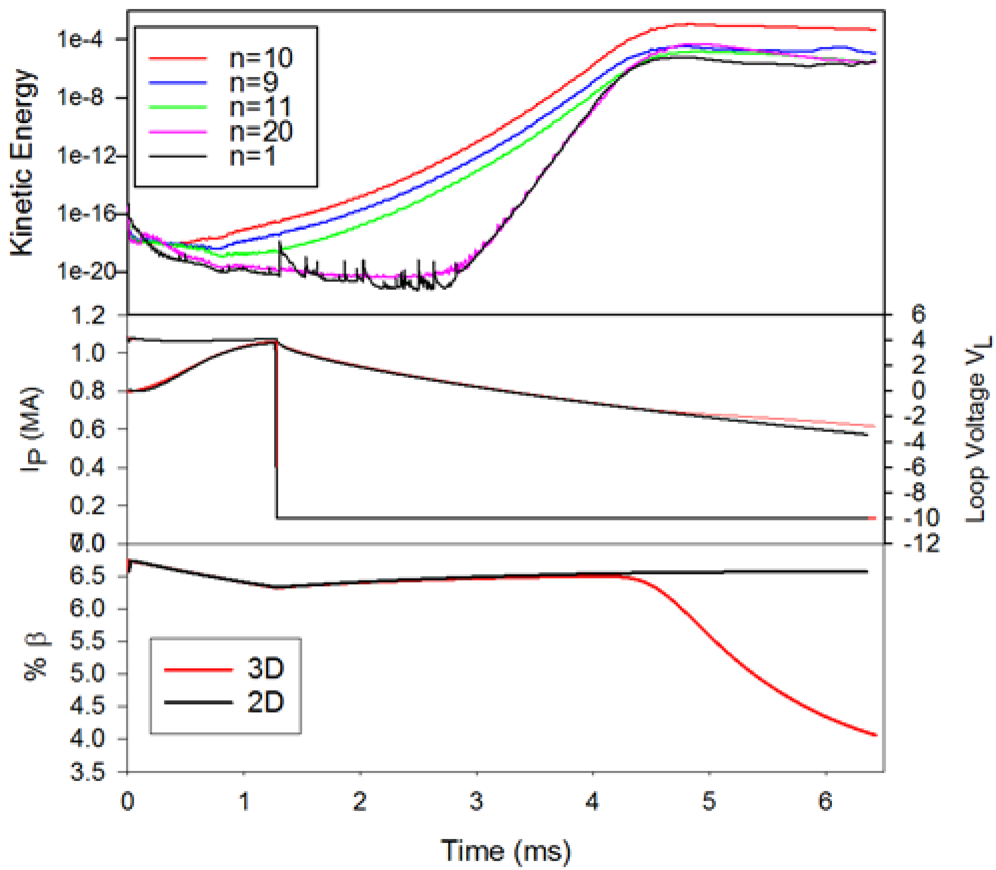
(1) Hard Disruptive Limits:

1.1 Current ramp-down disruption
1.2 Vertical Displacement Event
1.3 Island overlap disruption

(2) Soft Limit

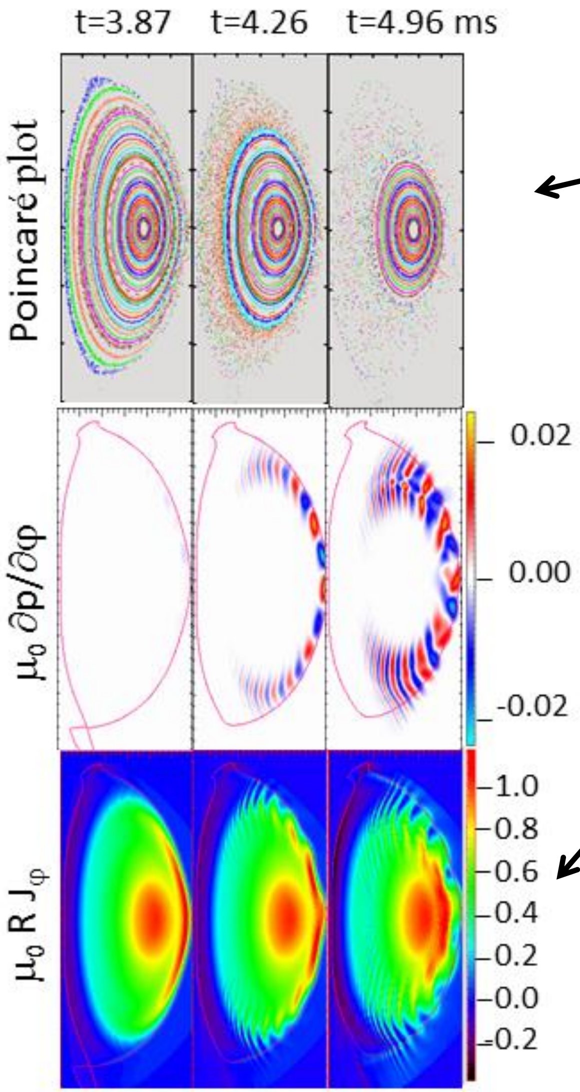
2.1 Heating past the beta limit
2.2 Self-organized stationary states and long-lived modes
2.3 Edge-Localized modes and pacing with pellet injection

1.1 Current Ramp-down Disruption



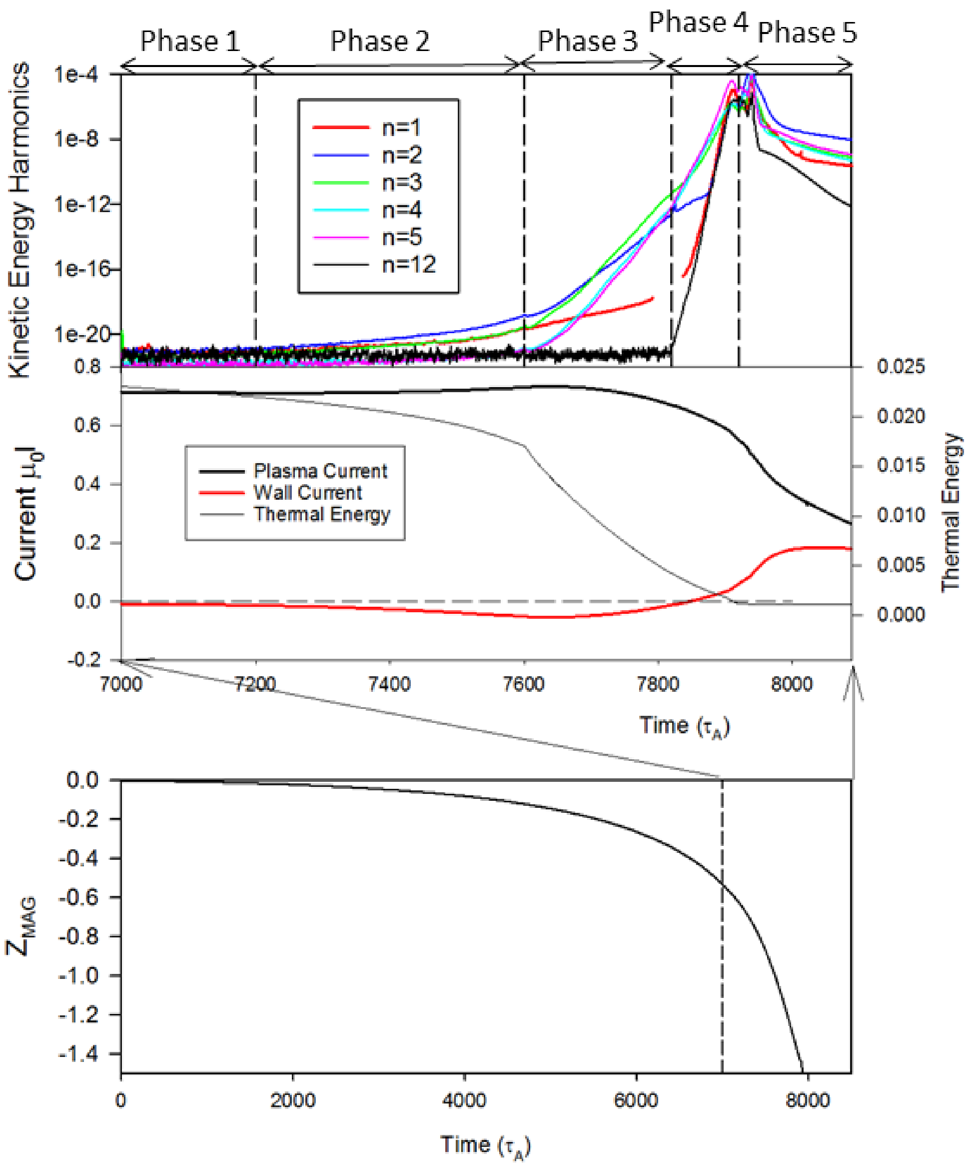
- NSTX discharges normally disrupt when applied loop voltage is suddenly reversed at the end of the discharge
- Modeling this with M3D-*C*[1] shows n=9,10,11 modes grow fastest
- These modes nonlinearly drive modes with n~20 and n~1
- As modes with n > 20 grow, they generate higher harmonics that cannot be resolved on numerical grid
- Comparison of 3D results with equivalent 2D calculation shows β-drop due to 3D effects

1.1 Current Ramp-down Disruption (cont)



- Top row shows Poincaré plots at three times showing surfaces are destroyed from the outside in
- Middle row shows *toroidal derivative* of pressure at 3 times with same color scale. Ballooning nature is evident
- Bottom row shows contours of current density illustrating filamentation as time proceeds
- These high resolution simulations are now being redone with some hyper-resistivity to prevent modes with n > 40 from growing

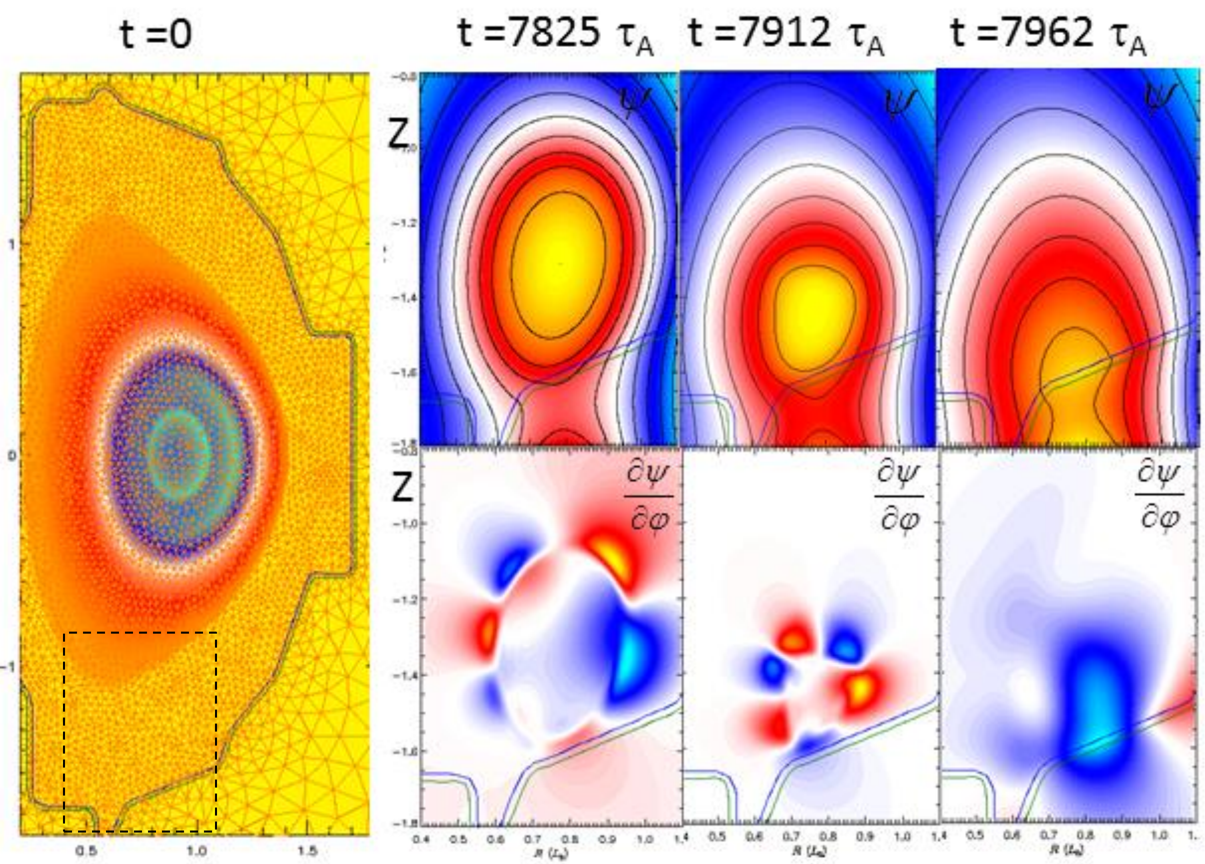
1.2 Vertical Displacement Event



- Vertical position control is turned off at t=0 as in NSTX shot 132859

- Calculation begins in 2D. At t=7000 τ_A, transferred to 3D and proceeds through 5 phases:
- **Phase 1:** Plasma remains axisymmetric drifting downward
- **Phase 2**: A n=2 tearing modes starts to grow
- **Phase 3**: This is joined by a n=3 tearing mode
- **Phase 4:** The n=1 external mode becomes strongly unstable and higher-n modes grow as well
- **Phase 5:** Plasma gets scraped off and disappears

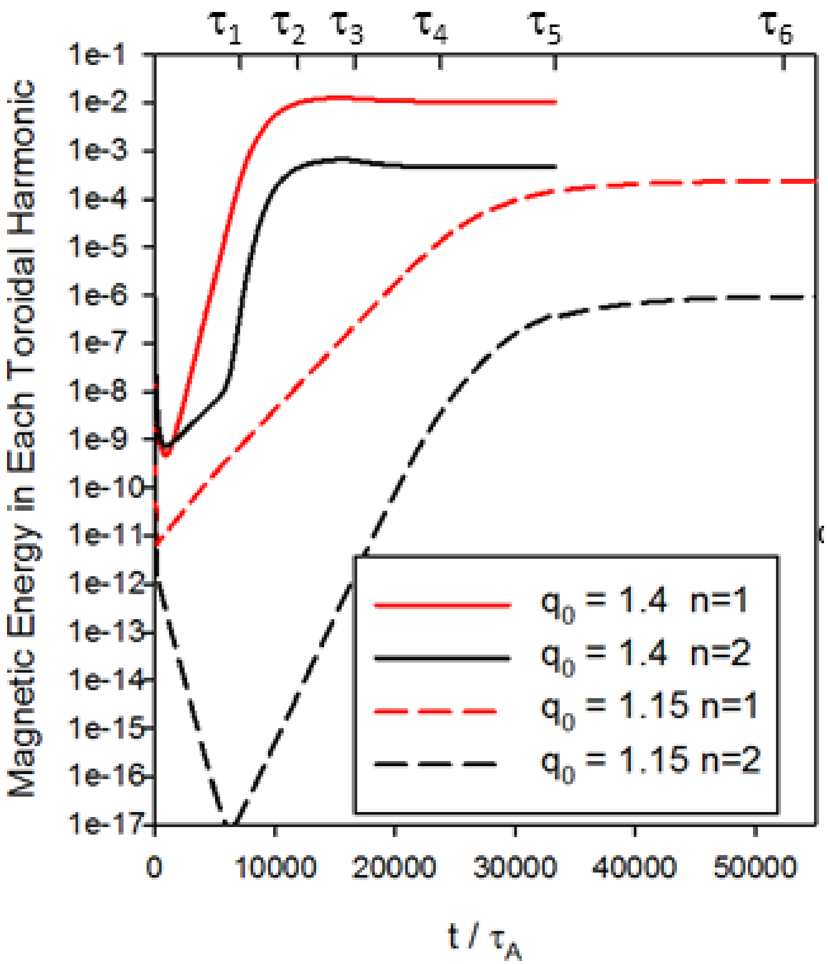
1.2 Vertical Displacement Event (cont)



Initial plasma current, vessel, and mesh

- Final phases show plasma being scraped off by vessel
- Top three frames show poloidal (ψ)flux at late times
- Halo current flows along open field lines into and out of vessel
- Bottom frames of toroidal derivative of ψ show mode structure

1.3 Island Overlap Disruption



- As part of an ITPA benchmark, we have examined the nonlinear stability of two cylindrical equilibrium:

$$q(r) = 1.15\left[1 + \left((r/a)^2 / 0.6561\right)\right]$$

  - Unstable to a single (2,1) tearing mode

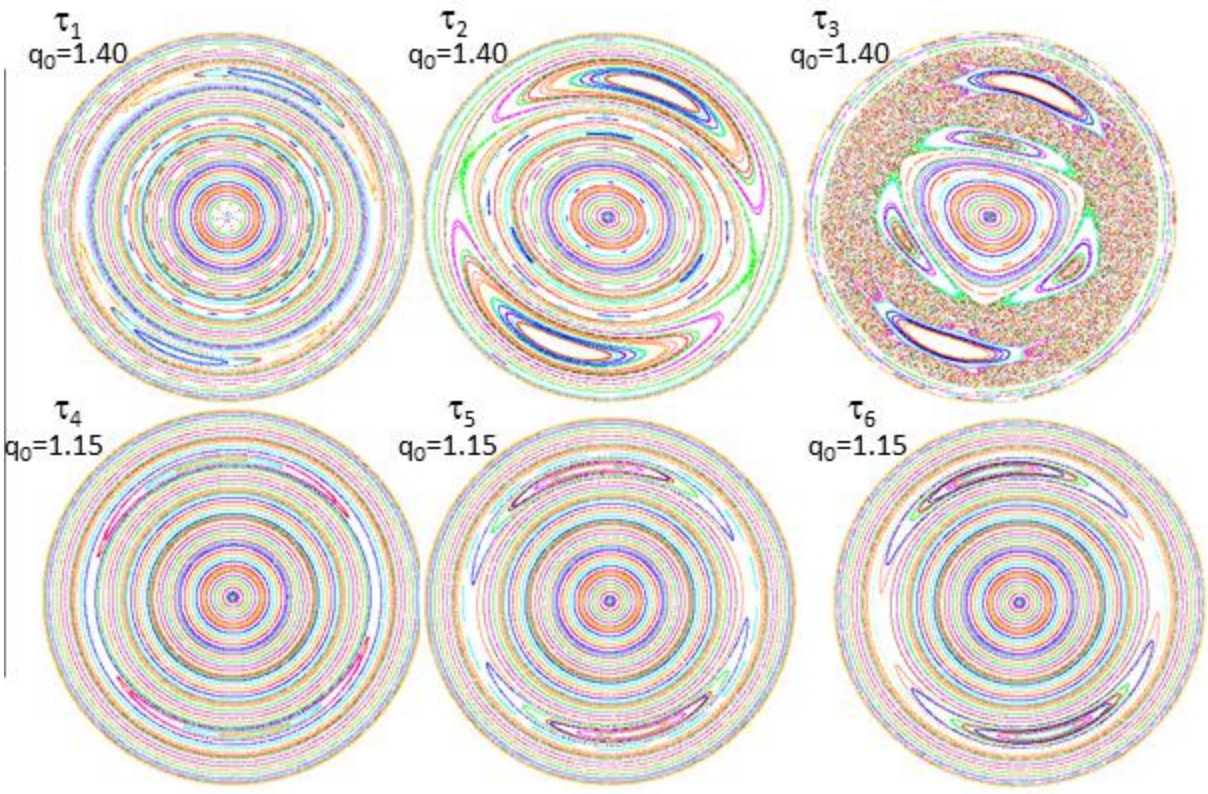
$$q(r) = 1.40\left[1 + \left((r/a)^2 / 0.5476\right)^2\right]^{1/2}$$

  - Unstable to both a (2,1) and (3,2) mode

- Here we plot the magnetic energy in the n=1 and n=2 toroidal harmonics for the two nonlinear calculations

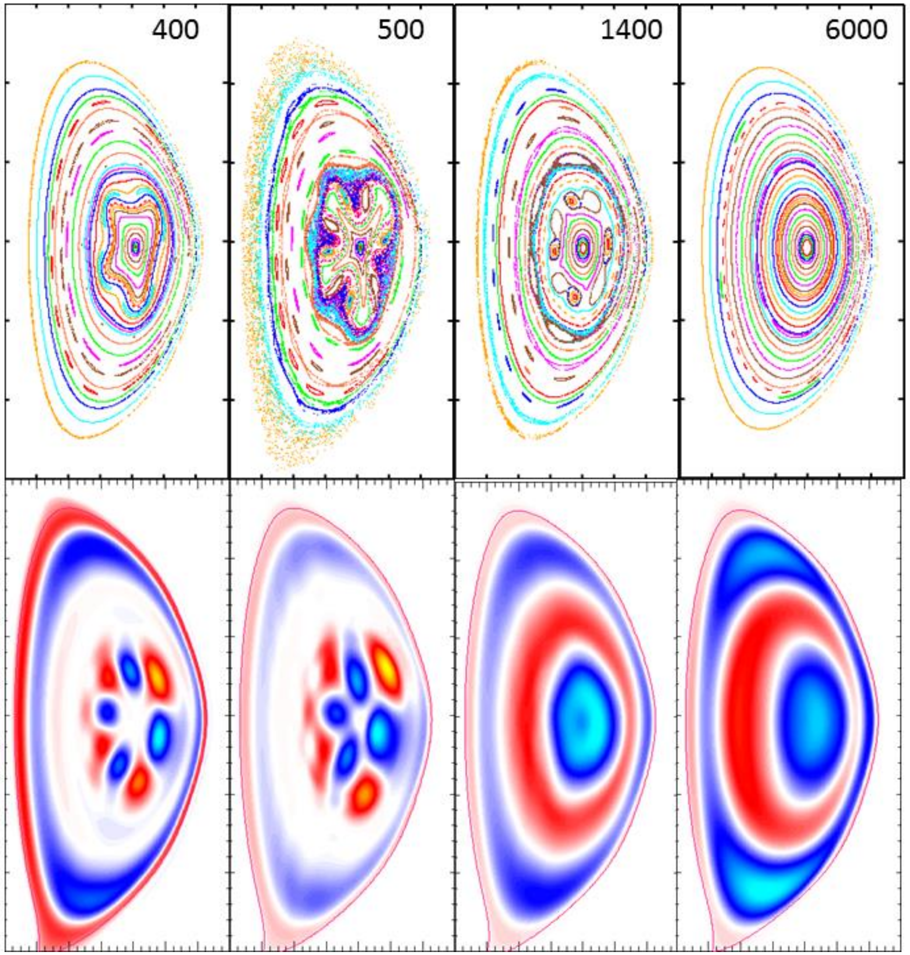
- It is seen the q_0 = 1.4 case grows to much larger amplitude and leads to ergodic field lines

1.3 Island Overlap Disruption (cont)



- Top row shows 2-unstable mode case which leads to island overlap and a disruption
- Bottom row shows single unstable mode case with a single saturated island

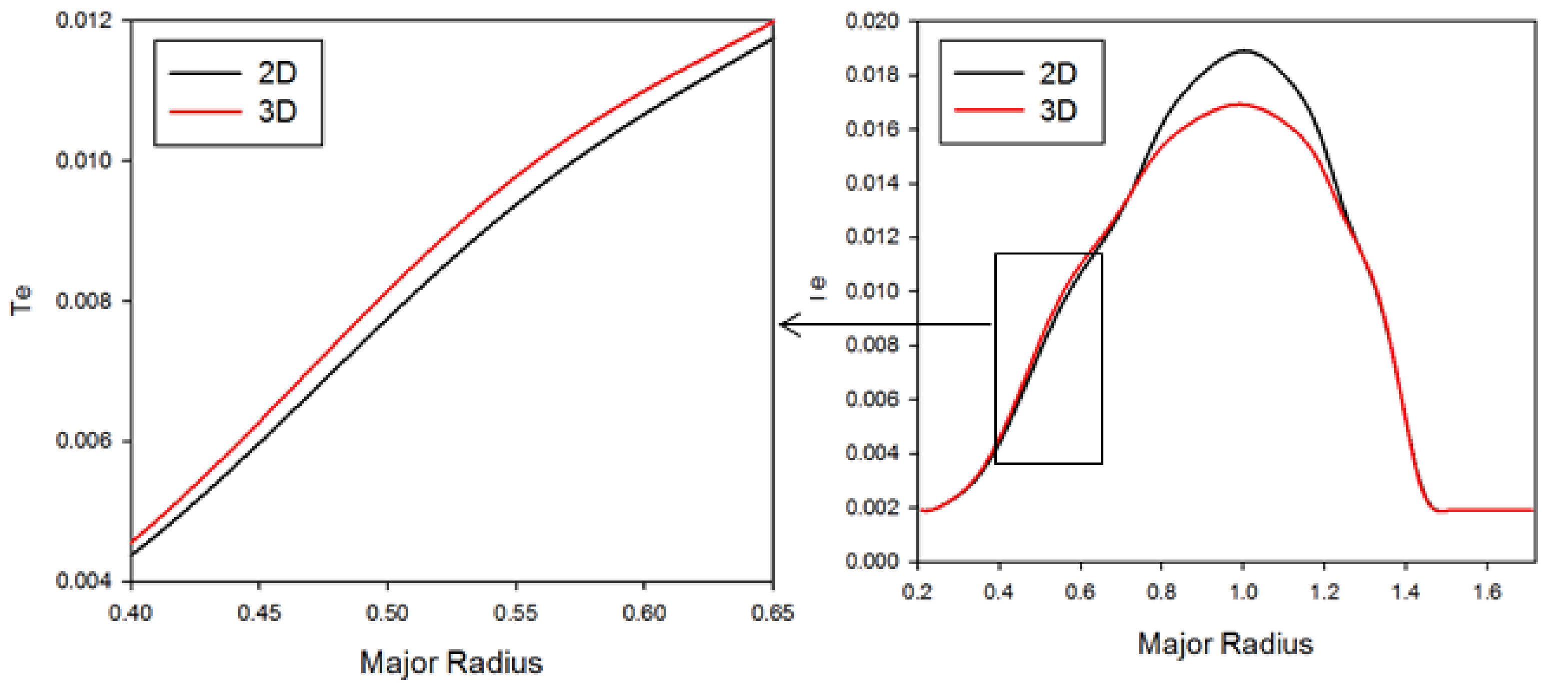
2.1 Heating Past the Beta Limit



Poincaré plots (top) and change in temperature (bottom) at 4 times (units of τ_A)

- NSTX plasma discharge 124379 at t=0.64 sec.
- Initial pressure in EFIT file is slightly above β limit, causing instability
- An internal (4,3) mode goes unstable near the q=1.33 surface
- Instability distorts the magnetic surfaces in such a way that $\chi_{||}$ acts to reduce the pressure in the center.
- Discharge becomes stable and re-symmetrizes

2.1 Heating Past the Beta Limit (cont.)

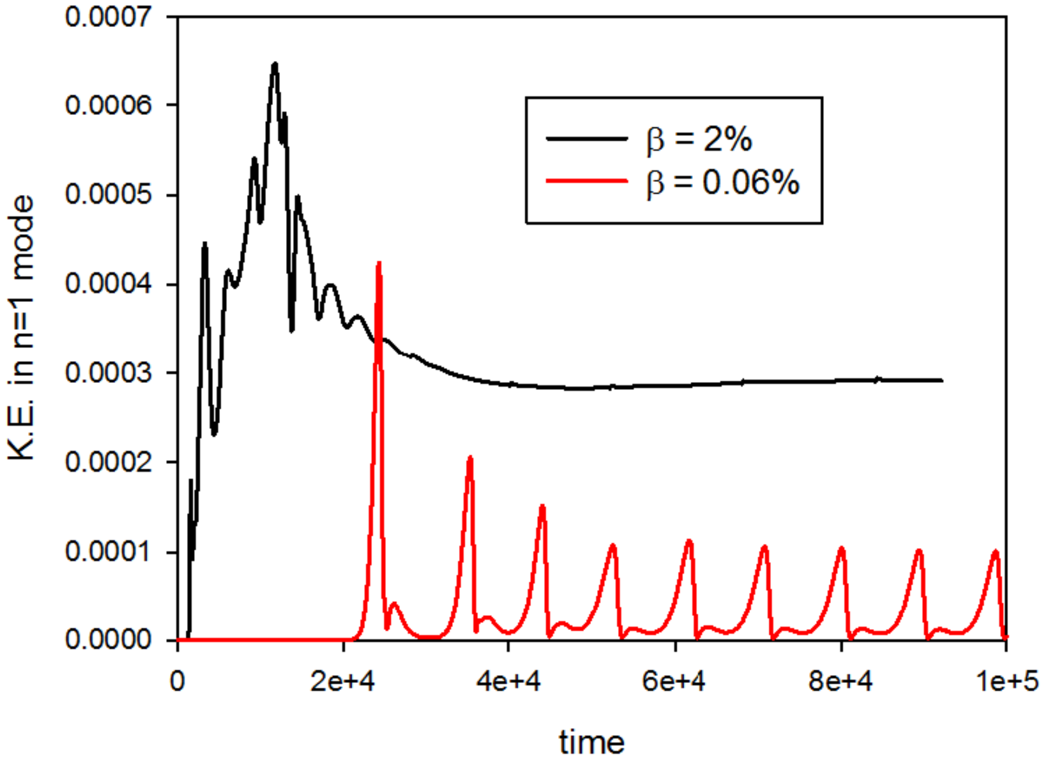


- Final mid-plane temperature profiles for the 3D calculation and for an equivalent 2D calculation with the same transport coefficients.

- It is seen that the net effect of the 3D instability is to reduce the temperature in the center slightly and increase it at mid-radius.

- Thus, the nonlinear effect is simply to increase the central transport.

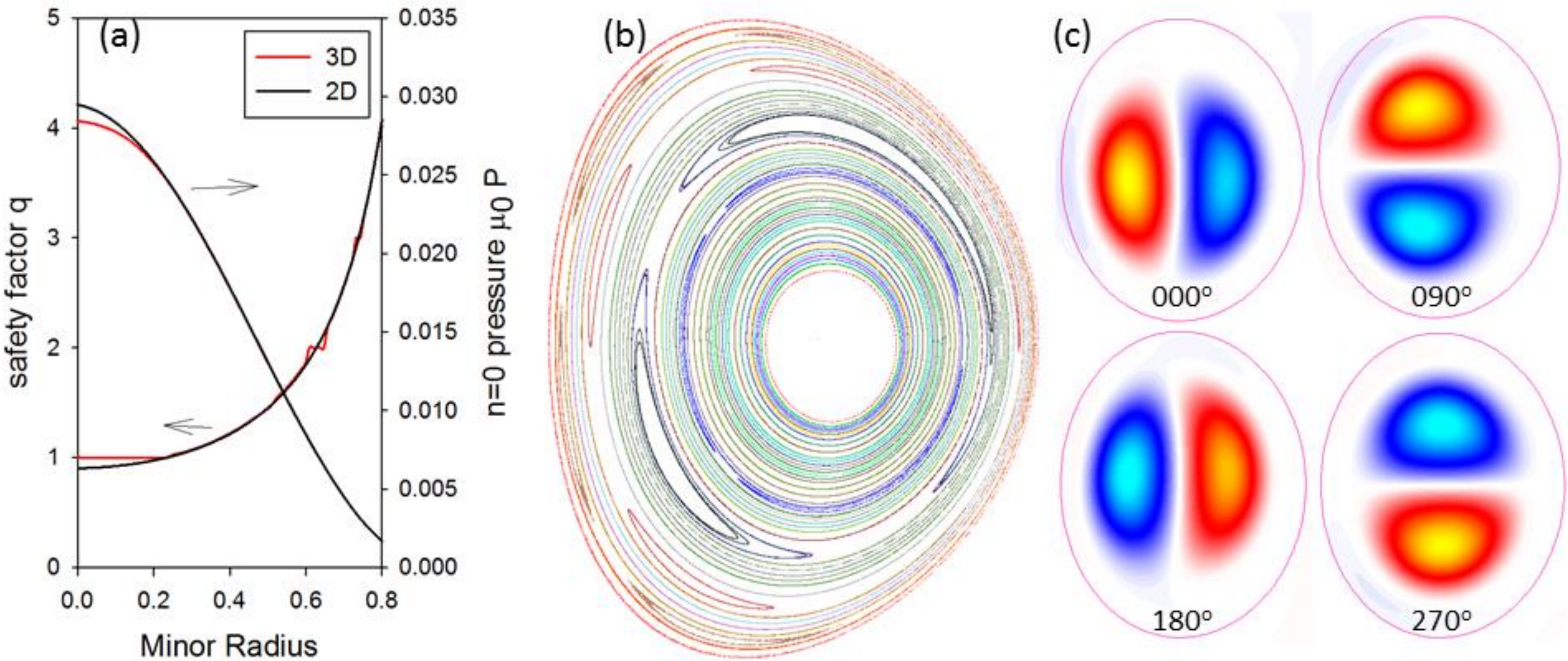
2.2 Self-organized stationary states



Low β discharge (in red) goes through periodic Kadomsev reconnection events (sawtooth). Higher β discharge (in black) goes to stationary state with non-zero kinetic energy

- The kinetic energy in a β=0.06% simulation of a sawtoothing discharge is shown in red.
- For the same configuration, if we increase the β to 2%, the kinetic energy does not oscillate in time but reaches a stationary state with a non-zero kinetic energy as shown in the black curve
- We find that under certain conditions, and for sufficiently high plasma-β, the plasma can self-organize to produce a shear-free region in the center with q~1.

2.2 Self Organized Stationary States (cont)

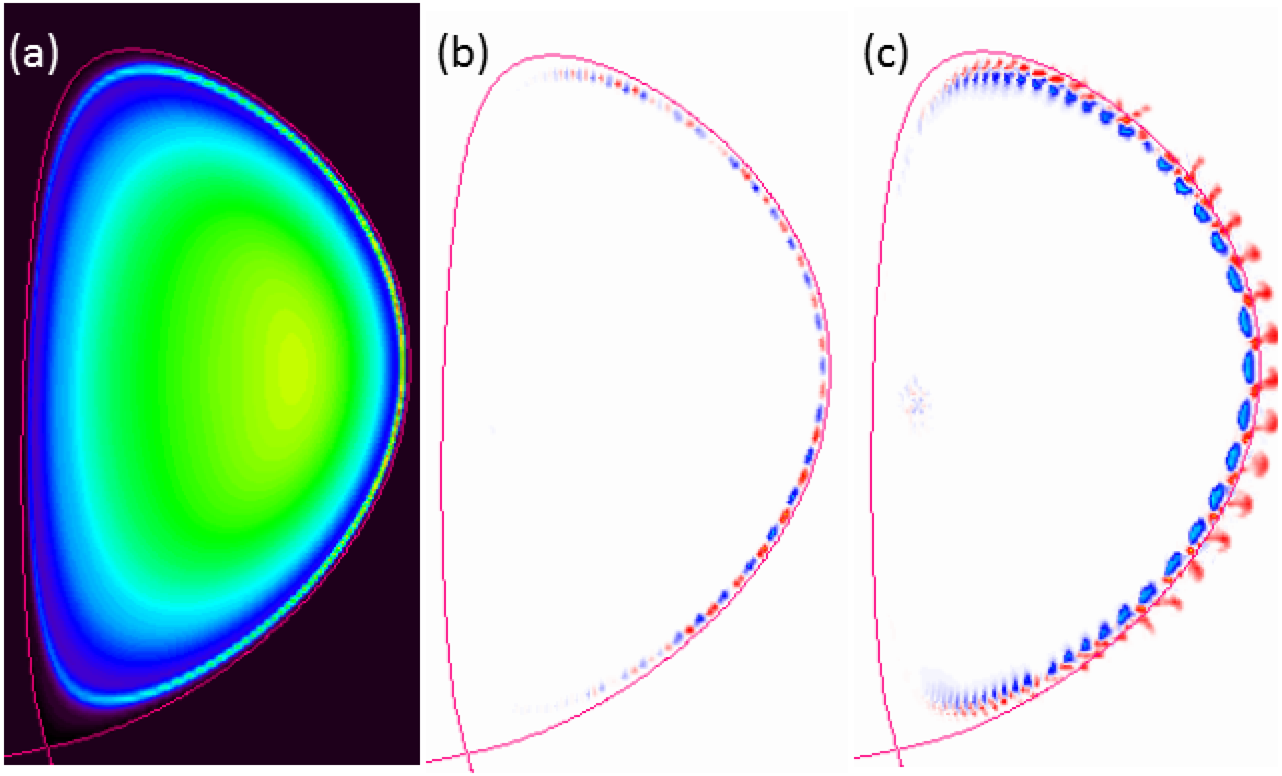


(a) For the 2% β (stationary) configuration, we compare a 2D simulation with a 3D simulation, showing the 3D case has lower central pressure and q=1 region in center

(b) Poincaré plots showing region in center with q=1 and no flux surfaces. The stationary (1,1) perturbations drives other islands through toroidal coupling

(c) Contours of the velocity stream function in the central region at 4 different toroidal locations showing the eigenfunction of the stationary (1,1) mode

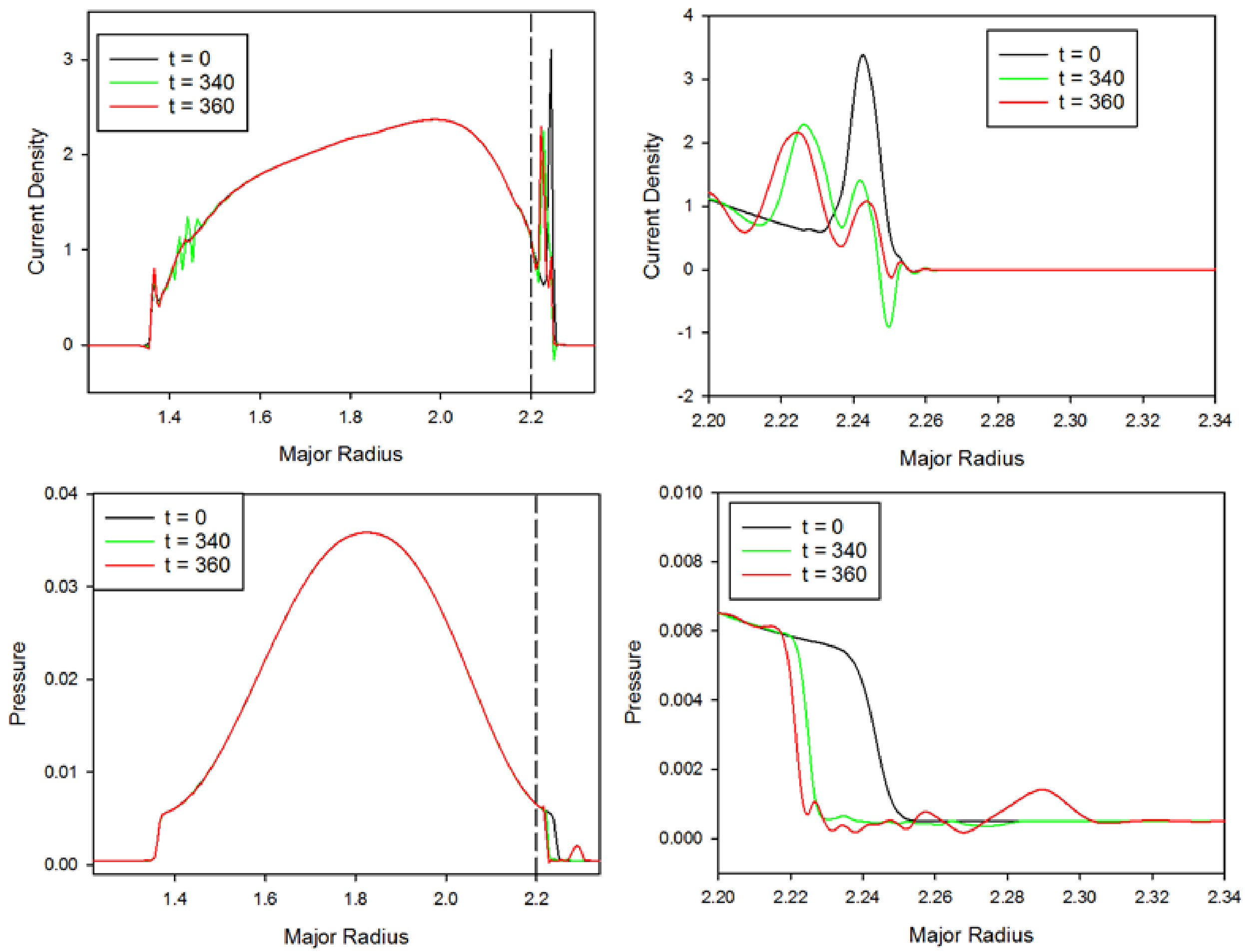
2.3 Edge Localized Modes



(a) Initial current density for KSTAR discharge #7328 at time t = 4.36 s

(b) and (c) show the perturbed pressure at two time, showing the expulsion of pressure blobs across the separatrix into the SOL

2.3 Edge Localized Modes (cont)



- Mid-plane profiles of the current density (top) and pressure for the calculation on the previous slide
- Note how localized the perturbation is, only affecting a narrow region near the edge

Summary and Issues

(1) Hard Disruptive Limit:

- Physics of thermal quench
  - Rapid current ramp-down disruption
  - Modeling of rapid heat loss
  - Can we reproduce current spike?
  - Physics of locked modes.
- Physics of 3D VDE
  - Halo current formation
  - Non-axisymmetric forces
  - Extrapolation to ITER
- Island overlap disruption
  - When will 2 TM lead to disruption?
  - Effect of sheared rotation

(2) Soft Limit

- Heating past the beta limit
  - Disruption or increased transport?
  - Mechanism for heat transport
  - Reduced model for TRANSP?
  - Relation to Cowley theory of NL ballooning
- Self-organized stationary states
  - When to expect non-sawtoothing discharges
  - Role of (2,1) and (3,2) islands
  - Explain central breaking due to (2,1) RMP?
- Edge-Localized modes
  - 3D modeling of pellet pacing and comparison with experiment