A New Explanation of the Sawtooth Phenomena in Tokamaks

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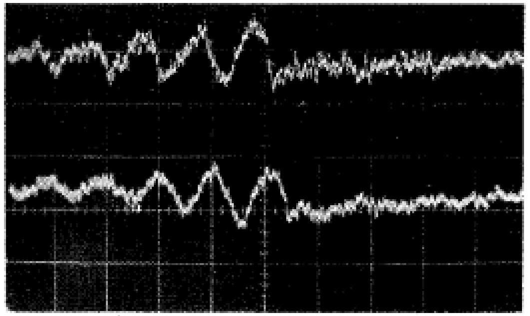
First measurement of sawtooth oscillations

VOLUME 33, NUMBER 20 PHYSICAL REVIEW LETTERS 11 NOVEMBER 1974

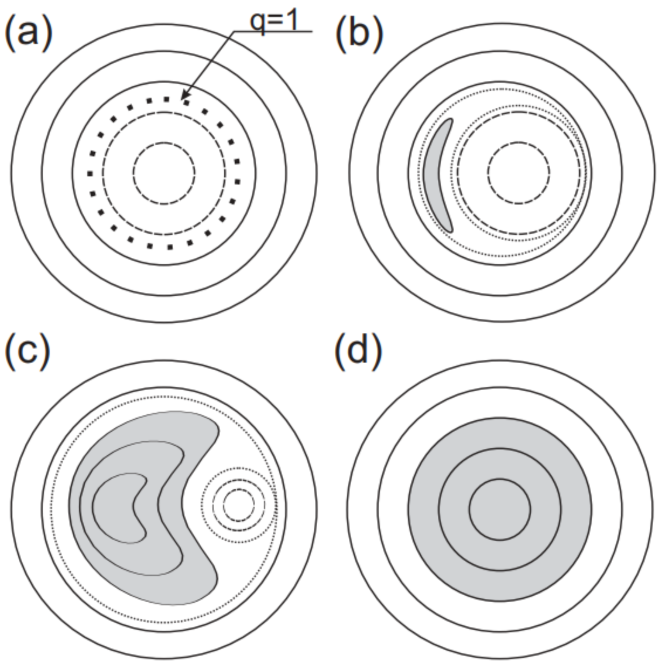
Studies of Internal Disruptions and $m = 1$ Oscillations in Tokamak Discharges with Soft–X-Ray Techniques*

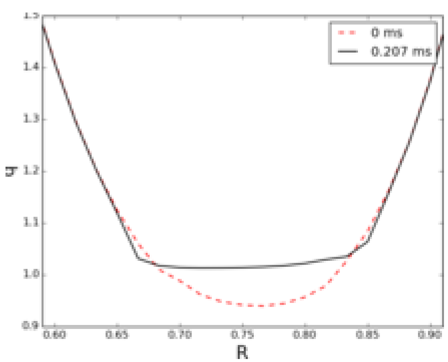
S. von Goeler, W. Stodiek, and N. Sauthoff
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
(Received 11 July 1974)



- ST Tokamak: Te = 800 eV , ne = .5 x 10^{14}
- Quasi-periodic (1,1) oscillations in central temperature
- Phase inverted around radius where q=1 surface was thought to be

Oscillations were explained shortly afterwards by Kadomtsev





- Current peaks and q_0 drops below 1 due to resistive diffusion with peaked temperature profile

$$\tau_R \sim \eta^{-1} \sim S$$

- When $q_0 < 1$, (1,1) resistive kink instability begins to grow.

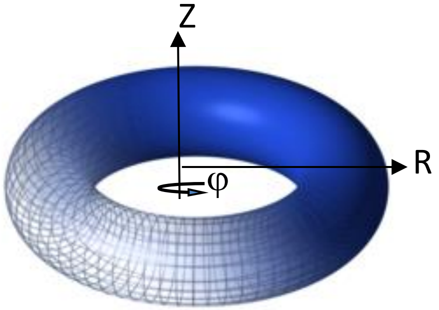
$$\gamma \sim \eta^{1/3} \sim S^{-1/3}$$

- After several e-folding times, complete reconnection restores q_0 to 1

$$S \equiv \frac{\tau_R}{\tau_A} = \frac{a^2 B_0}{\eta R}\left[\frac{\mu_0}{n_0 M_i}\right]^{1/2} \gg 1$$

Kadomtsev,, B. Fiz. Plazmy 1 710 (1975) [Sov. J. Plasma Phys. 1 389 (1976)

M3D-C^1 code used to simulate Kadomtsev model



$$\frac{\partial n}{\partial t} + \nabla \bullet (n\mathbf{V}) = \nabla \bullet D_n \nabla n + S_n$$

$$\frac{\partial \mathbf{A}}{\partial t} = -\mathbf{E} - \nabla\Phi, \quad \mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{J} = \nabla \times \mathbf{B}, \quad \nabla_\perp \bullet \frac{1}{R^2}\nabla\Phi = -\nabla_\perp \bullet \frac{1}{R^2}\mathbf{E}$$

$$nM_i\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \bullet \nabla\mathbf{V}\right) + \nabla p = \mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{\Pi}_i + \mathbf{S}_m$$

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{ne}\left(\mathbf{R_c} + \mathbf{J} \times \mathbf{B} - \nabla p_e - \nabla \bullet \mathbf{\Pi}_e\right) - \frac{m_e}{e}\left(\frac{\partial \mathbf{V}_e}{\partial t} + \mathbf{V}_e \bullet \nabla \mathbf{V}_e\right) + \mathbf{S}_{CD}$$

$$\frac{3}{2}\left[\frac{\partial p_e}{\partial t} + \nabla \bullet \left(p_e \mathbf{V}\right)\right] = -p_e \nabla \bullet \mathbf{V} + \frac{\mathbf{J}}{ne} \bullet \left[\frac{3}{2}\nabla p_e - \frac{5}{2}\frac{p_e}{n}\nabla n + \mathbf{R}_c\right] + \nabla\left(\frac{\mathbf{J}}{ne}\right) : \mathbf{\Pi}_e - \nabla \bullet \mathbf{q}_e + Q_\Delta + S_{eE}$$

$$\frac{3}{2}\left[\frac{\partial p_i}{\partial t} + \nabla \bullet \left(p_i \mathbf{V}\right)\right] = -p_i \nabla \bullet \mathbf{V} - \mathbf{\Pi}_i : \nabla \mathbf{V} - \nabla \bullet \mathbf{q}_i - Q_\Delta + S_{iE}$$

$$\mathbf{V}_e = \mathbf{V}_i - \mathbf{J} / ne$$

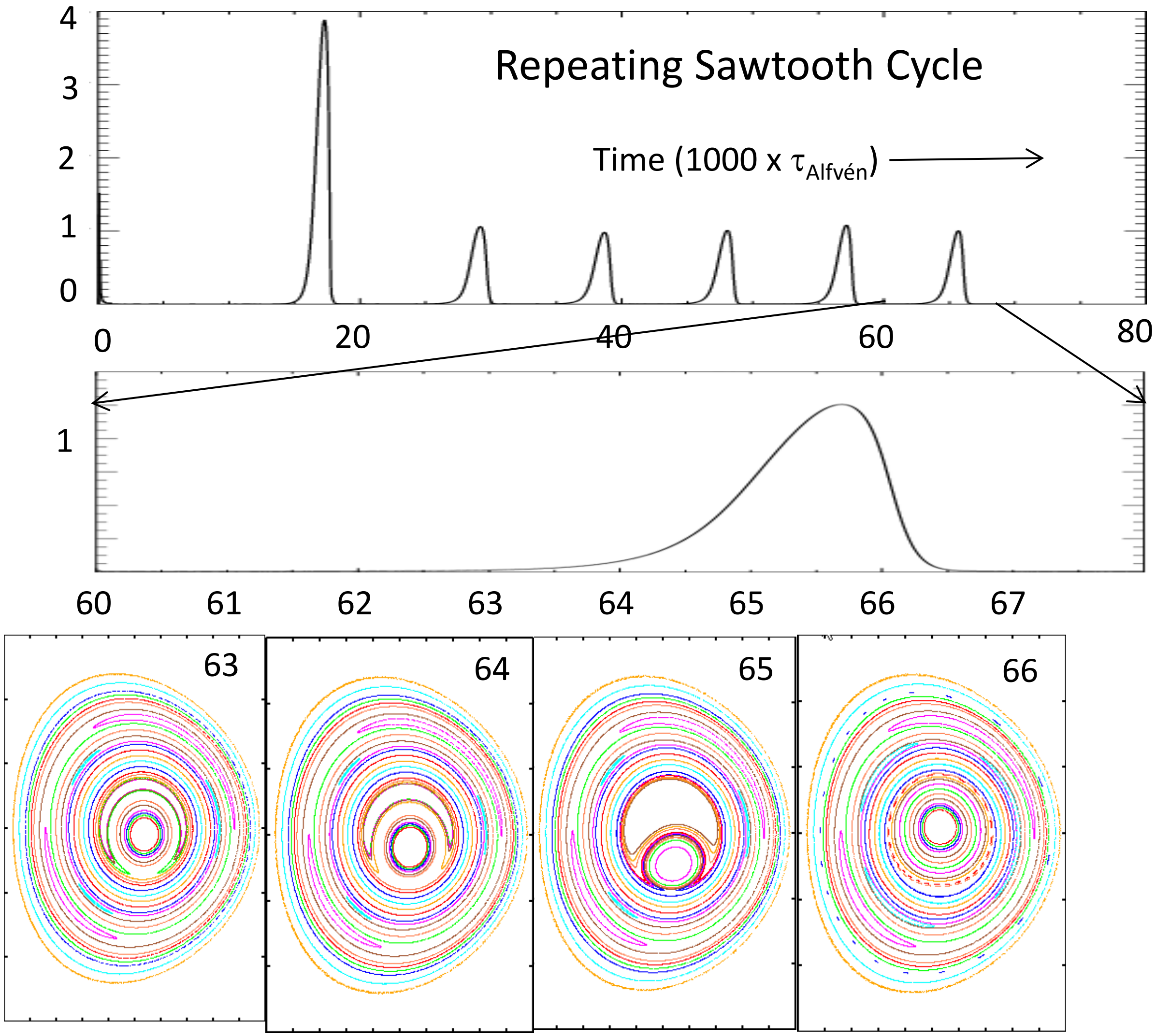
$$\mathbf{R}_c = \eta ne\mathbf{J}, \qquad \mathbf{\Pi}_i = -\mu\left[\nabla\mathbf{V} + \nabla\mathbf{V}^\dagger\right] - 2(\mu_c - \mu)(\nabla \bullet \mathbf{V})\mathbf{I} + \mathbf{\Pi}_i^{GV}$$

$$\mathbf{q}_{e,i} = -\kappa_{e,i}\nabla T_{e,i} - \kappa_\parallel \nabla_\parallel T_{e,i}$$

$$\mathbf{\Pi}_e = (\mathbf{B} / B^2)\nabla \bullet \left[\lambda_h \nabla\left(\mathbf{J} \bullet \mathbf{B} / B^2\right)\right], \qquad Q_\Delta = 3m_e\left(p_i - p_e\right) / \left(M_i \tau_e\right)$$

Blue terms are 2-fluid terms. Also, now have impurity and pellet models for disruption mitigation. **NOT reduced MHD**.

M3D-C1 finds ST results consistent with Kadomtsev Reconnection



- q_0 drops below 1 with growth rate ~ η^{-1}
- Resistive kink becomes unstable with growth rate ~$\eta^{1/3}$
- Mode takes a few e-folding times to grow and reconnect
- Typically $0.95 < q_0 < 1.0$ for S ~ 10^5-10^6, low-β

HOWEVER:

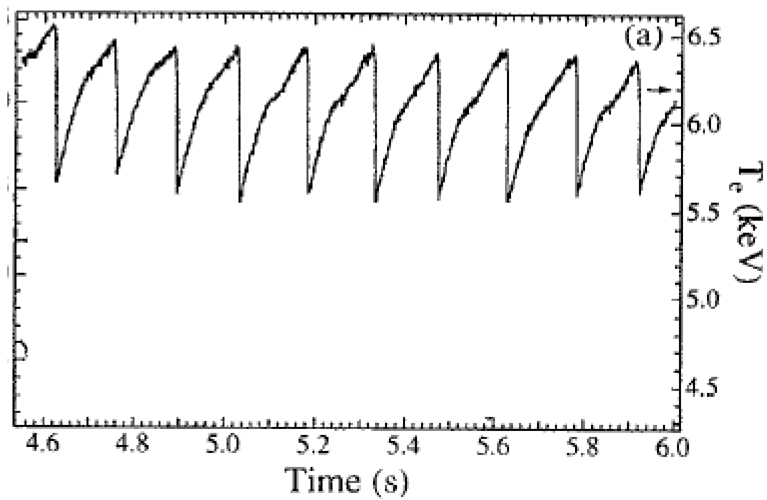
- At higher temperatures, (smaller η) q_0 does not drop substantially before kink mode sets in

High-T_e plasmas show much faster crash times than $\eta^{1/3}$

Investigation of magnetic reconnection during a sawtooth crash in a high-temperature tokamak plasma

M. Yamada, F. M. Levinton,[a] N. Pomphrey, R. Budny, J. Manickam, and Y. Nagayama[b]
Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543

(Received 2 March 1994; accepted 9 June 1994)

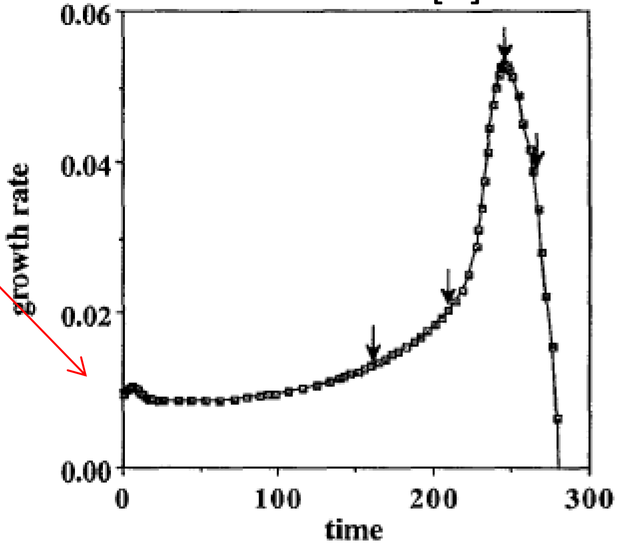


- TFTR electron temperature crash time is very fast, ~ 100 μs, even though T_e is over 10 times greater than T_e in the ST
- Sawtooth period and fast crash times on TFTR and other large tokamaks apparently not consistent with Kadomtsev model

Many theory papers have offered explanations for fast crash times

- With the Kadomtsev model in mind, many authors have “explained” fast *crashes* as being due to fast *magnetic reconnection*:
  - Anomalous electron viscosity[1]
  - Two-fluid effects [2-4]
  - High-n ballooning modes [5]
  - Plasmoids [6]
  - Plasma compressibility [7]
- However, all these studies start with a unstable plasma with $q_0 << 1$
  - How did the plasma get into this unstable state?

From Ref. [2]

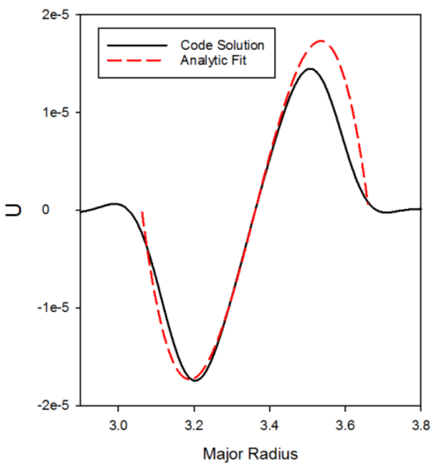


[1] Aydemir, A. Y., Phys. Fluids B 2 2135 (1990)
[2] Aydemir, A. Y., Phys. Fluids B 4 3469 (1992)
[3] Yu, Q., Gunter, S., and Lackner, K., Nucl. Fusion 55 113008 (2015)
[4] Beidler, M., Cassak, P., Jardin, S., Ferraro, N., Plasma Phys. and Control. Fusion 59 025007 (2017)
[5] Nishimura, Y., Callen, J. D., Hegna, C., Phys. Plasma 6 4685 (1999)
[6] Gunter, S., Yu, Q., Lackner, K., et al. Plasma Phys. Control. Fusion 57 104017 (2015)
[7] Sugiyama, L. Phys. Plasmas 21, 022510 (2014)

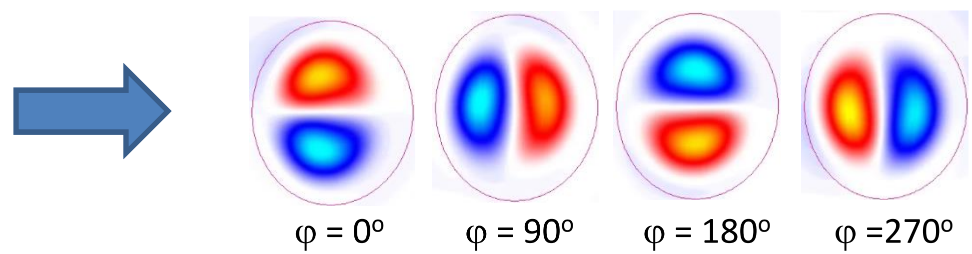
An alternative to Kadomtsev model is the interchange model

- First introduced by Wesson [8] (coined the name quasi-interchange)
- It has now been shown analytically [9,10] and numerically [9,11,12] that a tokamak with q_0 slightly exceeding 1 and with very low central shear is unstable to a pressure-driven (1,1) interchange mode.
- We now know that this (1,1) interchange mode will saturate at a low amplitude, producing a (1,1) flow field that partially flattens the pressure.

$$\mathbf{V}_{1,1} = R^2 \nabla U_{1,1} \times \nabla \varphi$$



$U_{1,1}$



- This (1,1) flow field found in M3D-C^1 simulations [11,12] agrees with the linear eigenfunction found in [9]

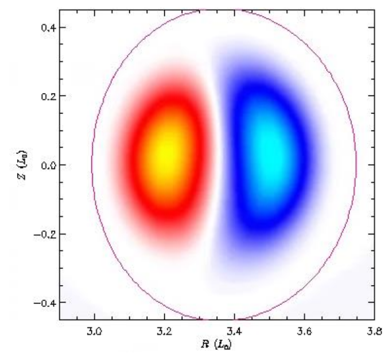
[8] J. Wesson, PPCF 28 243 (1986)
[9] J. Hastie and T. Hender, NF 28 585 (1988)
[10] F. Waelbroeck and R. Hazeline, PF 31 1217 (1988)
[11] S. Jardin, N. Ferraro, I. Krebs, PRL 115, 215001 (2015)
[12] I. Krebs, S. Jardin, S. Gunter, et al, PP 24, 102511 (2017)

(1,1) flow field produces a dynamo voltage that opposes drop in q_0

$$\nabla\Phi_{1,1} - \mathbf{V}_{1,1} \times \mathbf{B} = -\eta\mathbf{J} + \frac{V_L}{2\pi}\nabla\varphi$$

These 2 large terms must almost cancel

potential $\Phi_{1,1}$ at one toroidal plane



- Perturbed electric potential $\Phi_{1,1}$ very similar in form to perturbed stream function $U_{1,1}$

- Velocity field also perturbs the pressure and creates a $\mathbf{B}_{1,1}$ magnetic field:

$$\nabla p_{1,1} = \mathbf{J}_{1,1} \times \mathbf{B}_{0,0} + \mathbf{J}_{0,0} \times \mathbf{B}_{1,1}$$
$$\nabla \times \mathbf{B}_{1,1} = \mu_0 \mathbf{J}_{1,1}$$

- Perturbed electric potential and magnetic field produce a counter loop-voltage in center, keeping q_0 from dropping below 1:

$$V_{0,0} = \mathbf{B}_{1,1} \bullet \nabla\Phi_{1,1} + \cdots$$

[1]Jardin, Ferraro, Krebs, PRL , 21 215001 (2015)
[2]Krebs, Jardin, Guenter, et al, Phys. Plasmas 24 102511 (2017)

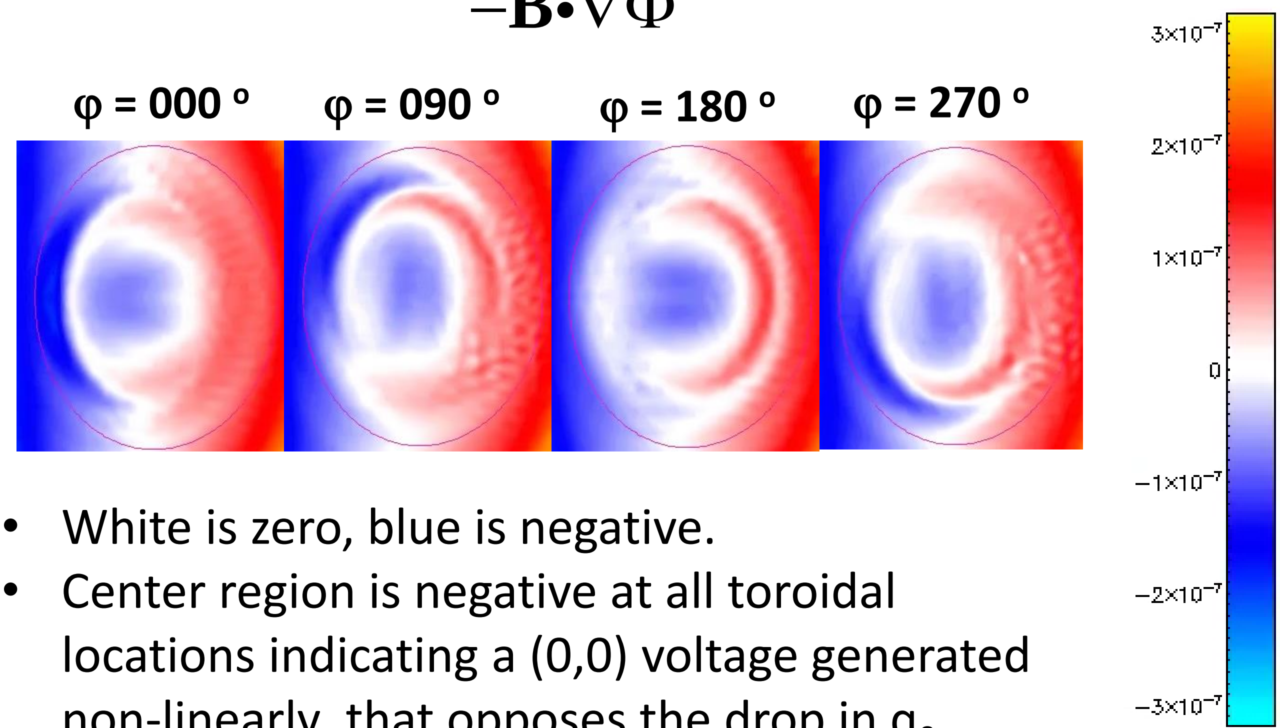
Consider the terms in the parallel Ohm's law

In 3D, the $\mathbf{B}_{1,1} \bullet \nabla\Phi_{1,1}$ term leads to an effective voltage along the field in center

$$\mathbf{B}\bullet\left[\nabla\Phi - \mathbf{V}\times\mathbf{B} + \eta\mathbf{J} = \frac{V_L}{2\pi}\nabla\varphi\right]$$

$$\Rightarrow \qquad \eta\mathbf{J}\bullet\mathbf{B} = -\mathbf{B}\bullet\nabla\Phi + \frac{V_L}{2\pi}\mathbf{B}\bullet\nabla\varphi$$

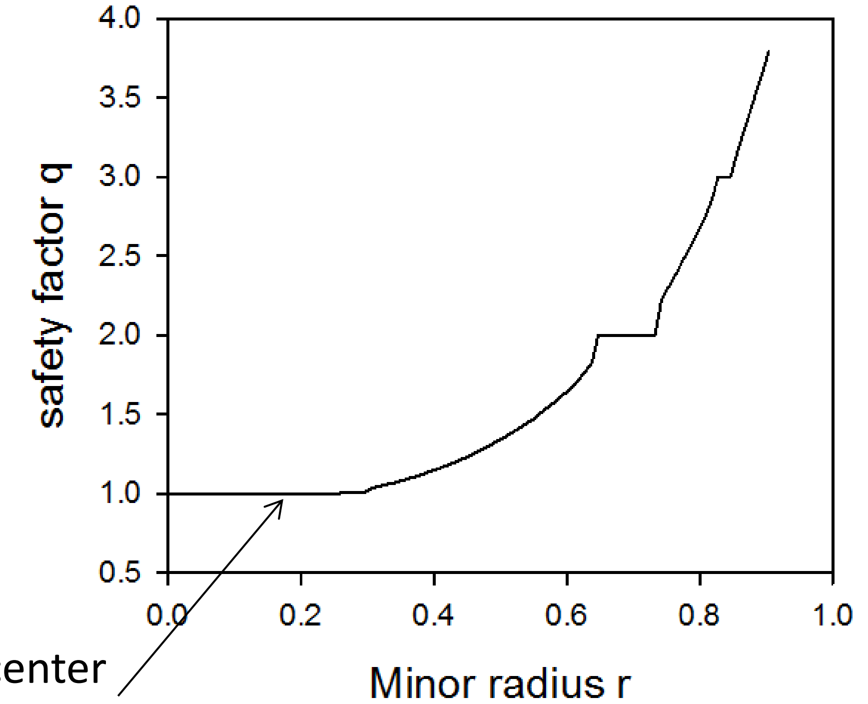
$$-\mathbf{B}\bullet\nabla\Phi$$



- White is zero, blue is negative.
- Center region is negative at all toroidal locations indicating a (0,0) voltage generated non-linearly that opposes the drop in q_0
- This mechanism keeps $q_0 = 1 + \varepsilon$ as shown on next slide

The $V_{0,0}$ voltage from $B_{1,1} \bullet \nabla\Phi_{1,1}$ keeps $q_0 > 1$

Results from long-time M3D-C^1 simulation



$\beta = 2\%$

$S = 10^6$

Large region in center with $q = 1+\varepsilon$

- Since the interchange instability drive and hence $U_{1,1}$ is strongest at $q_0 = 1+\varepsilon$, this provides a natural feedback mechanism that keeps q_0 just above 1.0

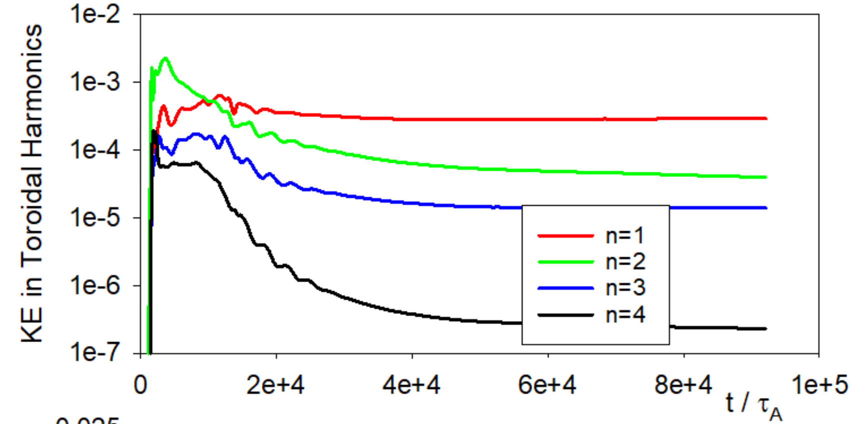
Long time non-sawtoothing nonlinear simulation

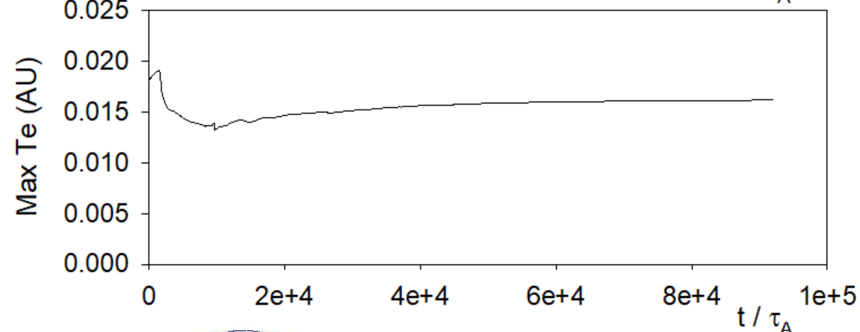
- We start with a standard, non-sawtoothing, hybrid case with q_0=1 studied in [1]

NEW:

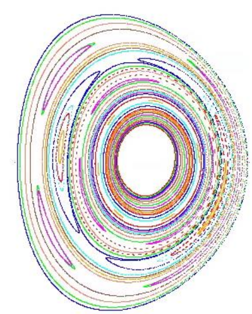
- What happens if we apply additional central heating so the central temperature continues to peak?

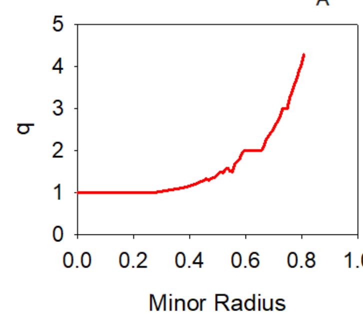
Case h: non-sawtoothing discharge





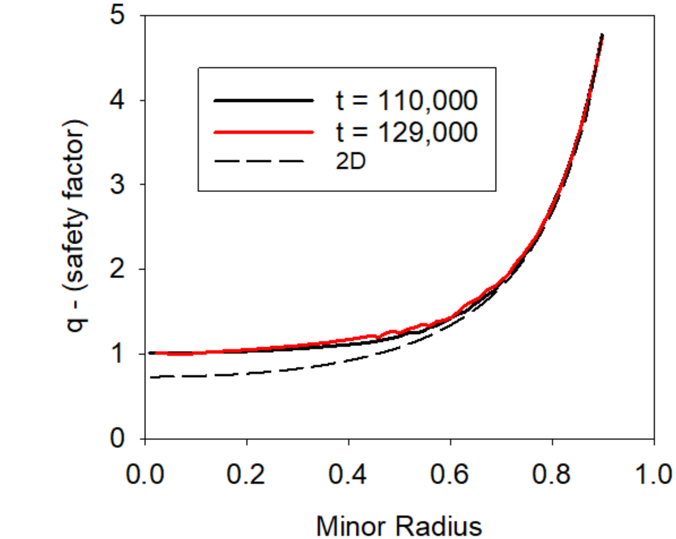
Original Case-h obtains stationary state with large (1,1) velocity field, q_0=1 with no shear in center.

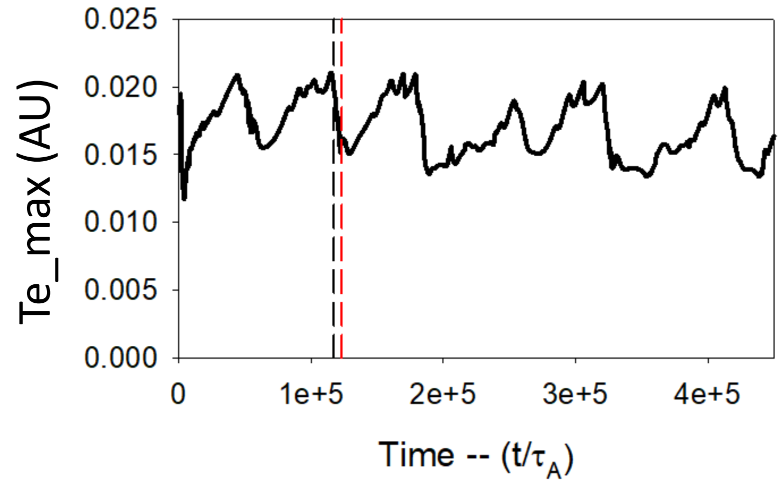




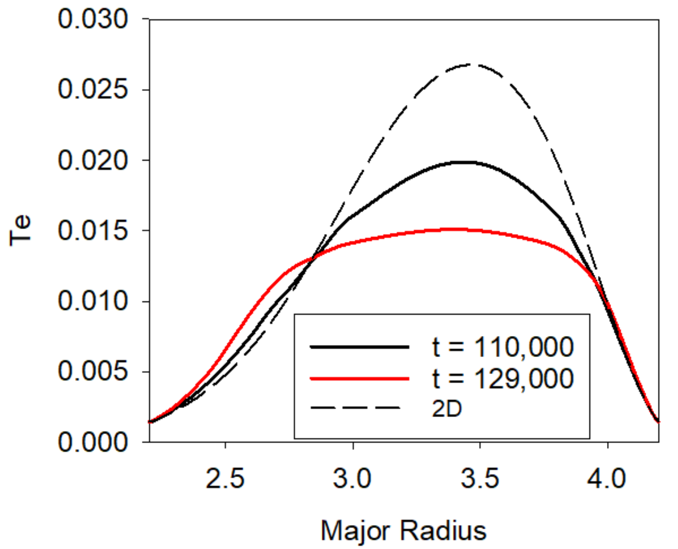
[1] Case-h in Krebs, et al, Phys. Plasmas. (2017)

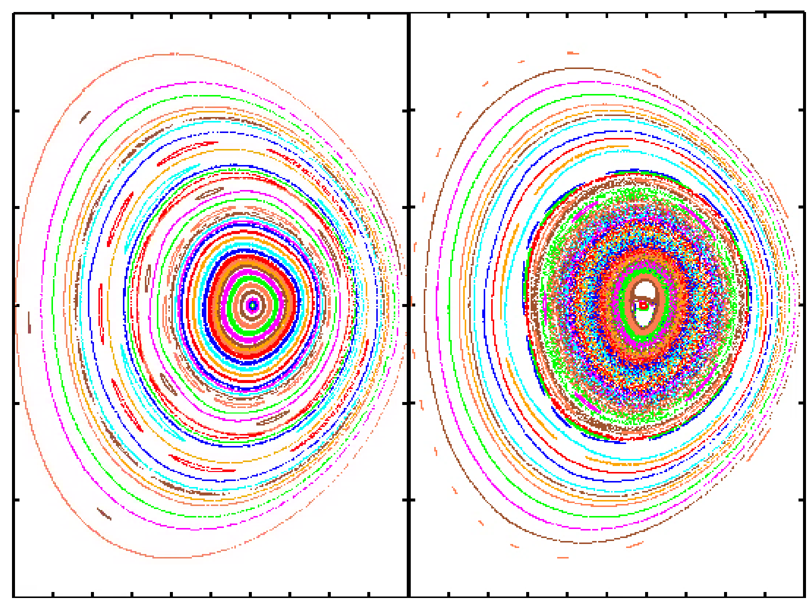
Increased heating leads to periodic oscillations in Te(0)





B_T = 1 T
R_0 = 3.2 m
n_0 = 4x10^{19}

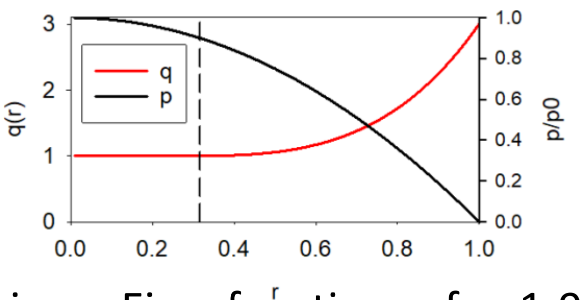




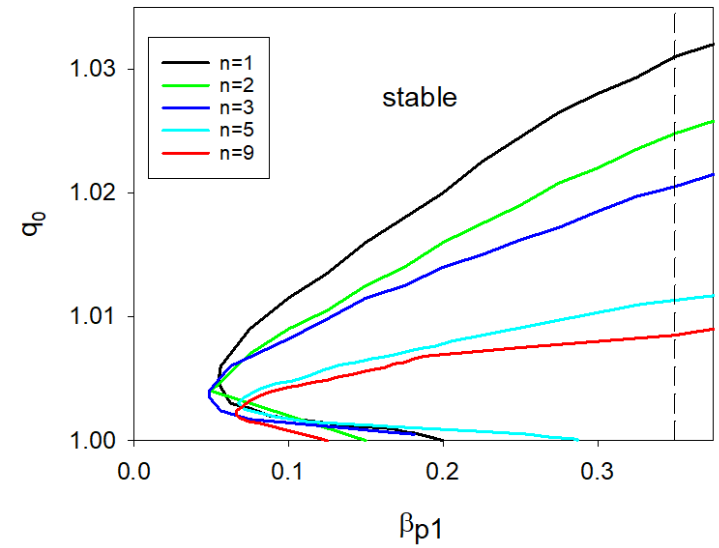
t = 110,000 t = 129,000

Run CMOD-04

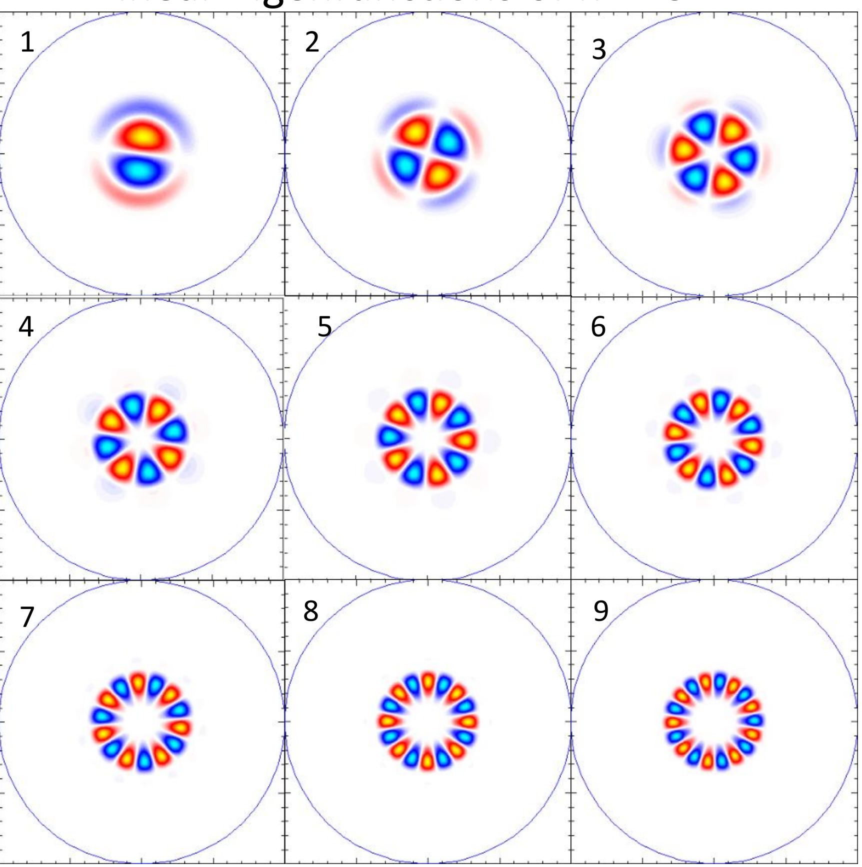
What causes Te oscillations (and crash)? Consider linear stability of modes with n=1-9 in circular cylinder geometry with M3D-C[1]

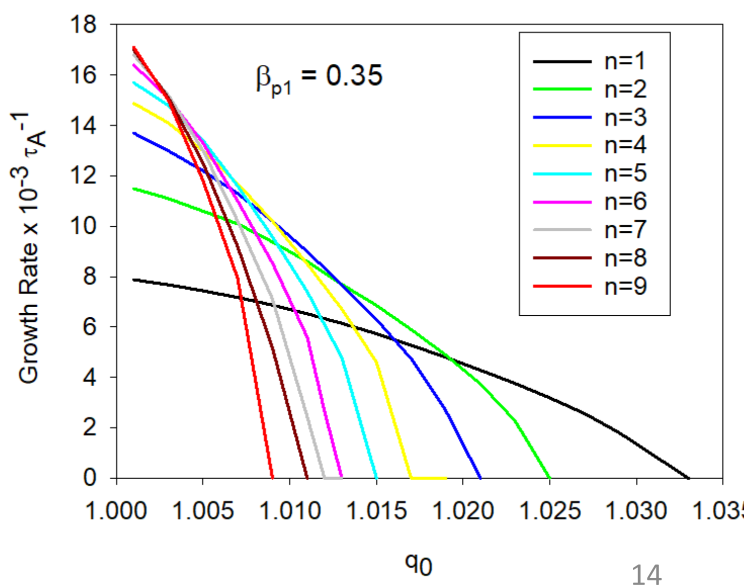


$$\beta_{p1} = \frac{\int_0^{r_1} \left[p(r) - p_1 \right] dV}{\int_0^{r_1} \frac{1}{2} B_p^2 dV}$$

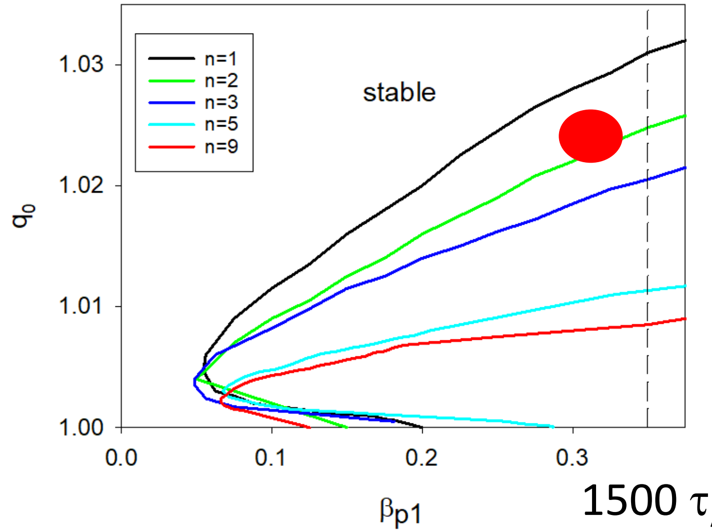


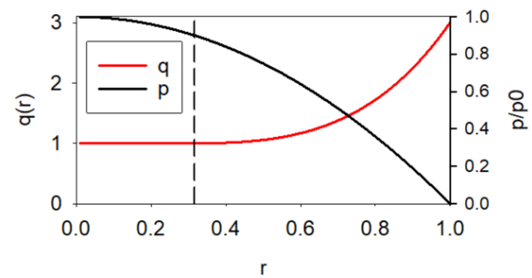
Linear Eigenfunctions of n=1-9





Initiate a NL M3D-C[1] run with one of these equilibria

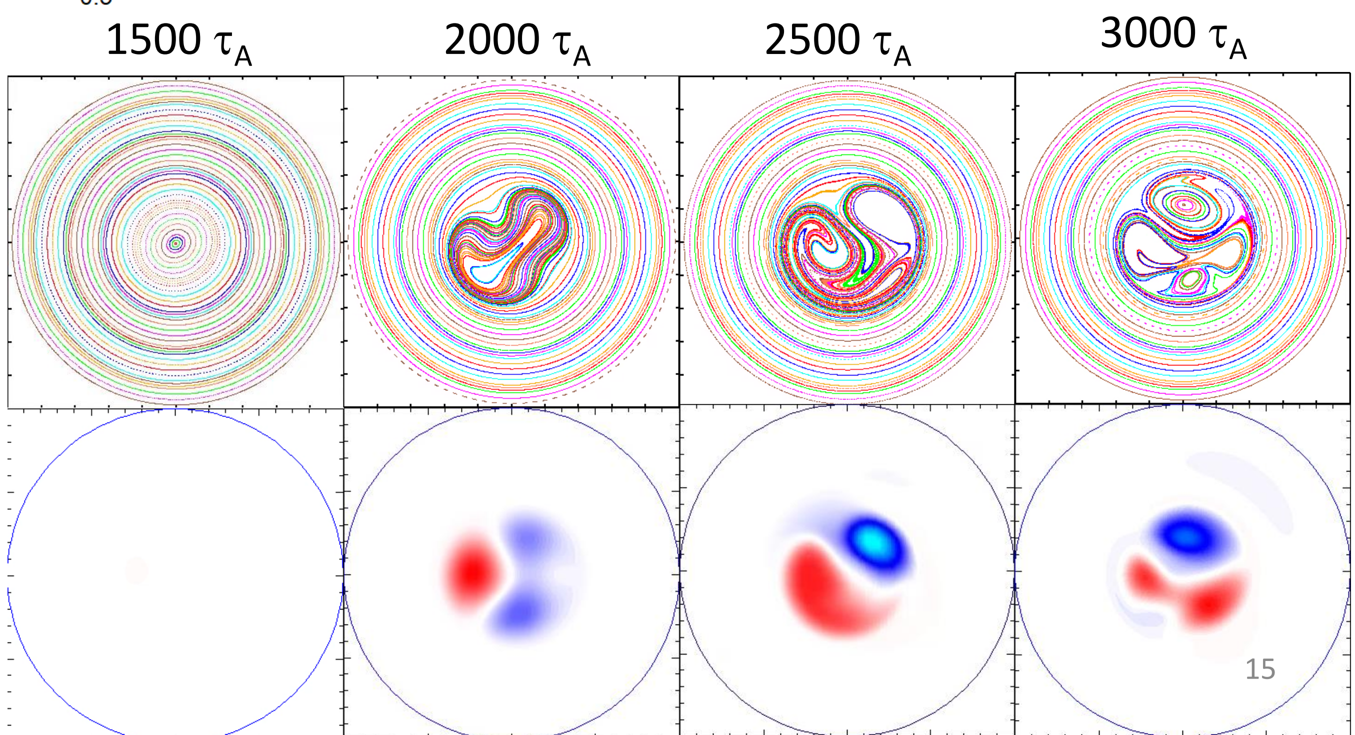




Assume there are sources to maintain equilibrium profiles. (eqsubtract = 1)

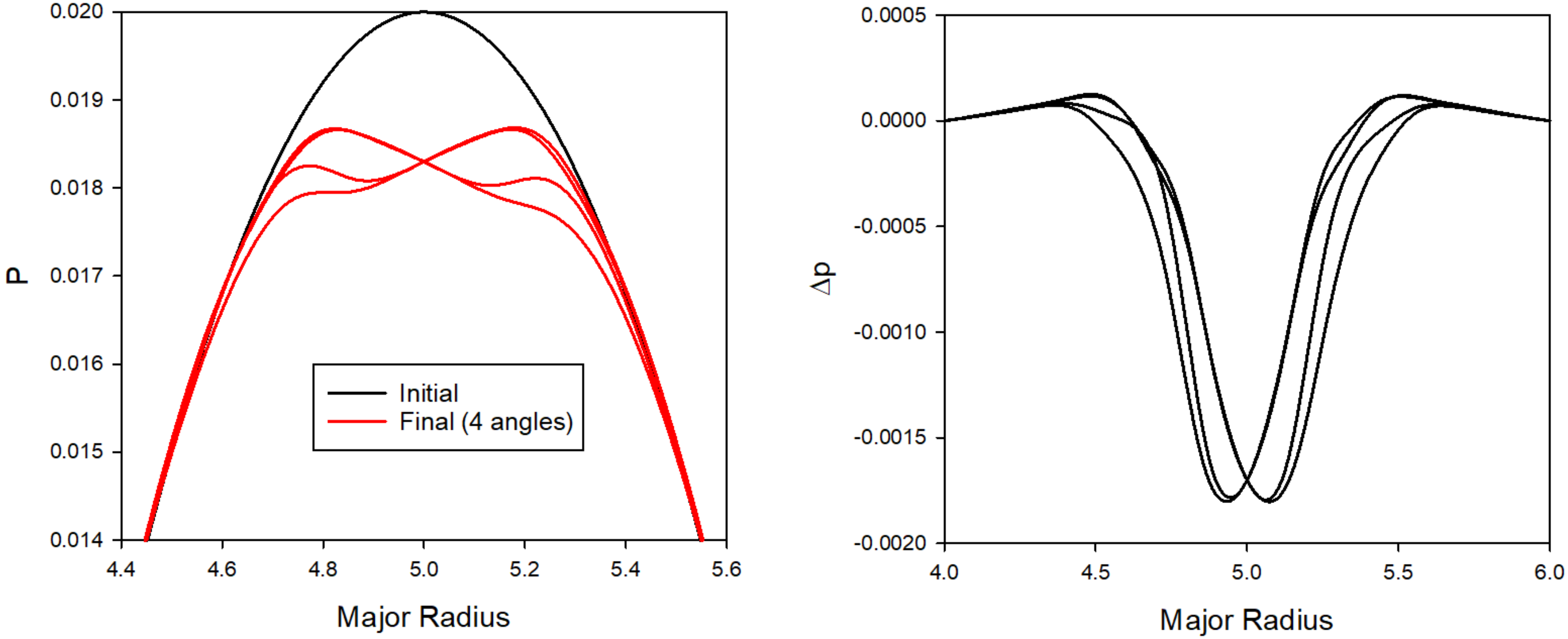
Poincare→

Velocity stream → function

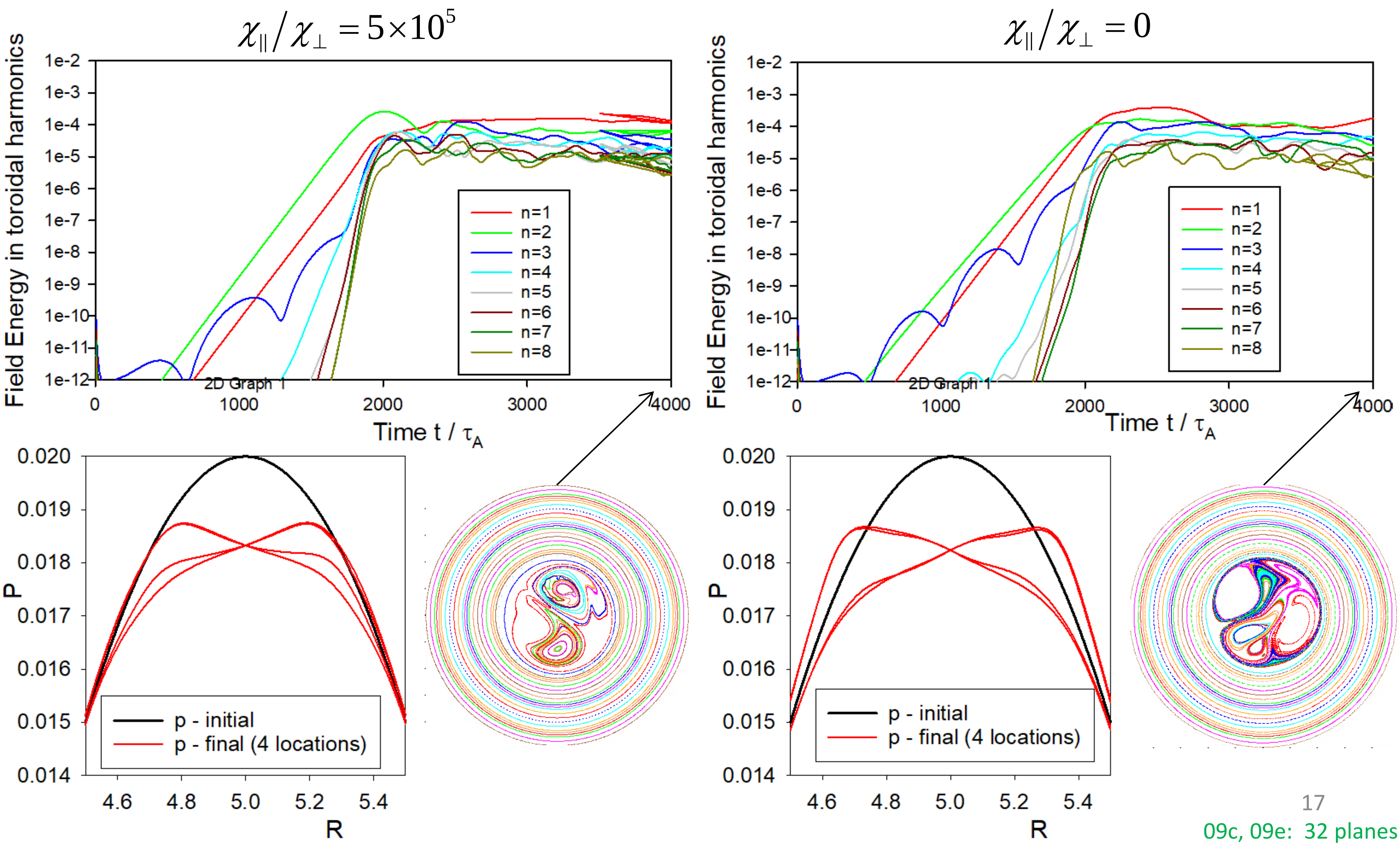


09a: 22,23,25,27: 32 planes

Central pressure flattens without affecting region with q > 1

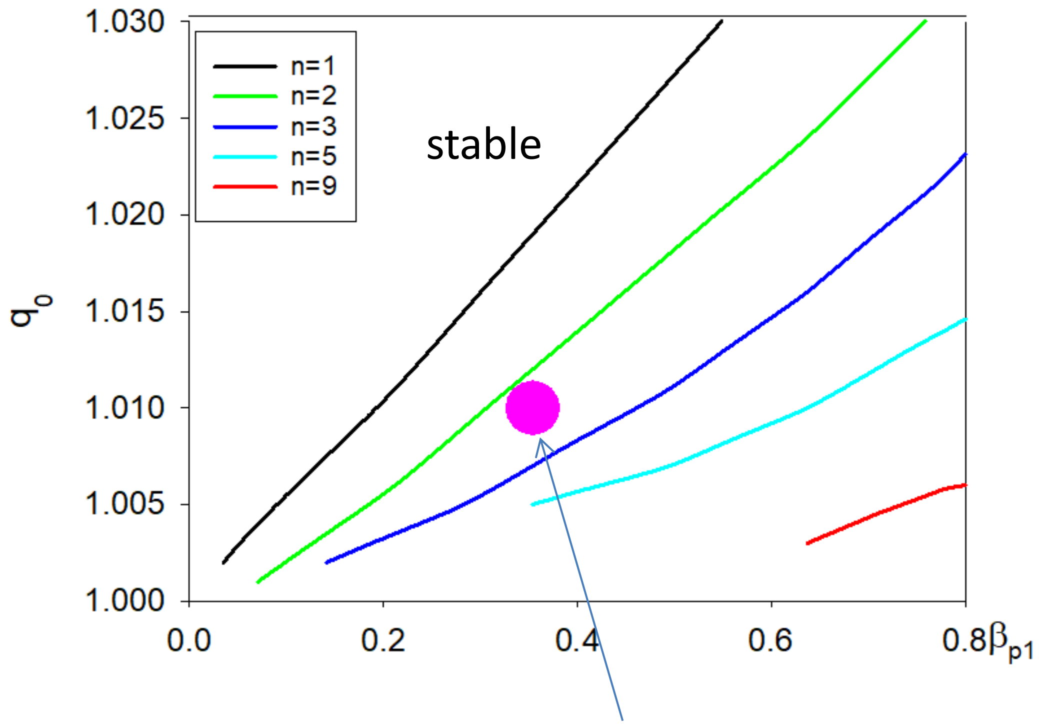


Crash has very little dependence on $\chi_{||}$



09c, 09e: 32 planes

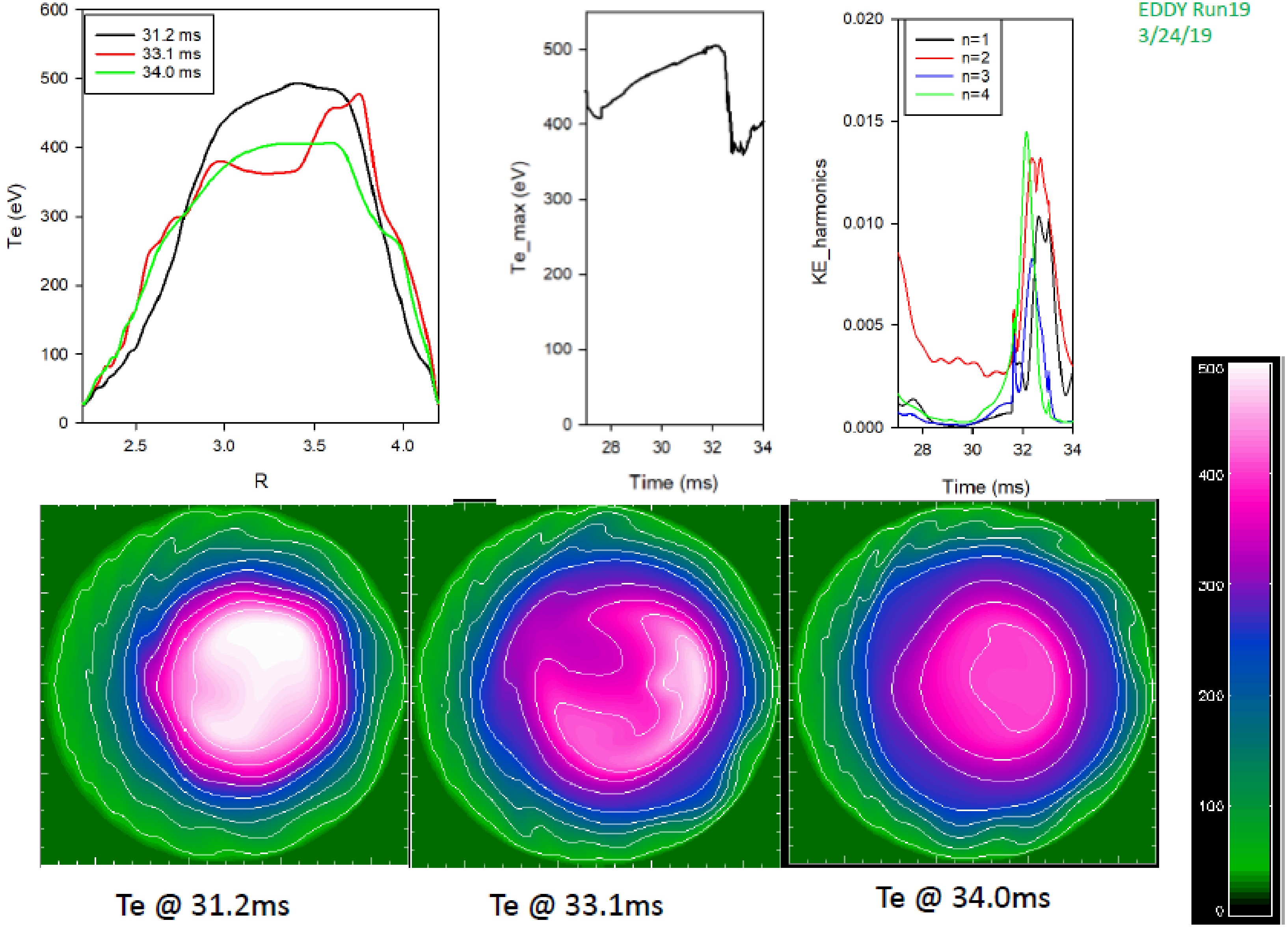
Next, switch to toroidal geometry and start a fully nonlinear calculation which is unstable only to the n=1 and n=2 modes



Initiate nonlinear run from this equilibrium

Run16

Clearly shows fast crash due to higher-n modes



Te @ 31.2ms

Te @ 33.1ms

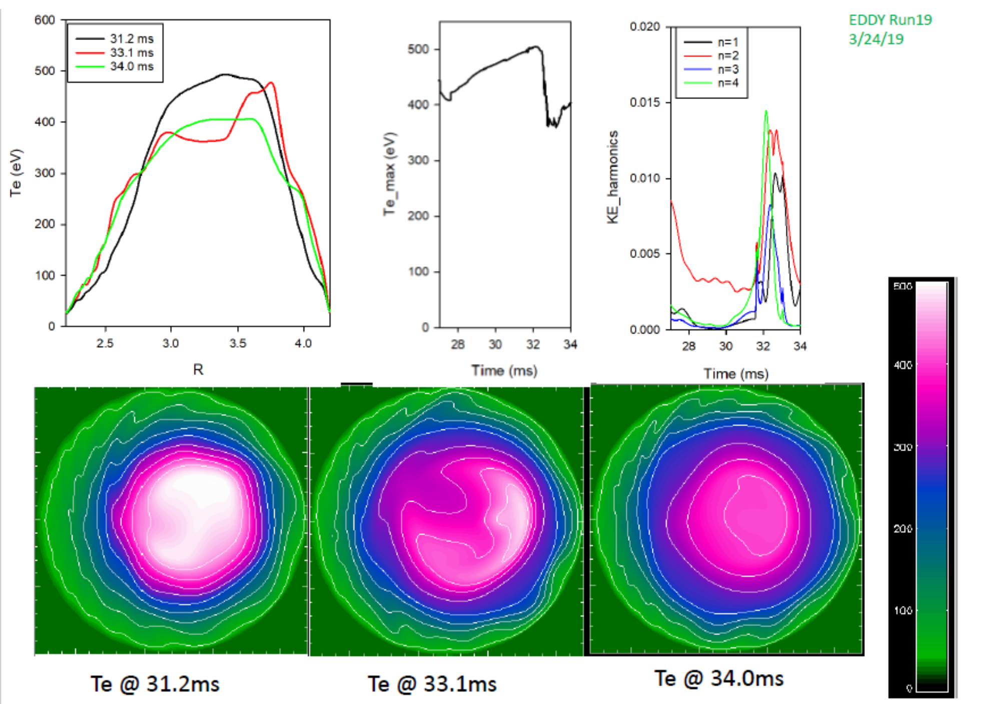
Te @ 34.0ms

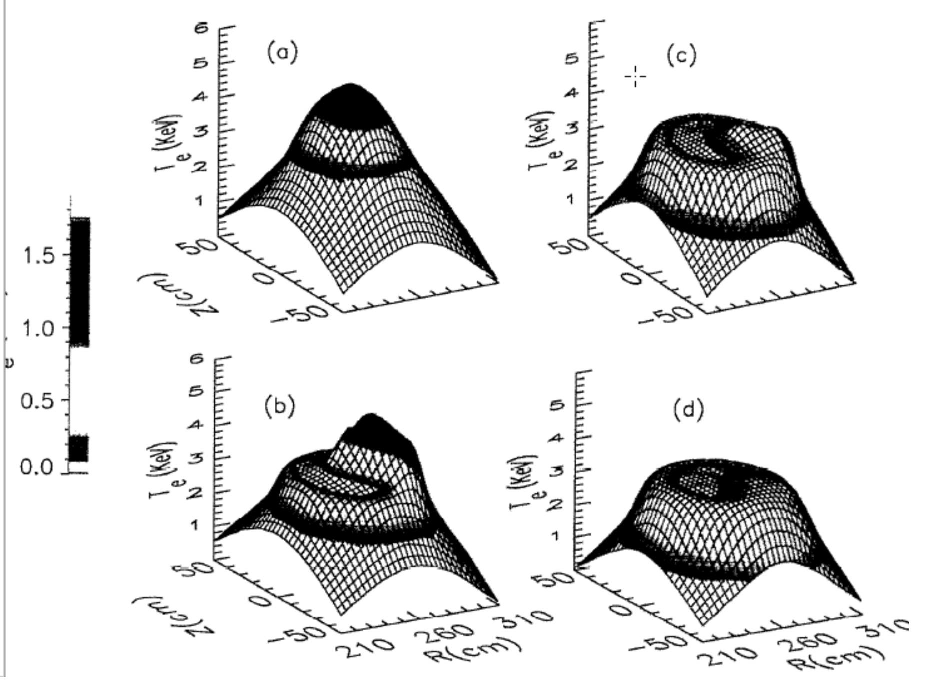
Note similarities with published TFTR crash data

Investigation of magnetic reconnection during a sawtooth crash in a high-temperature tokamak plasma

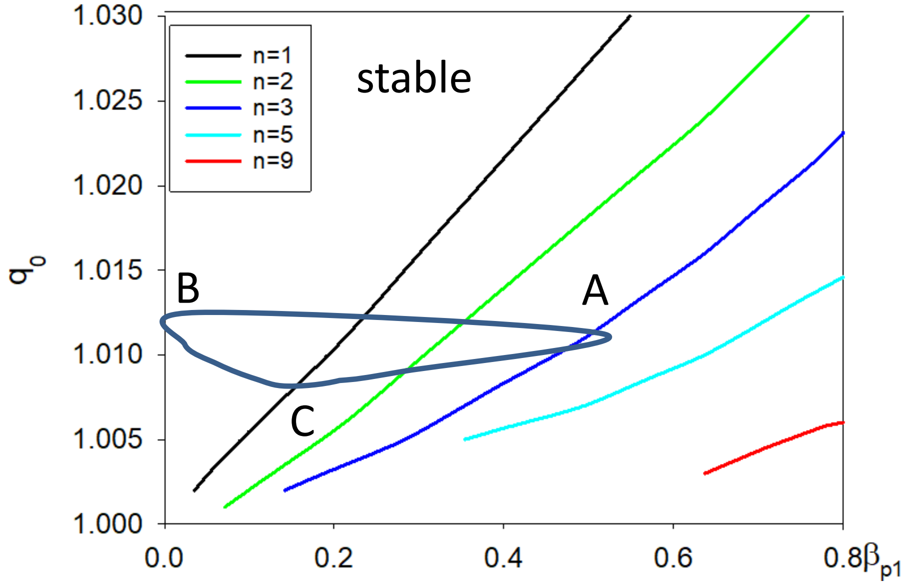
M. Yamada, F. M. Levinton,[a] N. Pomphrey, R. Budny, J. Manickam, and Y. Nagayama[b]
Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543

(Received 2 March 1994; accepted 9 June 1994)





The Sawtooth Cycle



A. Fast crash when (2,2) ideal stability boundary is crossed. Other modes also excited by steep gradients that form in inner shear-free region
B. At low β_{p1}, plasma becomes axisymmetric, surfaces reform, β_{p1} begins to increase due to heating, and q_0 drops due to resistive diffusion
C. As (1,1) stability boundary is crossed, dynamo action works to increase q_0 as β_{p1} continues to increase due to heating.

q_0 = 1 with low central shear was observed on first measurement of q_0

Radially resolved measurements of "*q*" on the adiabatic toroidal compressor tokamak

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(Received 24 March 1978)

2346 Phys. Fluids **21**(12), December 1978

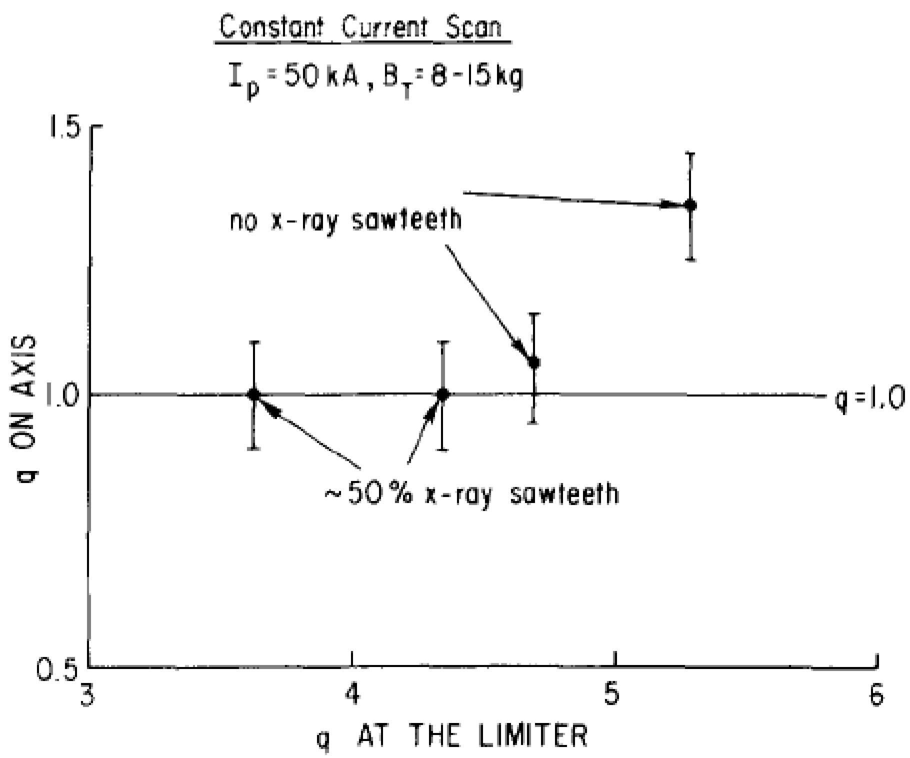


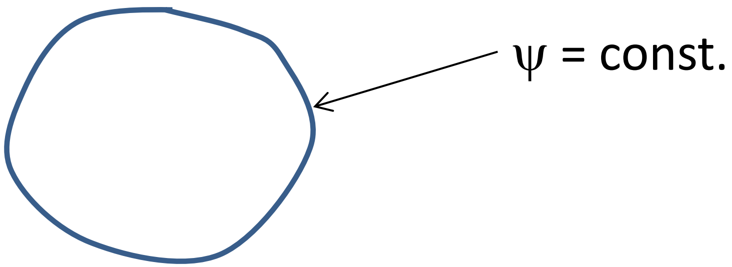
FIG. 9. $q(0)$ an $q(a)$ is changed by varying B_T.

- q_0 is about 1.8 times higher than if one assumed $J \sim T_e^{3/2}$ using measured profiles (both Spitzer and neoclassical)
- The lowest q(a) case, instead of exhibiting a parabolic current profile, observed very low shear (flat current) near q=1.
- "Strong confirmation … that magnetic fluctuations within the plasma prevent the Kruskal-Shafranov limit from being exceeded"

What about early measurements that show q_0 << 1 ?

- q_0 changed from 0.7 to 0.8 in TFTR [1]
- 8% change from 0.77 on TEXTOR [2]
- $q_0 = 0.7 \pm 0.05$ and increasing with edge q on TEXT [3]
- q_0 ranges from 0.7 to 0.85 throughout the sawtooth cycle on JET [4]

$$q(\psi) = RB_T \oint \frac{d\ell}{R\left|\nabla \Psi_P\right|}$$



- The q-profiles is very difficult to measure experimentally
- Must take the limit as contour size → 0, $\nabla\Psi_p$ → 0
- Need to account for intrinsic electric field and ellipticity
- Is it possible that these early measurements had larger error bars than what was realized at the time?

[1] Yamada, M., Levinton, F., Pomphrey, N., et al Phys.Plasmas 1 3269 (1994)
[2] Soltwisch, H., Rev. Sci. Instrum, 59, 1599 (1988)
[3] West, W. P., Thomas, D. M., DeGrassie, J.S. et al Phys.Rev. Lett. 58, 2758 (1987)
[4] Wolf, R. C., Orourke, J., Edwards, A. W., et al , Nucl. Fusion 33, 663 (1993)

More recent experimental evidence is that q_0 stays near 1 during the entire sawtooth cycle.

- Wroblewski and Huang quote a value of q_0 very near unity in TEXT for several discharges with differing edge-q and infer a low shear central region, especially at low edge-q [1,2]
- Weisen used resonant Alfven waves to deduce that TCA had a time averaged q profile with a flat central region with q_0 close to unity[3]
- Gill analyzed X-ray emission in JET when an injected pellet crosses the q=1 surface and found that the magnetic shear, dq/dr, interior to the q=1 surface was very low.[4]
- Wroblewski reports that q_0 in DIII-D is close to unity and the increase during the sawtooth crash is of order of the measurement error, 0.05[5]
- Analysis of BAE modes during a sawtooth crash on TORE SUPRE imply that q_0 is normally slightly above unity after the sawtooth crash, and decreasing to unity[6]
- A recent study on KSTAR , supported by very high accuracy MSE measurements and supplemental MHD analysis concluded that q_0 was $\sim$ 1 in sawtoothing discharges with relative accuracy +/- 0.03 and with compelling evidence that it is slightly above 1 after the crash.[7]

[1] Wroblewski, D., Huang, L, Moos, H. W. it et al Phys. Rev. Lett. **61**, 1724 (1988)
[2] Huang, L. K., Finkenthal, M.,Wroblewski, D., Phys. Fluids B. **2** 809 (1990
[3] Weisen, H., Borg, G., Joye, B., et al, Phys. Rev. Lett. **62**, 434 (1989)
[4] Gill, R., Edwards, A., Weller, A., Nucl. Fusion **29** 821 (1989)
[5] Wroblewski, D., and Snider, R., Phys. Rev. Lett. **71**, 859 (1993)
[6] Amador, C', Sabot, R., Garbet, X., et al Nucl. Fusion **58**, 016010 (2018)
[7]] Nam, Y. B., Ko, J. S., Choe, G. H. et al Nucl. Fusion **58** 066009 (2018)

Summary and Future Directions

- Sawteeth in low temperature, low-β plasmas (like ST) can be explained by the Kadomtsev model
- Sawteeth in high-temperature, high-β tokamak discharges are caused by m=n > 1 modes causing turbulent convection with $q \cong 1$ in interior
- The n=m=1 mode saturates at a low amplitude, and is responsible for keeping $q \cong 1$ in the center with very low shear … not for the crash.
- The rapid onset and fast crash time is caused by many ideal-MHD modes whose rapid growth rates are sensitive functions of q_0 and p_0
- Since $q_0 \cong 1$ throughout the cycle, it is easy to see how (1,1) snakes can co-exist with sawteeth
- Next Step: Can this picture of sawteeth be used to explain “monster sawteeth” and RF sawtooth stabilization/destabilization?

Extra Slides

Some Puzzles explained

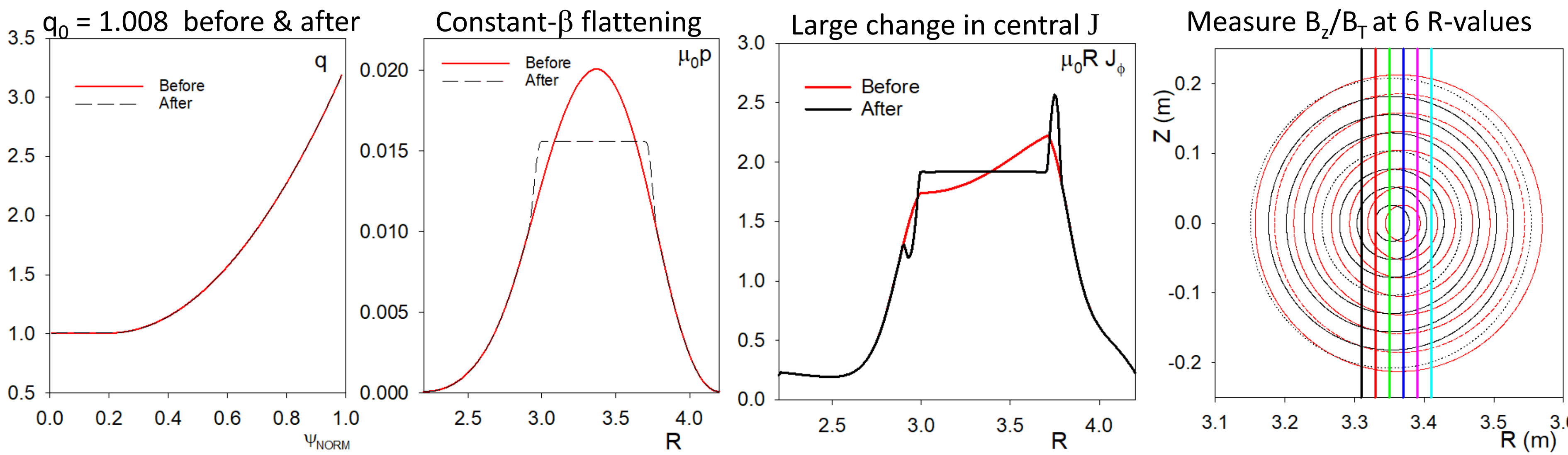
1. q-profile changes very little during sawtooth crash
   - Central q profile is always just above 1 and flat

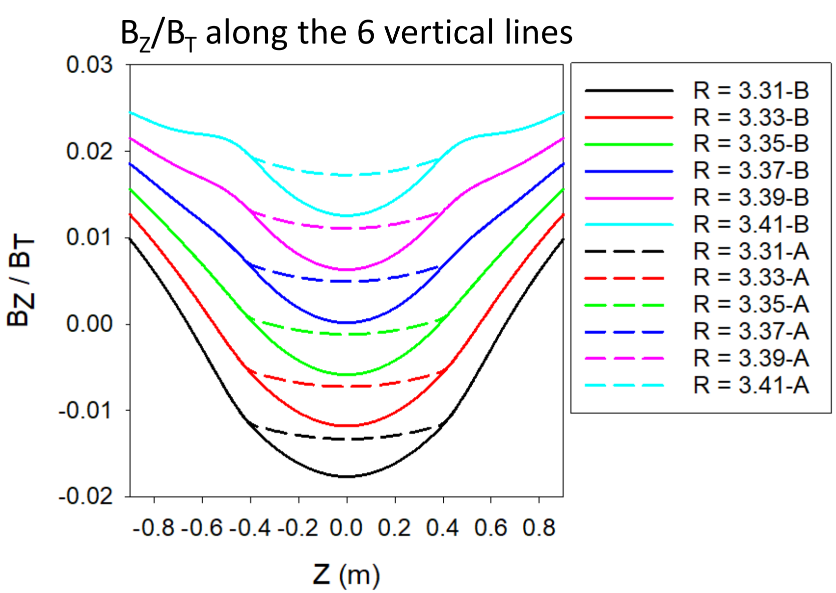
2. The sawtooth collapse is usually precursorless and very rapid
   - Sudden onset caused by crossing an ideal MHD stability boundary
   - Steep gradients from (2,2) mode excite higher (n,n) modes

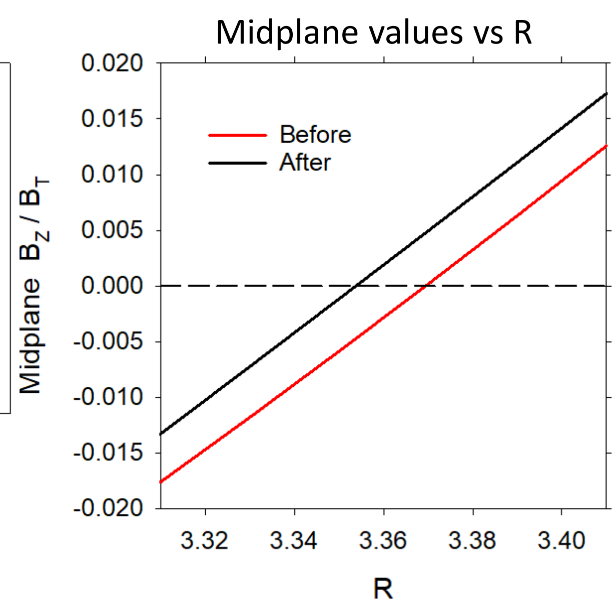
3. How to explain rapid impurity penetration during the sawtooth collapse
   - The collapse and flattening of the Te profile is caused by convective motion generated by many mid to high-n ideal instabilities
   - This same convective motion will transport and mix impurities.

4. Density snakes persist for many sawteeth
   - Large q=1 shearfree region allows snakes

For constant-q pressure drop: 3% intrinsic uncertainty in MSE







q_0 from synthetic MSE measurements gives 2-3% error

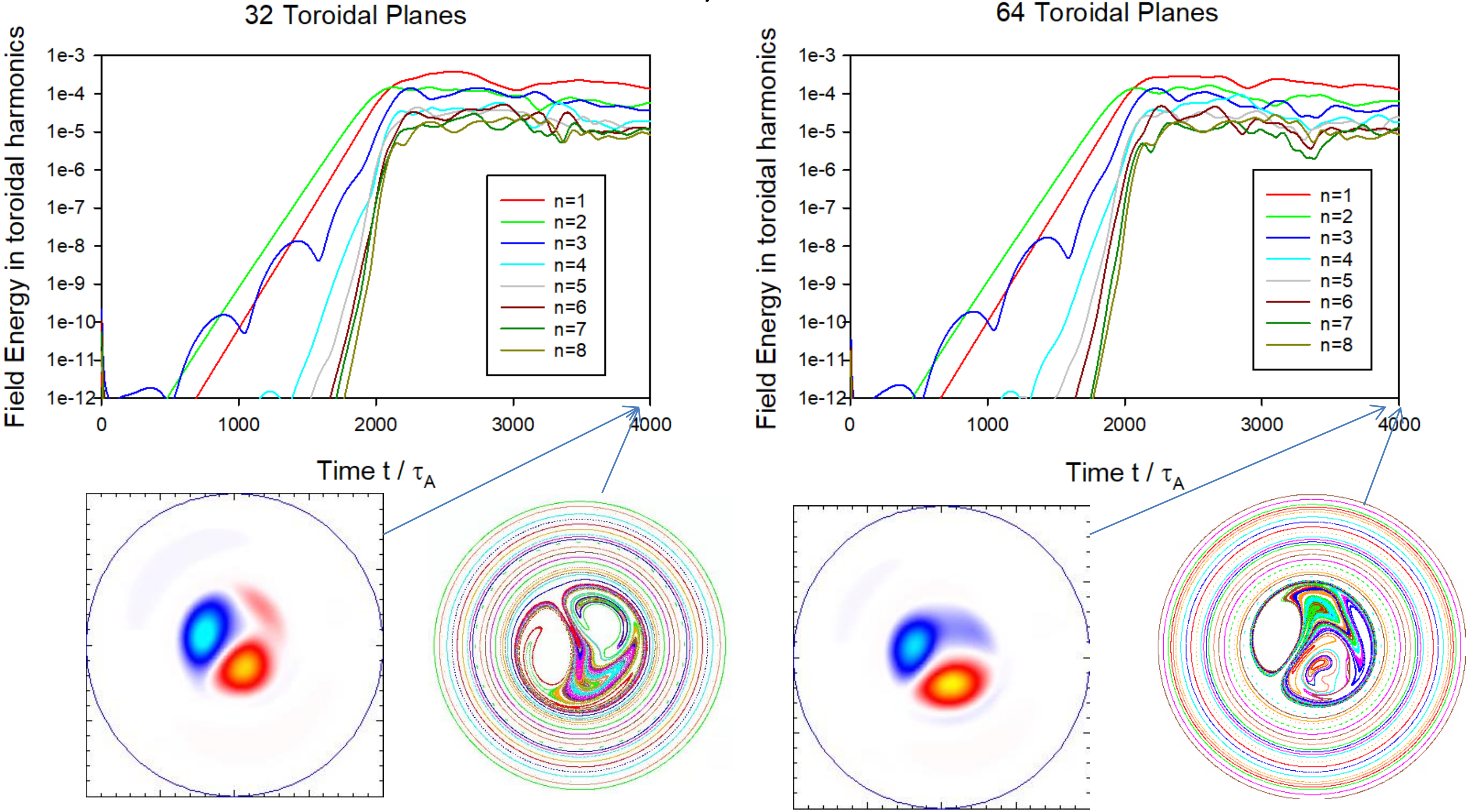
$$q_0 = \frac{1}{R_{MA}} \left[\frac{\partial}{\partial R} \left(B_Z / B_T \right) \right]^{-1}_{R=R_{MA}}$$

$= 0.983$ (before)

$= 0.974$ (after)

Convergence Study in # of Toroidal Elements

Error ~ $1/N^4$

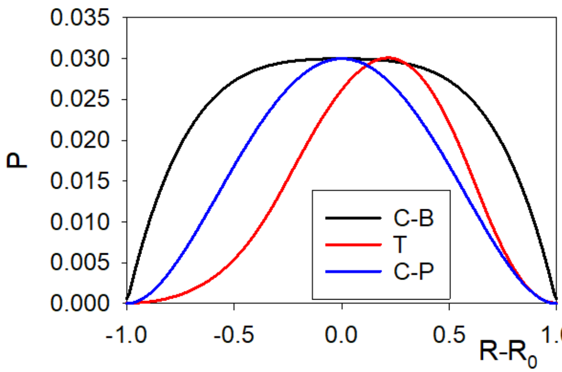


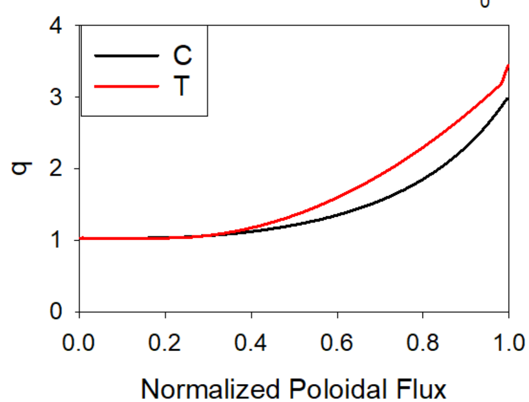
Run09a, Run09b

Results very similar but not identical (stochastic field lines)

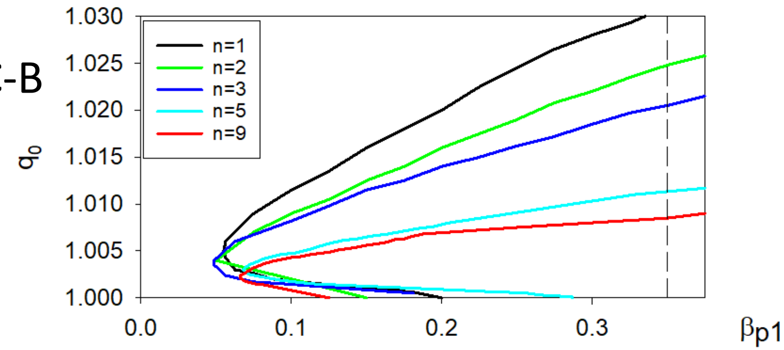
Similar results for peaked pressure profiles and for a torus

C-P	Cylinder, peaked pressure
C-B	Cylinder, broad pressure
T	Torus, peaked pressure

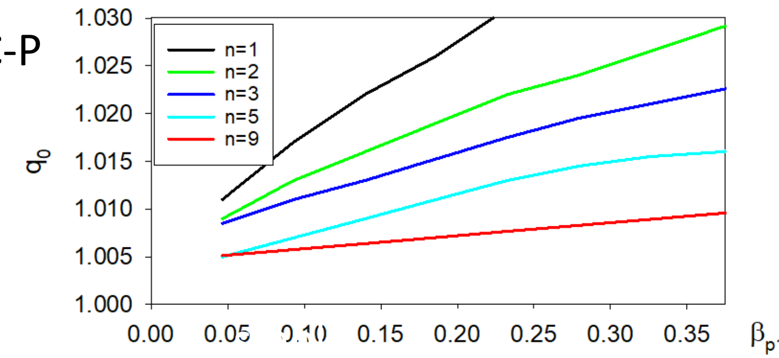




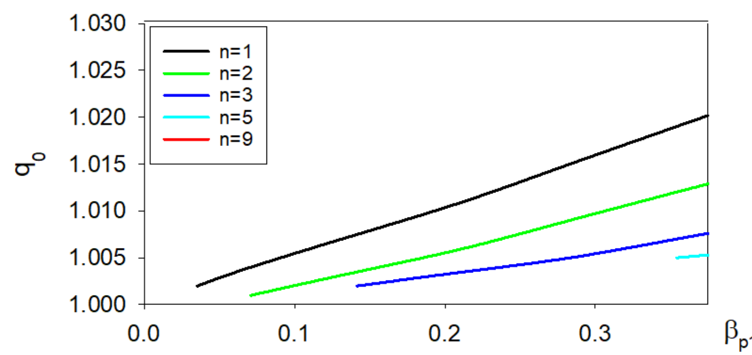
C-B



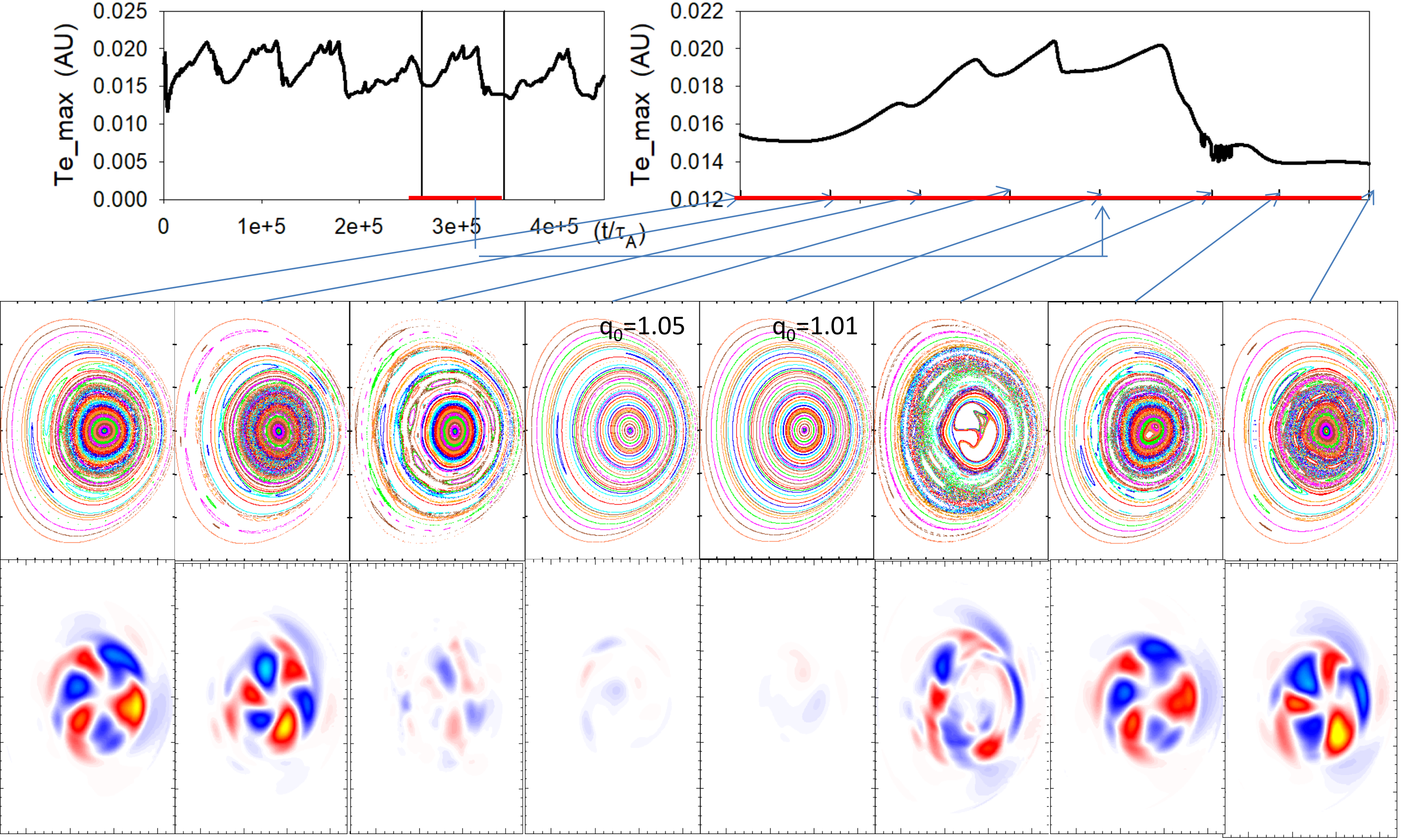
C-P



T



Closeup shows mechanism for sawtooth crash



First row is Poincare plots. Second row is non-axisymmetric part of $-\mathbf{V}\cdot\nabla T_e - T_e(\gamma-1)\nabla\cdot\mathbf{V}$

Crash is caused by modes with m=n > 1

NUMERICAL SIMULATIONS OF IDEAL INTERNAL KINK MODES WITH FLAT CENTRAL q-PROFILE

P. KIRBY
Culham Laboratory,
Euratom–UKAEA Fusion Association,
Abingdon, Oxfordshire,

NUCLEAR FUSION, Vol.28, No.2 (1988)

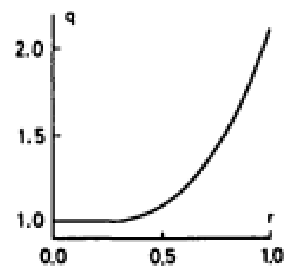


FIG. 1. The model q-profile. q is constant for r ≤ 0.3.

$$\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v} = -\nabla p + \vec{j}\times\vec{B}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v}\times\vec{B} - \frac{\eta}{S}\,\vec{j}\right)$$

$$\nabla\cdot\vec{v} = 0$$

$$\eta = \eta(r)$$

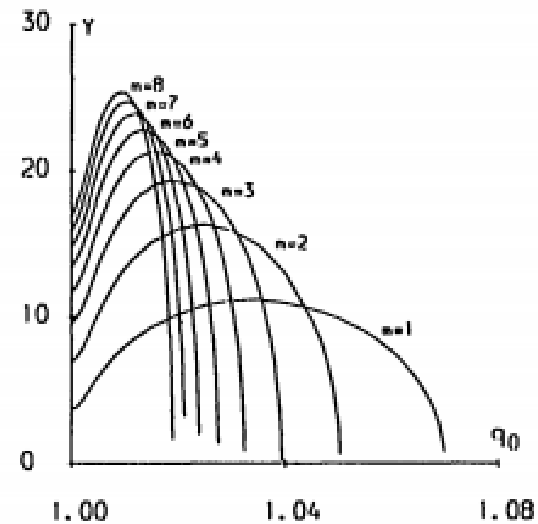


FIG. 2. Dependence of the ideal linear growth rate γ (in units of $10^{-3}/\tau_A$) on q_0 (the central value of q) for modes m/n = –1, m = 1–8.

A complicating feature of the simulation results is the existence of unstable higher modes with growth rates larger than that of the m = 1 mode. At present, it is not known whether such modes are important in experiment. The evidence from magnetic field

What happens if we increase the pressure further?

- The (1,1) velocity field tends to reduce the central pressure through convection: $\mathbf{V}\bullet\nabla p$

- However, if you apply sufficient central heating, the pressure in the center will rise

- This will cause an even stronger central dynamo voltage, causing q_0 to rise…which will tend to reduce the dynamo voltage, causing q_0 to fall.

- q_0 will find it's new equilibrium value with $q_0 > 1$, but increasing the pressure will cause ***higher-n modes with n=m*** to abruptly become unstable

- These localized high (m,n) modes in a region of very low shear cause the central region to become stochastic, causing the central temperature to rapidly drop, but having very little effect on the q-profile.

M3D-C^1 uses unique 3D high-order finite elements

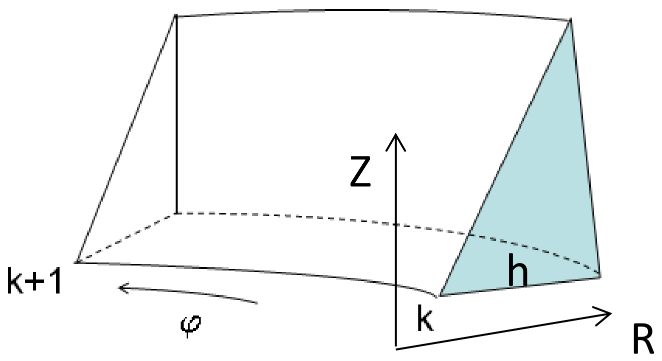
- M3D-C^1 uses high-order curved triangular prism elements

- Within each triangular prism, there is a polynomial in (R,φ,Z) with 72 coefficients

- The solution *and 1st derivatives* are constrained to be continuous from one element to the next.

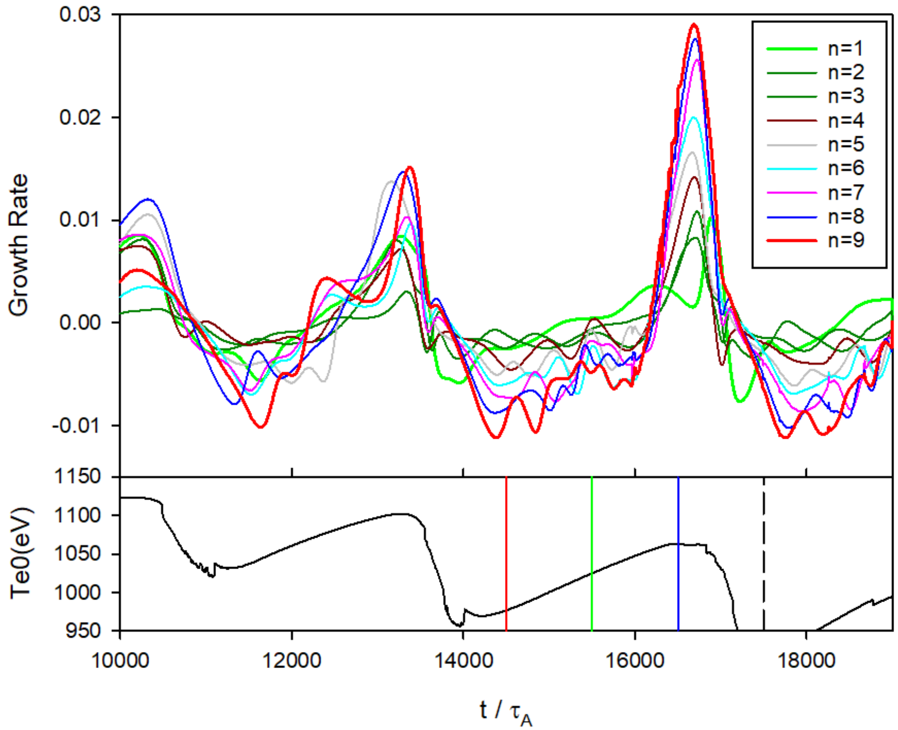
- Thus, there is much more resolution than for the same number of linear elements

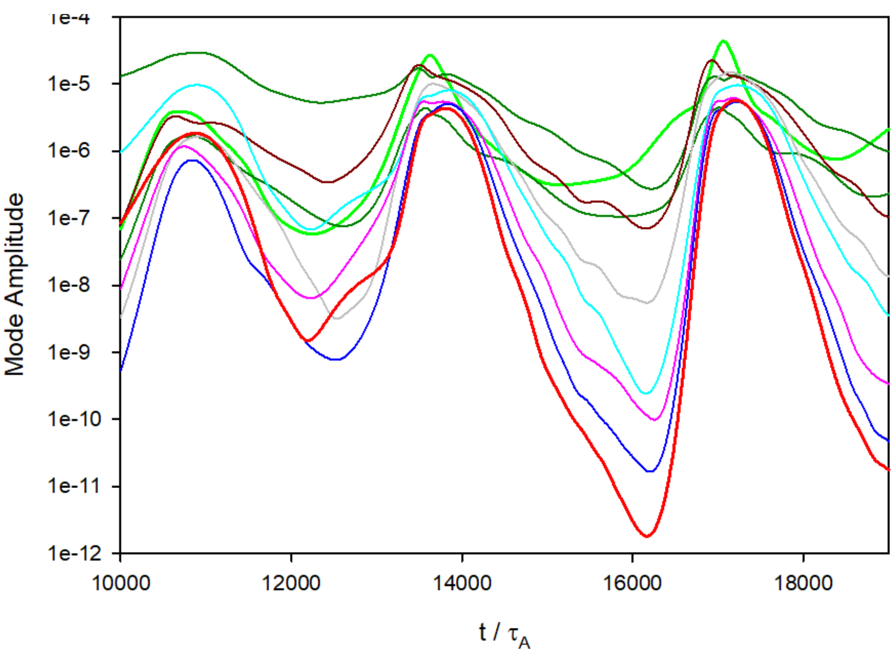
- Error ~ h^5

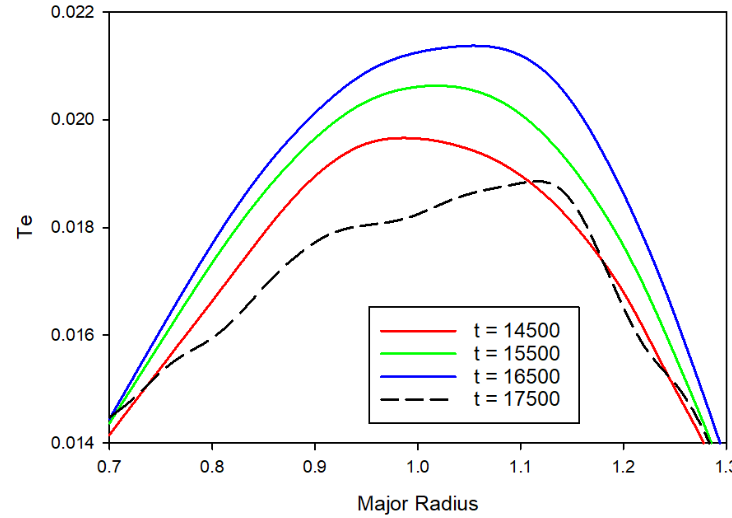


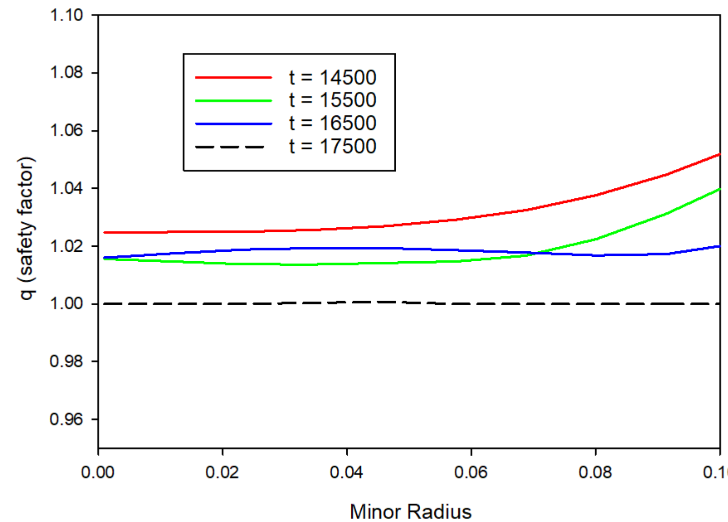
Also, implicit time-stepping allows for very long time simulations

NSTX

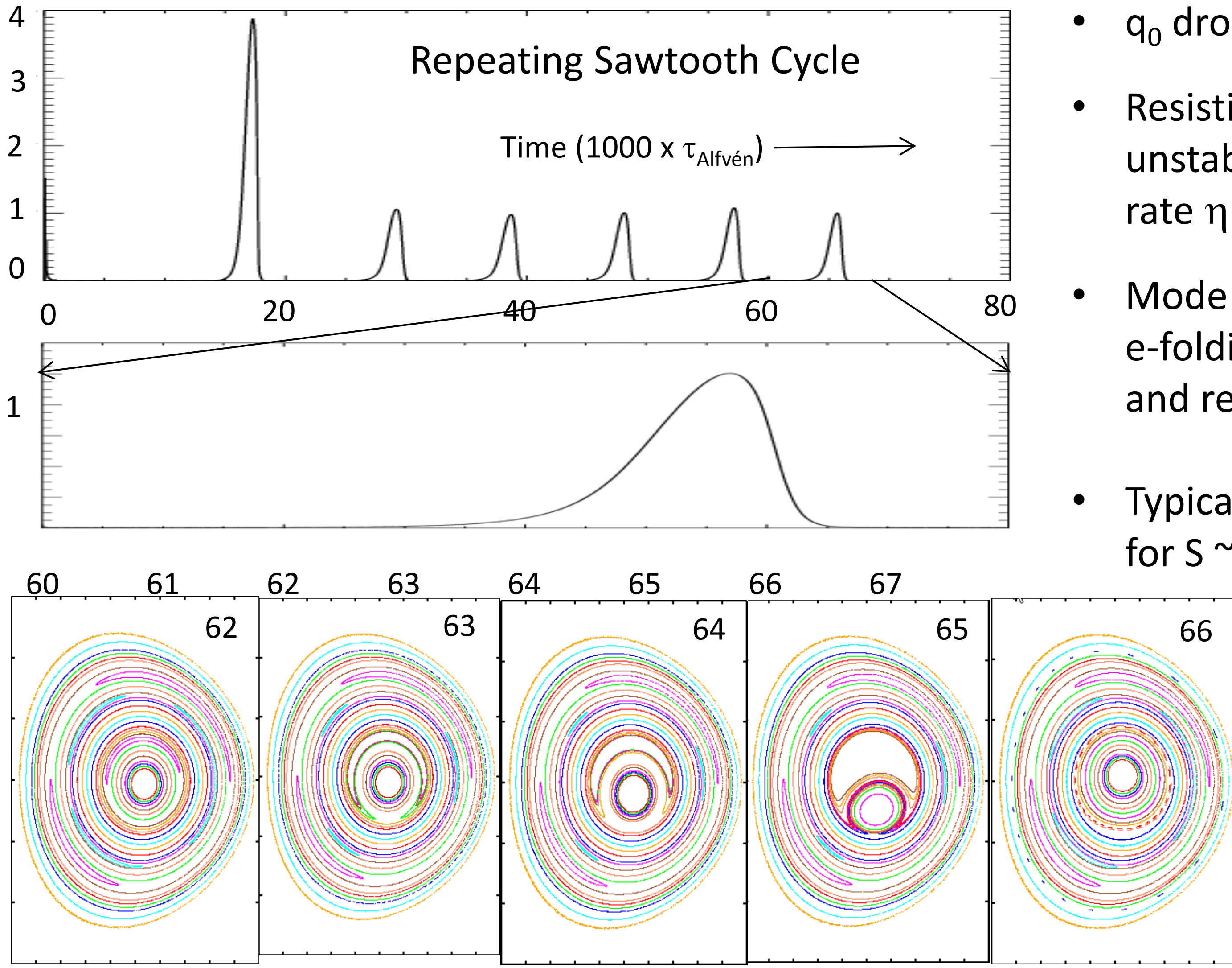

Growth Rate
Te0(eV)
t / τ_A
n=1
n=2
n=3
n=4
n=5
n=6
n=7
n=8
n=9


Mode Amplitude
t / τ_A


Te
Major Radius
t = 14500
t = 15500
t = 16500
t = 17500

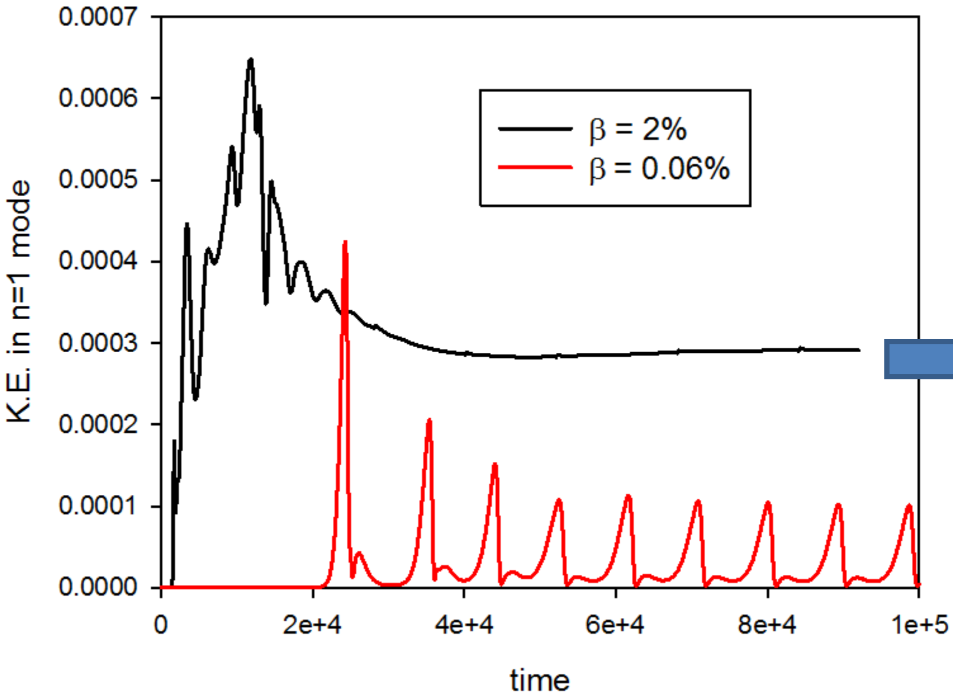

q (safety factor)
Minor Radius
t = 14500
t = 15500
t = 16500
t = 17500

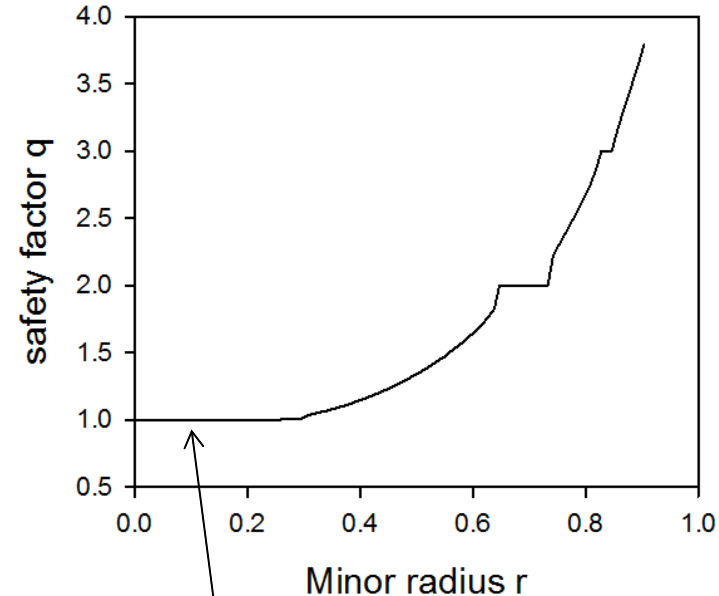
Low-β Kadomtsev Reconnection



- q_0 drops below 1 ~ η
- Resistive kink becomes unstable with growth rate $\eta^{1/3}$
- Mode takes a few e-folding times to grow and reconnect
- Typically 0.95 < q_0 < 1.0 for S ~ 10^5-10^6, low-β

$\beta \equiv \mu_0\, p/B^2$ =2% behavior much different from low β



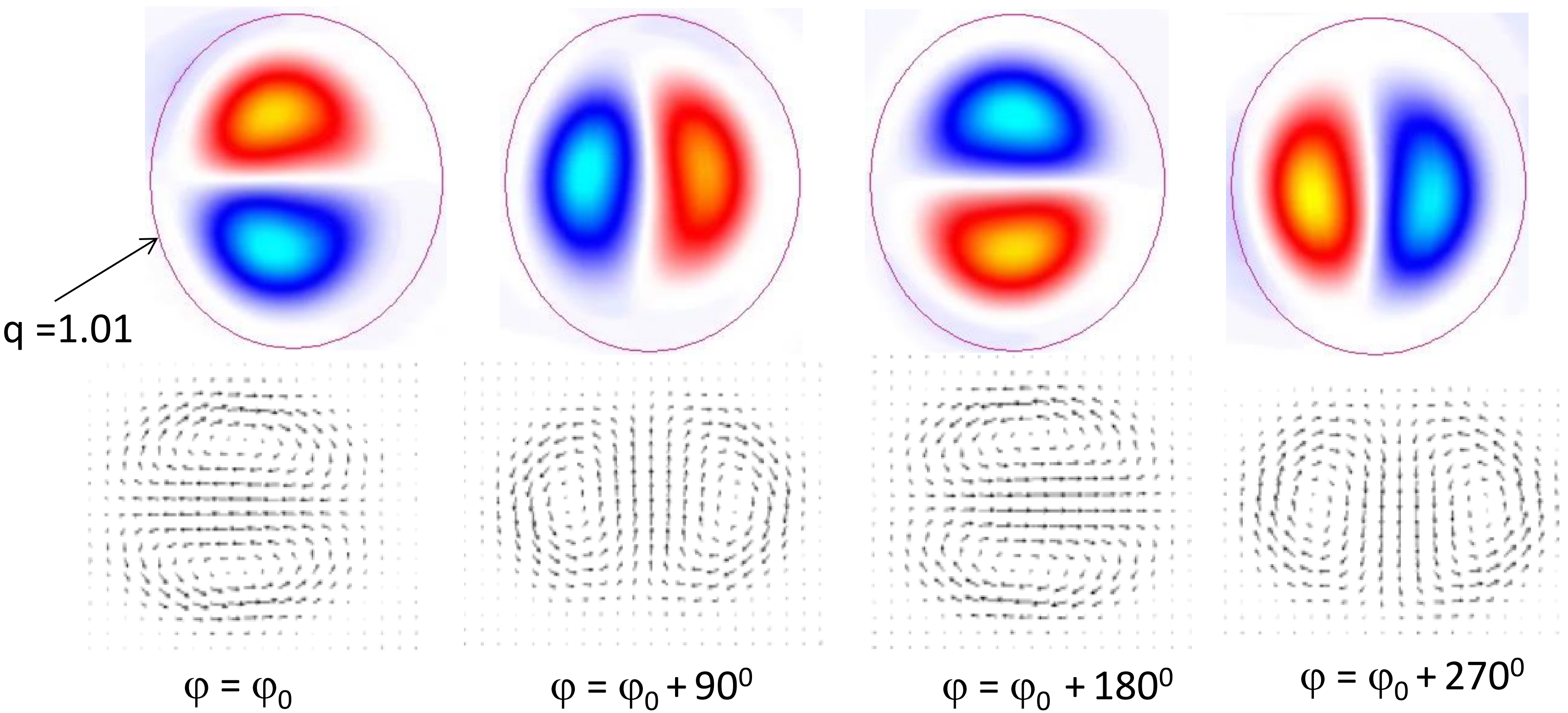


- At low-β, plasma kinetic energy (and T_{e0} and q_0) undergo periodic oscillations where current peaks, reconnection occurs and process repeats (sawteeth)

- At 2% β, plasma goes into a stationary state with large helical flow patterns and ultra-low magnetic shear with q=1 in center

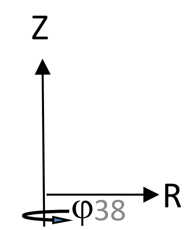
$$q = \frac{\#\ \text{of toroidal transits}}{\#\ \text{of poloidal transits}}$$

Stationary helical flow pattern persists driven by unstable interchange mode



Plotted on top is poloidal velocity stream function U where $\mathbf{V}_{1,1} = R^2 \nabla U \times \nabla \varphi$

On bottom are vectors of poloidal velocity $\mathbf{V}_{1,1}$



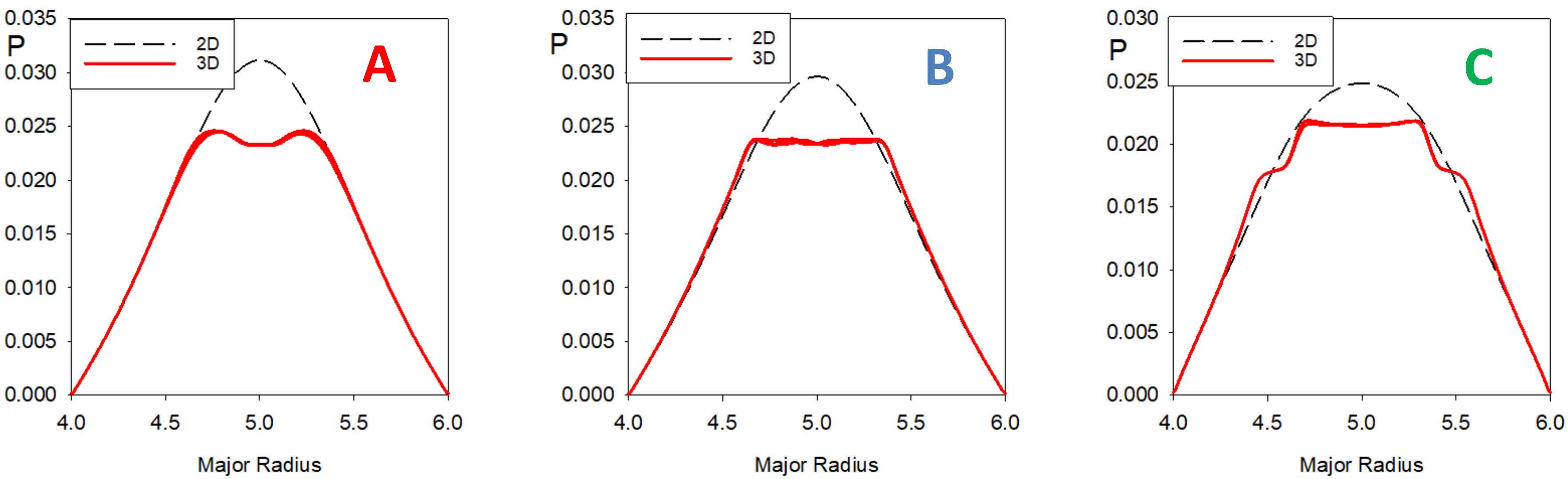
Next, start with the same cylindrical equilibrium but now add sources and evolve the equilibrium

In axisymmetric equilibrium: $\nabla \bullet \kappa_\perp \nabla T_e + S = 0$

$\kappa_\perp = 10^{-4}$ $S = 30$

$\kappa_\perp = 10^{-5}$ $S = 3.0$

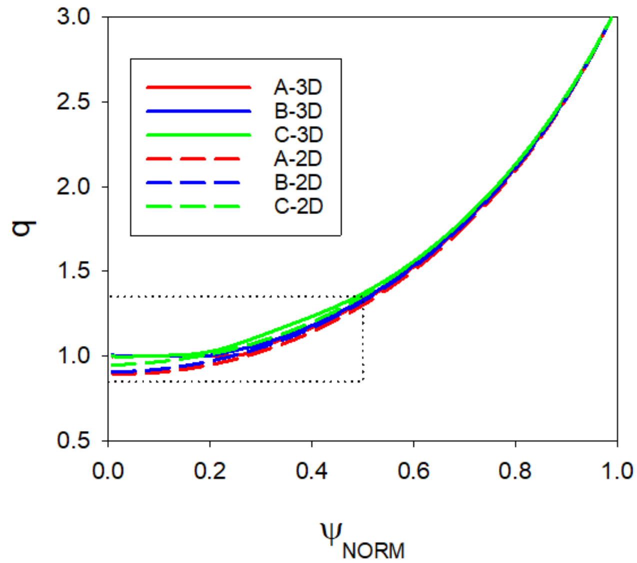
$\kappa_\perp = 10^{-6}$ $S = 0.3$

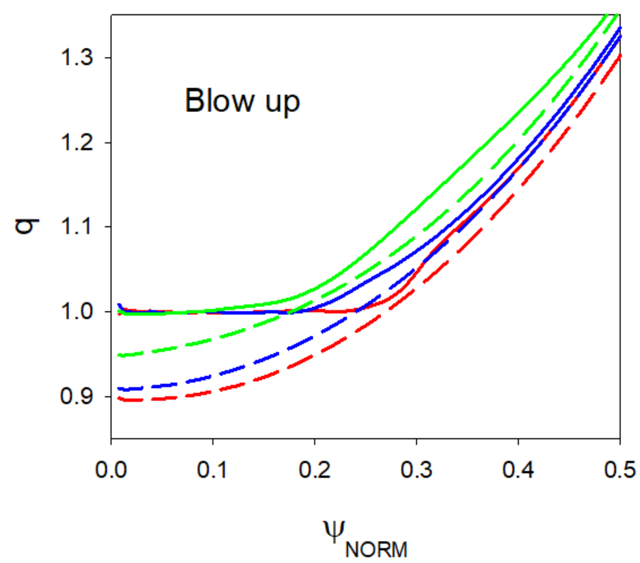


In all 3 cases, configuration evolves into a near axisymmetric equilibrium with pressure flattened in center: q ≥ 1 but **no sawtoothing** behavior

Runs 11,12,13: p0=.02, q0=1.02

Next, start with the same cylindrical equilibrium but now add sources and evolve the equilibrium (2)





In all 3 cases, q-profile evolves to a stationary state with q_0=1 and very low shear in center. **No sawtoothing**

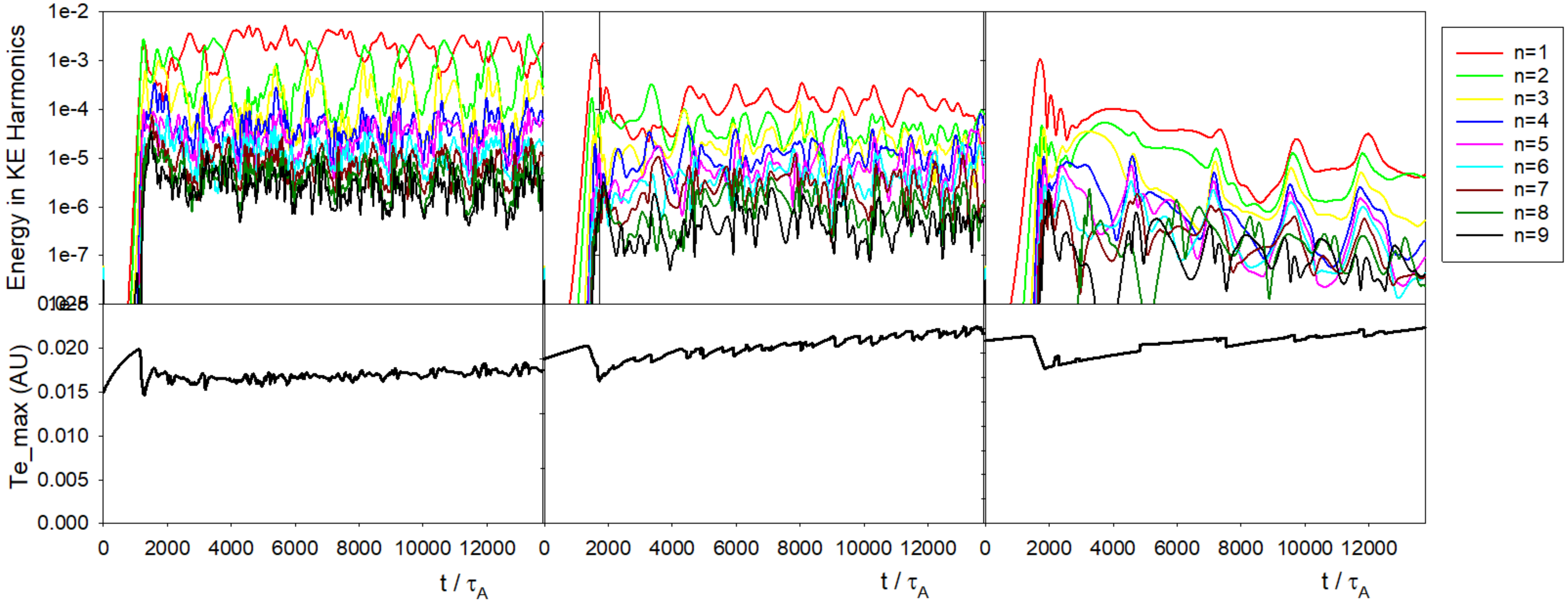
Also shown are 3 2D (axisymmetric) cases with the same transport and sources as the 3D cases

Next, start with the same cylindrical equilibrium but now add sources and evolve the equilibrium (3)

$\kappa_\perp = 10^{-4}$ $S = 30$ **A**

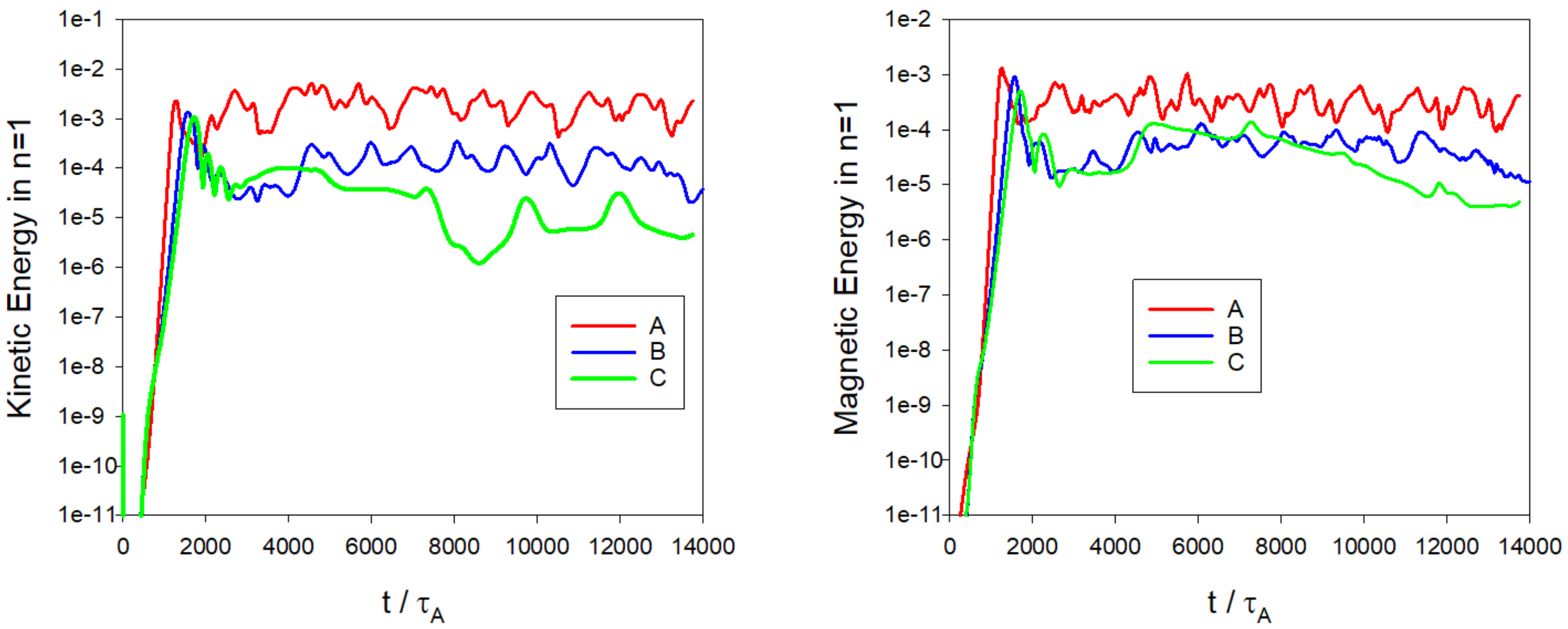
$\kappa_\perp = 10^{-5}$ $S = 3.0$ **B**

$\kappa_\perp = 10^{-6}$ $S = 0.3$ **C**



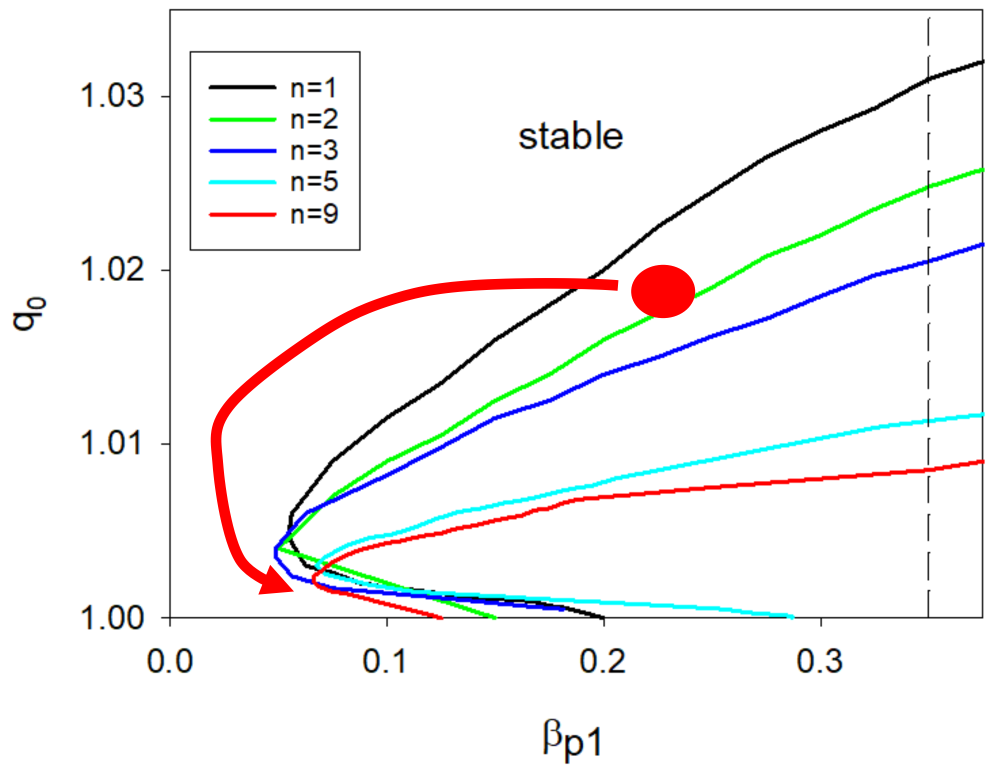
For all 3 cases, turbulence inside q=1 region for all harmonics calculated. **No sign of sawtooth activity**

Next, start with the same cylindrical equilibrium but now add sources and evolve the equilibrium (4)



The magnitude of the n=1 velocity and magnetic perturbations adjusts itself to keep q_0=1 via the dynamo mechanism. Larger values are needed for the case with the largest sources.

Next, start with the same cylindrical equilibrium but now add sources and evolve the equilibrium (5)



Trajectory in (q_0, β_{P1}) space is to a nearly stationary point at q_0=1 and very low β_{P1} limited by stability to the higher-n modes. **No sawtoothing**