Control of Sawtooth Oscillation Dynamics using Externally Applied Stellarator Transform

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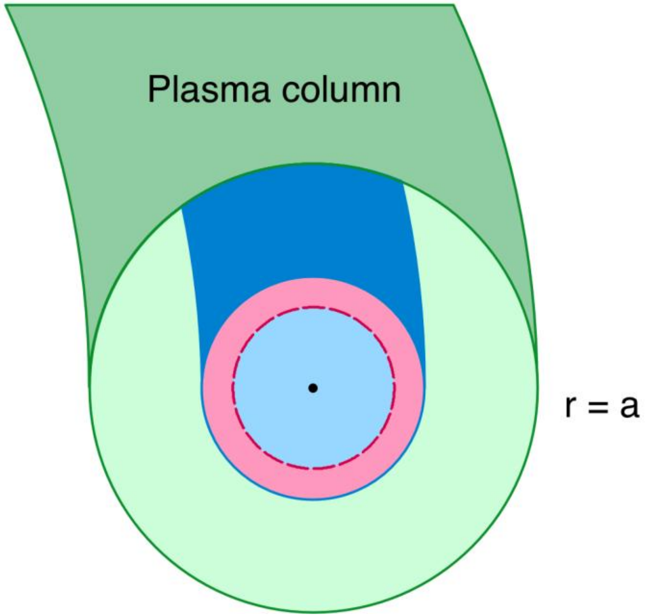
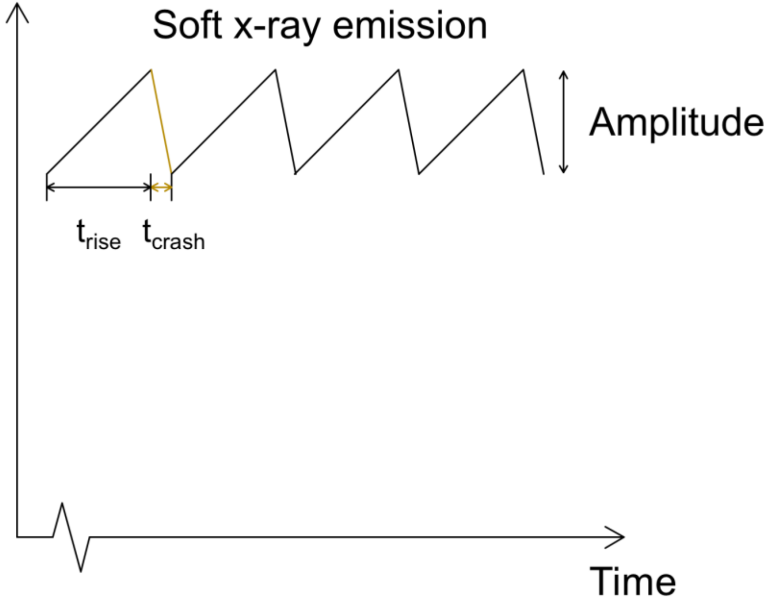
Understanding sawtooth physics and controlling their behavior is a critical tokamak research area

- First discovered in mid 1970s, physics understanding still an active area of research
- Large sawteeth have many deleterious effects on tokamak discharges:
  - Degradation of core confinement
  - Trigger for other MHD (ELMS, NTMS, locked modes) leading to disruption in some cases
- Control of large sawteeth are an important issue for ITER operation
- Small sawteeth, however, can be beneficial by flushing impurities and helium ash from the core plasma

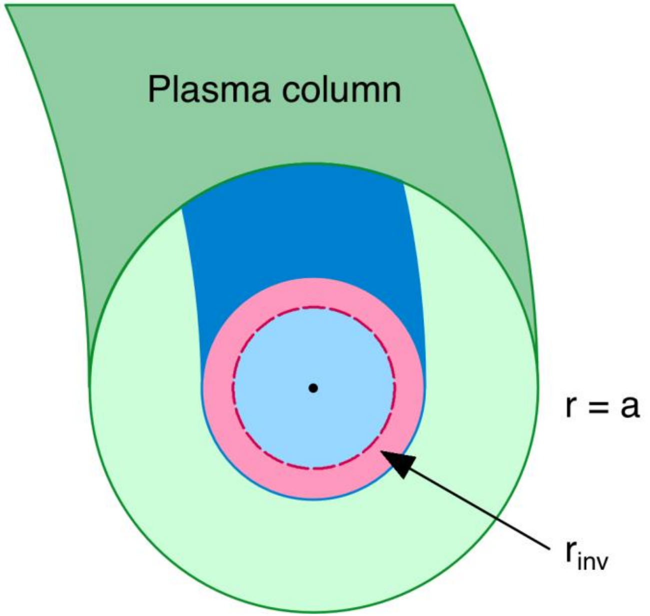
Sawteeth are periodic, MHD initiated mixing events, near the magnetic axis

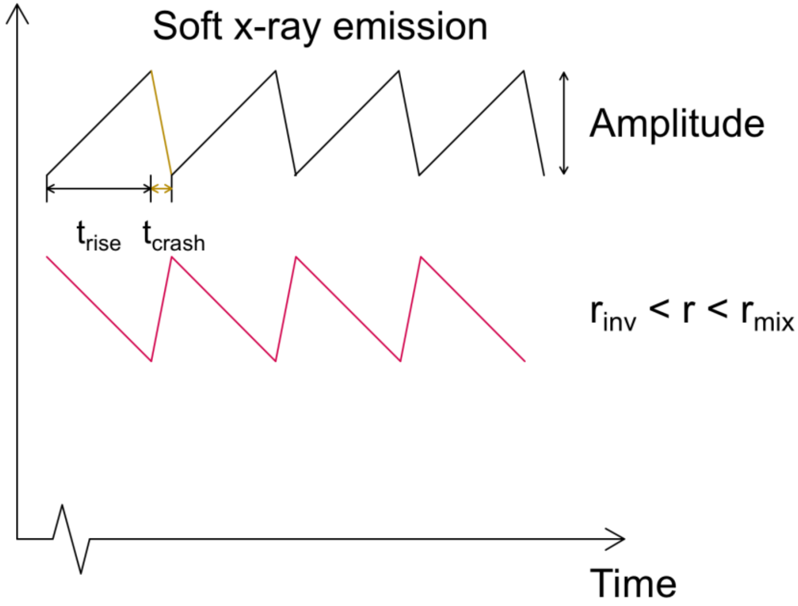




- Mechanism responsible for the sawtooth crash is instability of the *m*/*n*=1/1 internal kink/tearing mode when $q_0 < 1$

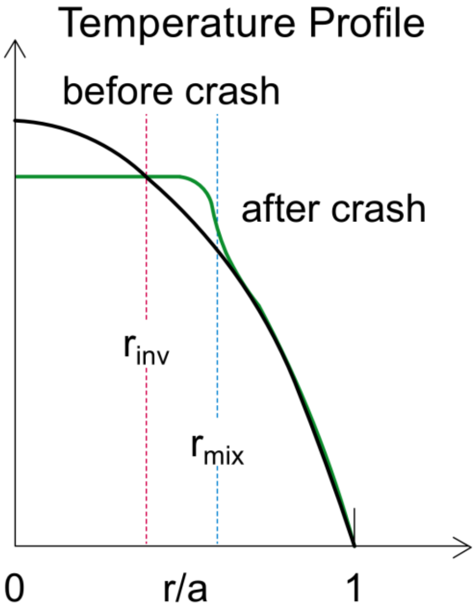
Thermal energy transport leads to inverted sawteeth for $r > r_{inv}$

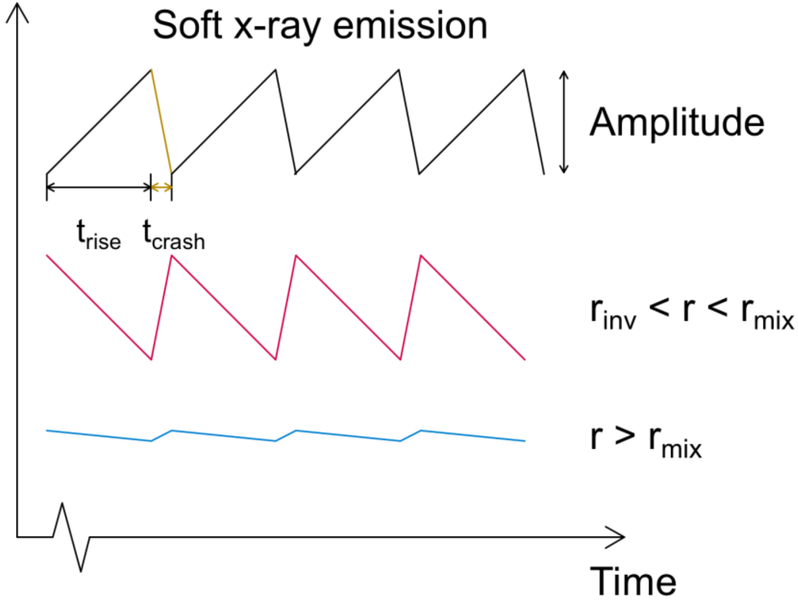




- Core plasma thermal energy inside the $q = 1$ inversion surface is rapidly transported and deposited outside of the inversion surface due to magnetic reconnection

Thermal energy transport leads to flat temperature profile after crash





- Study of non-ideal physics is important in order to understand the 1/1 mode evolution.

Various methods have been proposed for control of sawtooth period and amplitude

- Active control schemes based on different aspects of current understanding of $m/n=1/1$ mode stability physics
  - Energetic particle stabilization using ICRH or NBI
  - Changing local magnetic shear near the $q=1$ surface with ECCD and ECRH
  - Eliminate $q=1$ surface altogether by reversed shear operation

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- 2D equilibrium shaping is known to effect sawtooth dynamics
  - High elongation is destabilizing[1]
  - Triangularity is stabilizing[2]

1. Lütjens, H., Bondeson, A., Vlad G., Nucl. Fusion 32 (1992) 1625
2. Reimerdes, H. et. al., Plasma Phys. Control Fusion 42 (2000)

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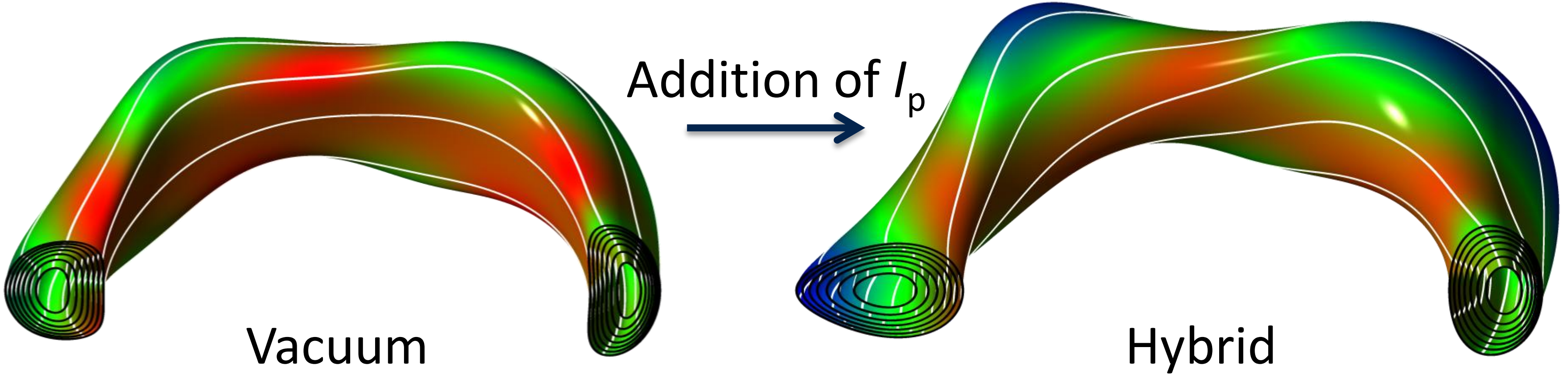
Can strong 3D shaping shed light on sawtooth physics and provide a passive control mechanism?

Compact Toroidal Hybrid (CTH) designed to study the effects of 3D shaping on MHD instabilities

- **Hybrid**: current driven within 3D equilibrium of a stellarator plasma
- Total rotational transform $\iota = \iota_{vac} + \iota_{current}$
  - ι_{vac} from external stellarator coils (3D magnetic shaping)
  - $\iota_{current}$ from plasma current
- CTH can vary the fractional transform, $\iota_{vac}(a)/\iota(a)$, from 4% to 100%



Major results

1. The observed sawtooth period and amplitude decrease with increasing 3D field
2. The sawtooth crash time does not change monotonically with increasing 3D field
3. The decreasing sawtooth period and amplitude are correlated with increasing mean elongation
4. NIMROD resistive MHD simulations capture similar trend with sawtooth cycle period as seen in experiment

Outline

- Compact Toroidal Hybrid
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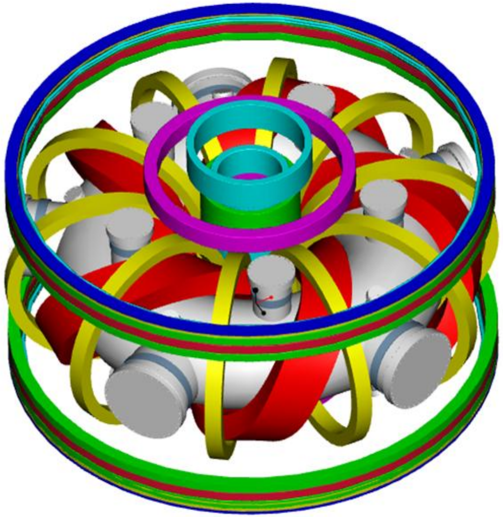
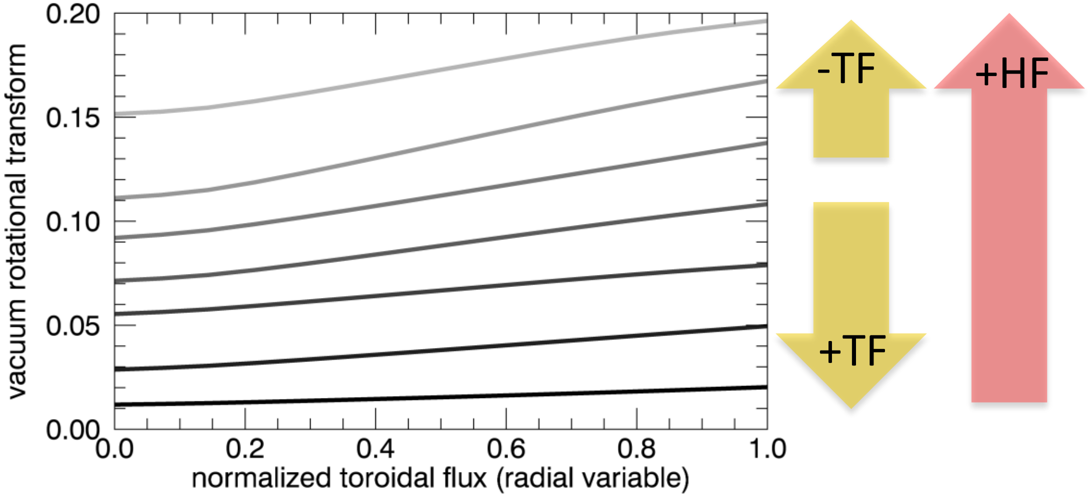
- Summary

CTH: Flexible magnetic configuration in low aspect stellarator/tokamak hybrid

- **Helical Field coil** and **Toroidal Field coil** currents adjusted to modify vacuum rotational transform ι_{vac}

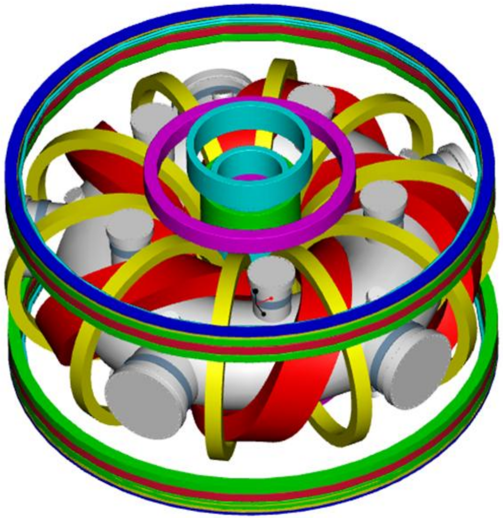
$R_0 = 0.75$ m $R/a \sim 4$ $n_e \leq 5\times10^{19}$ m^{-3} $T_e \leq 200$ eV $|B| \leq 0.7$ T

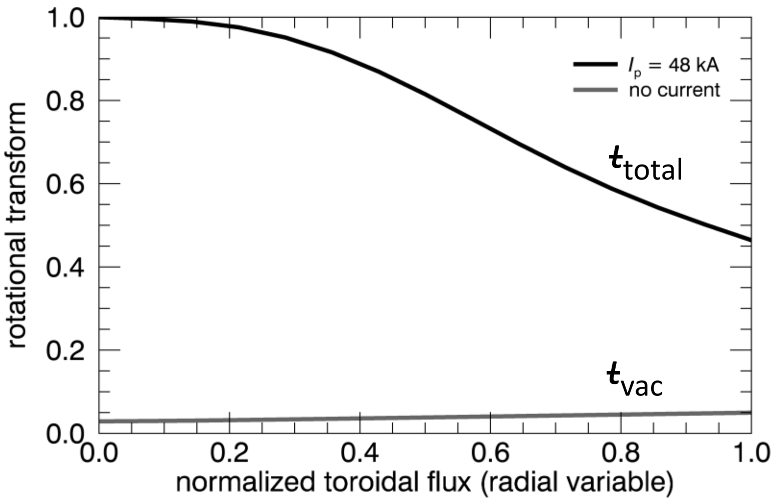




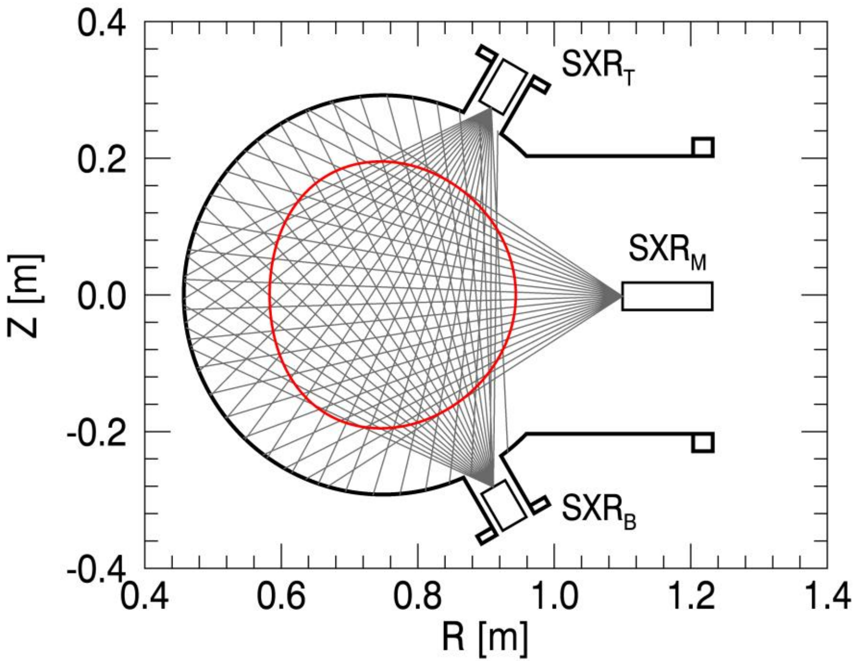
Ohmic coil allows induction of up to 95% of the total rotational transform from plasma current

- **Helical Field coil** and **Toroidal Field coil** currents adjusted to modify vacuum rotational transform ι_{vac}
- **Central solenoid** drives $I_p \leq 80$ kA, dominating total transform



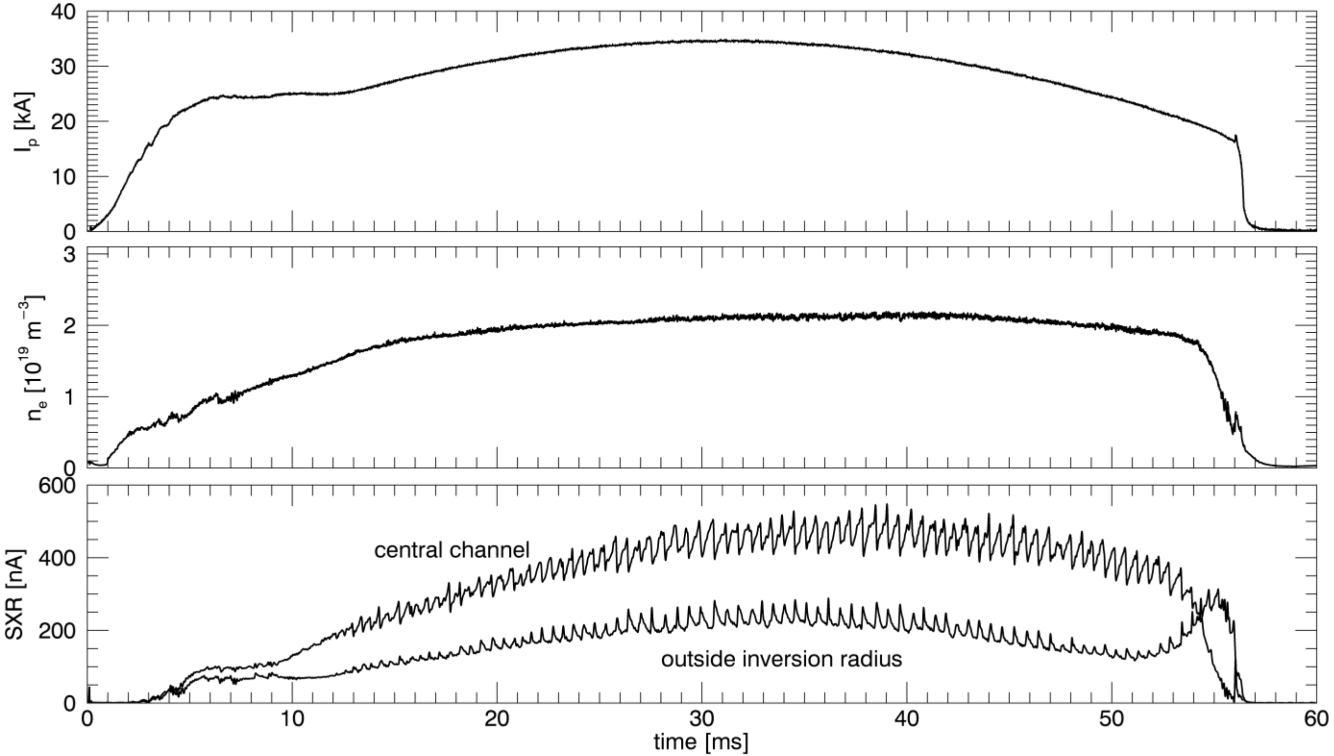


Sawtooth properties measured using a two-color SXR camera diagnostic



- The midplane SXR_M camera is used as an emissivity diagnostic to characterize sawtooth behavior with 3D shaping

Sawooth oscillations observed on CTH exhibit behavior similar to that of axisymmetric tokamaks



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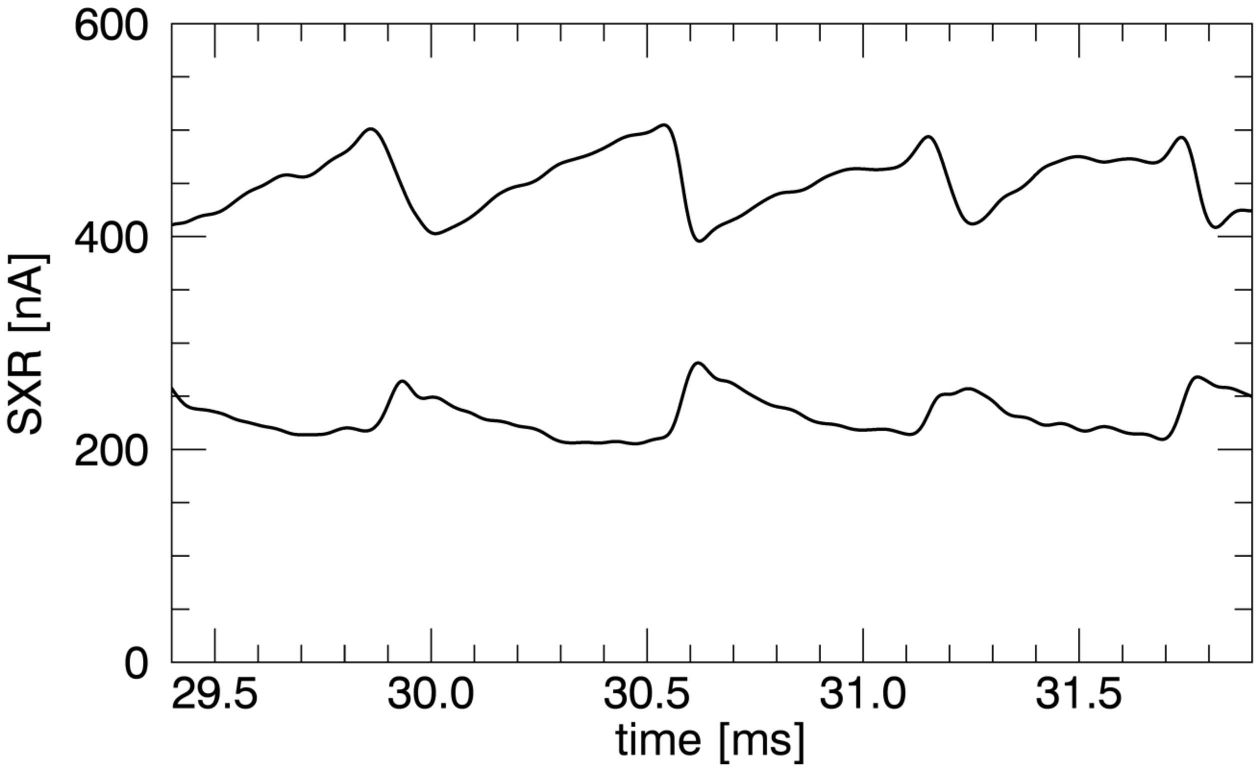
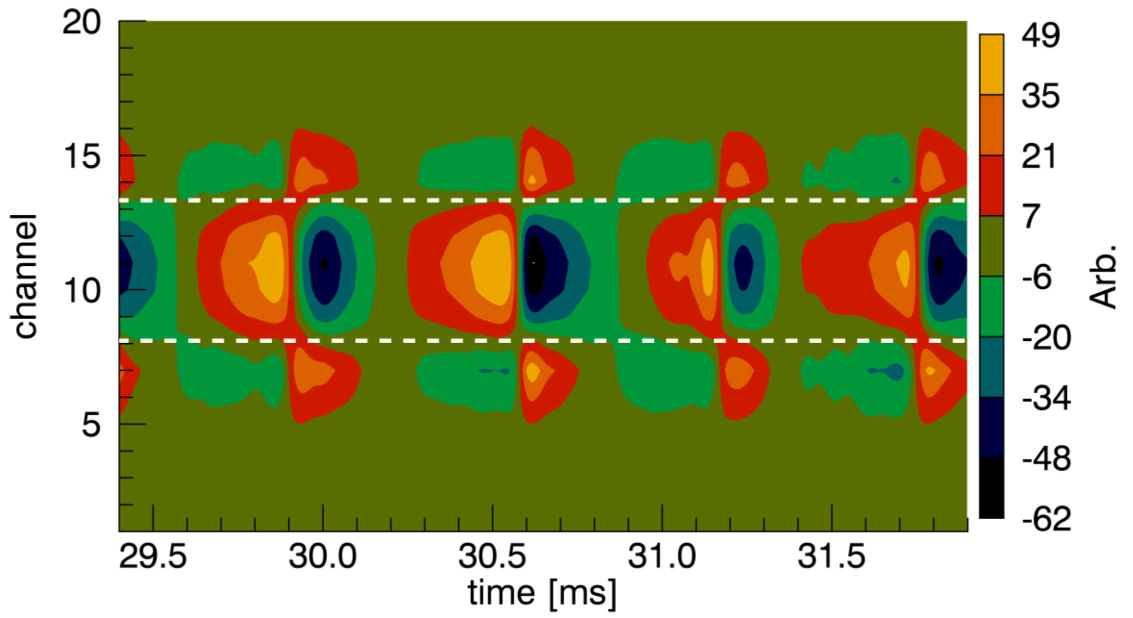
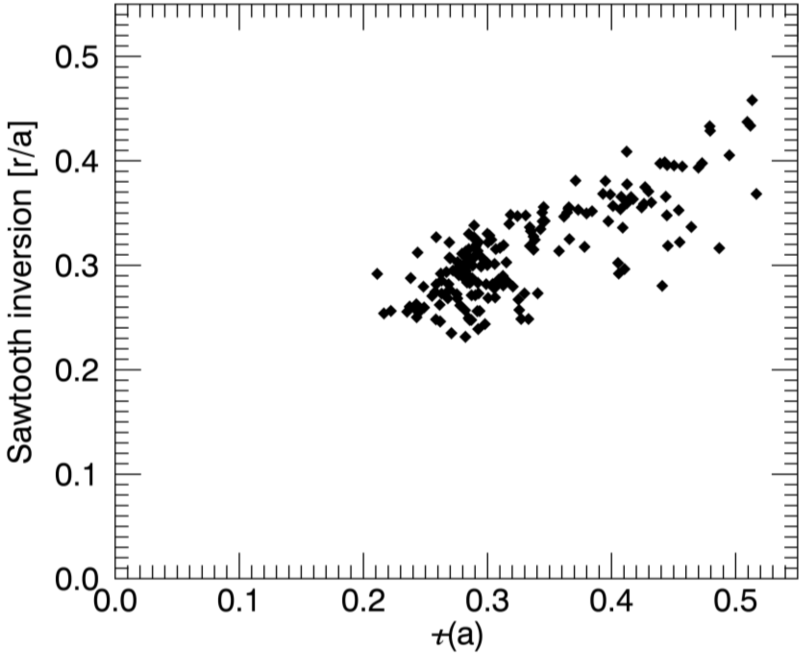


Reconstructed biorthogonal decomposition signals illustrate clear sawtoothing behavior and inversion radius



- Reconstructed SXR signals using the first two modes of BD
- Linear fit subtracted from each channel

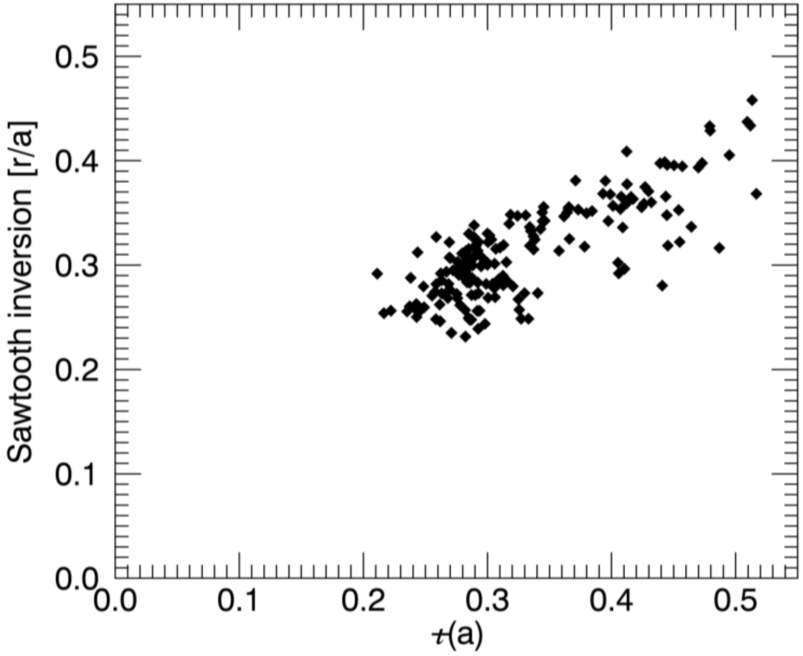
Sawteeth observed in CTH exhibit similar scaling of inversion surface size as in tokamaks

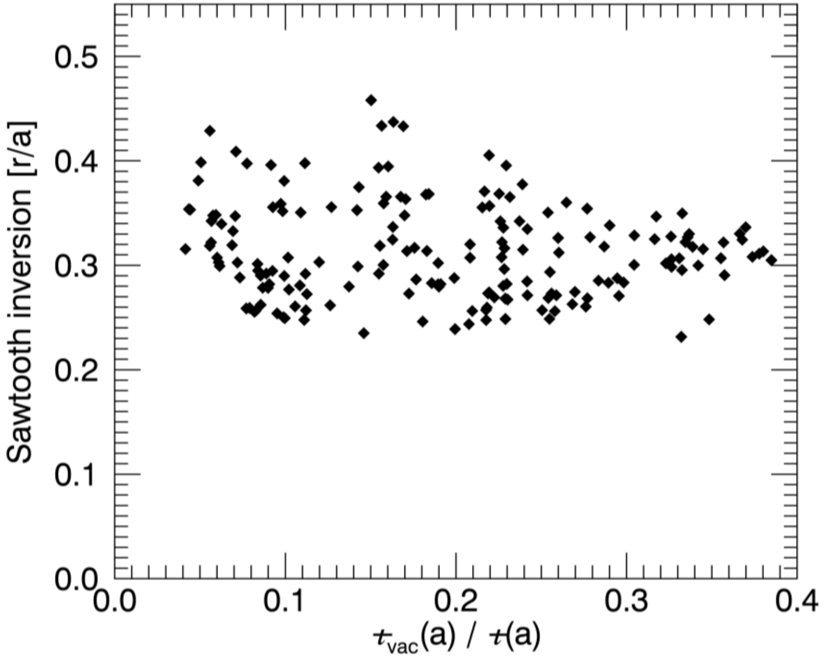


- Normalized sawtooth inversion radius is proportional to ɫ(a) = 1/q(a)[1]

1. Snider Nuclear Fusion 1990, Vol. 30 No. 11

Observed inversion surface radius does not scale strongly with the amount of 3D shaping





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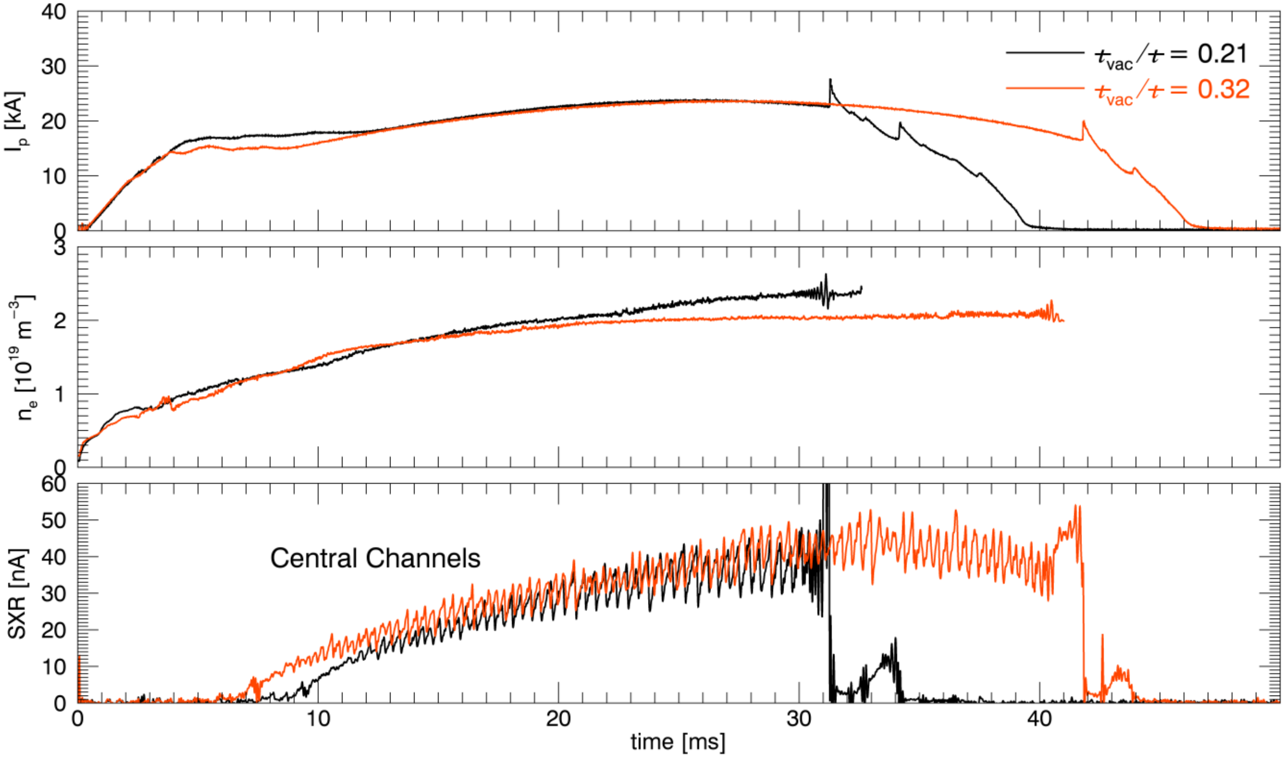
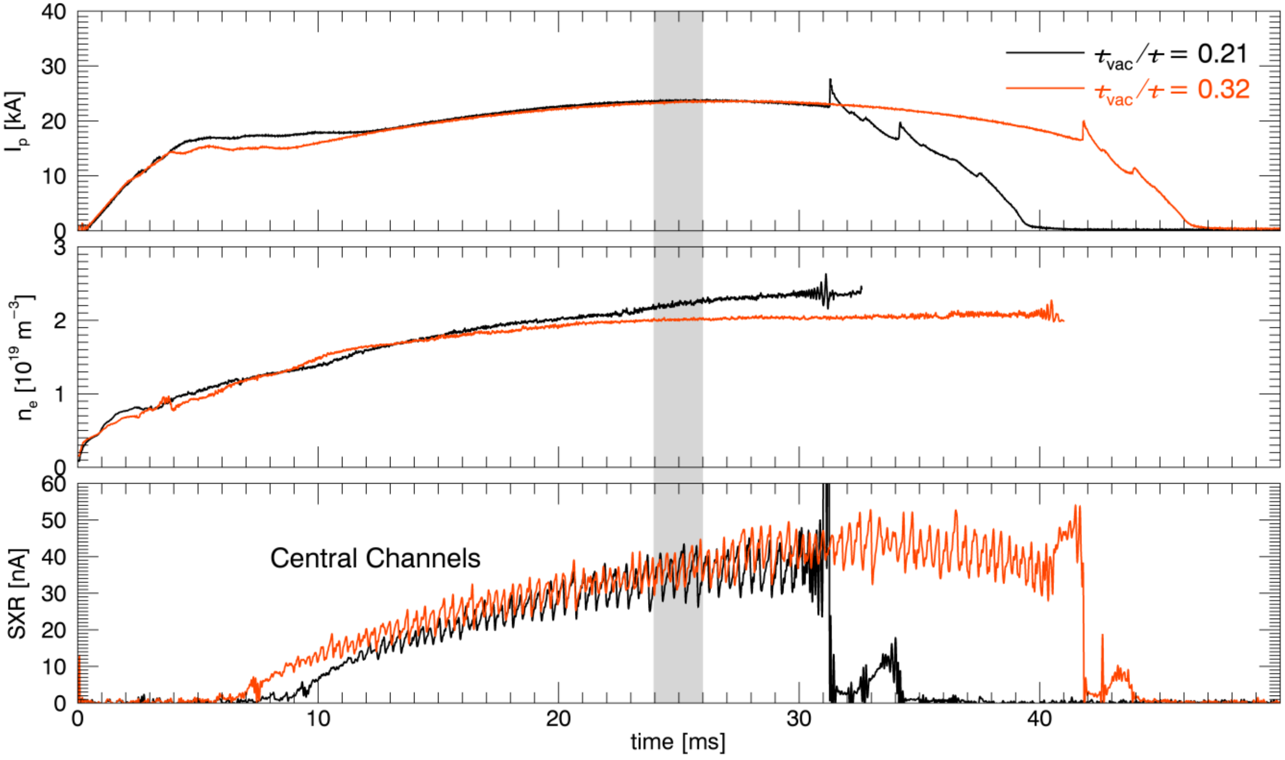
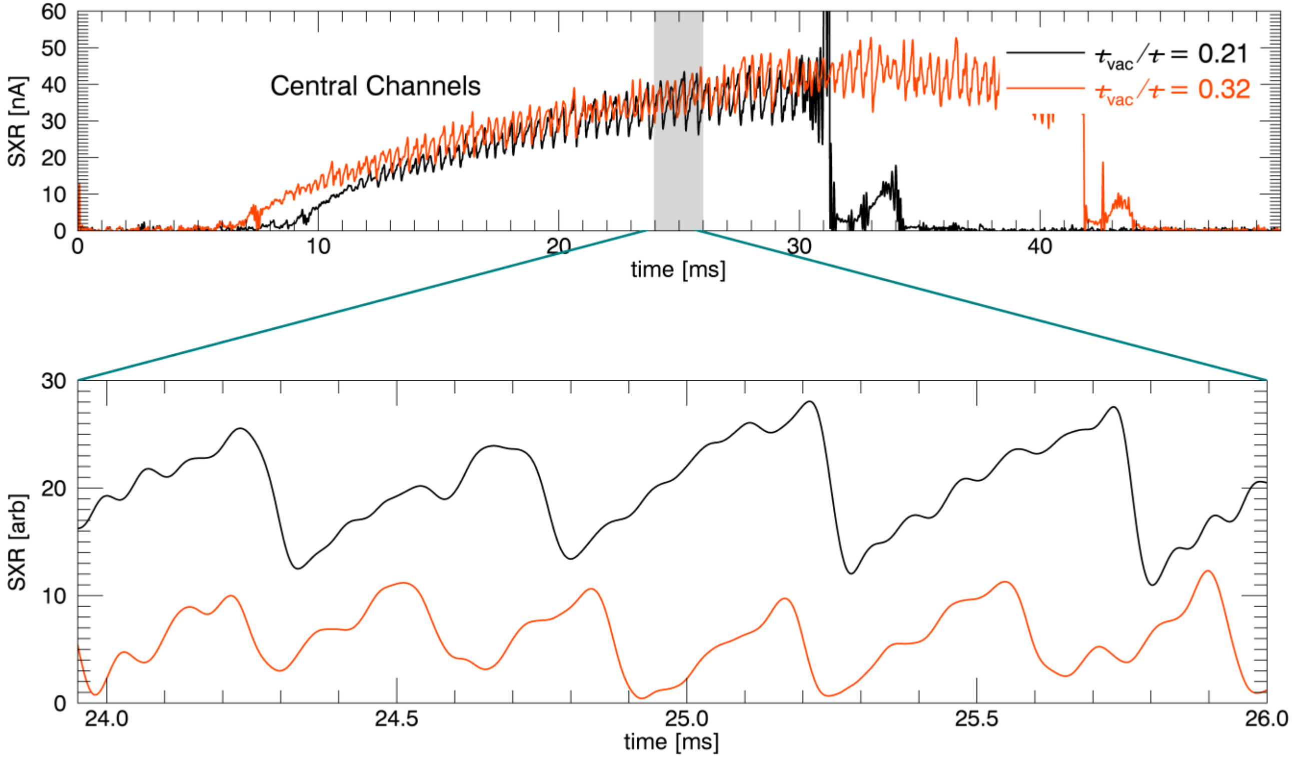
Increased 3D shaping observed to give rise to more frequent sawteeth



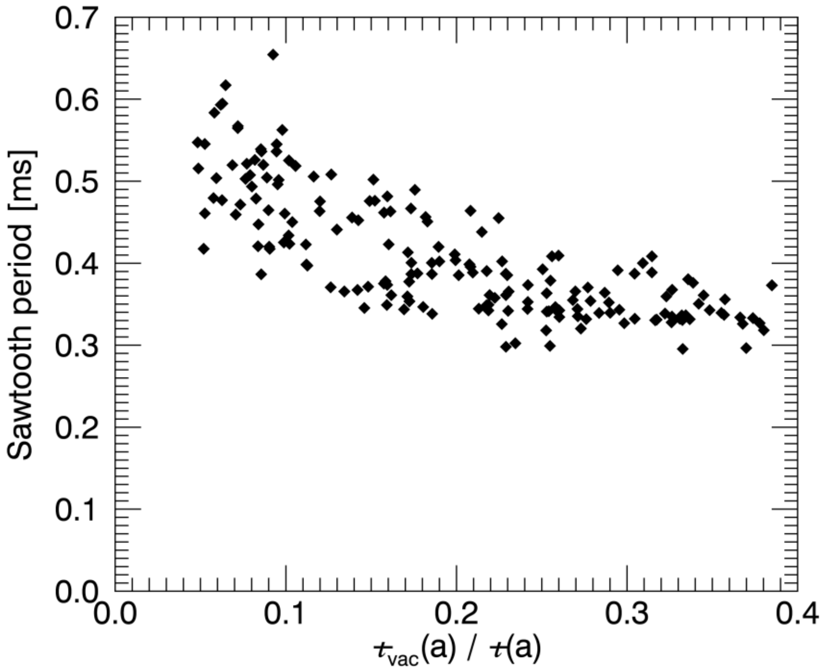
Increased 3D shaping generates more frequent sawteeth



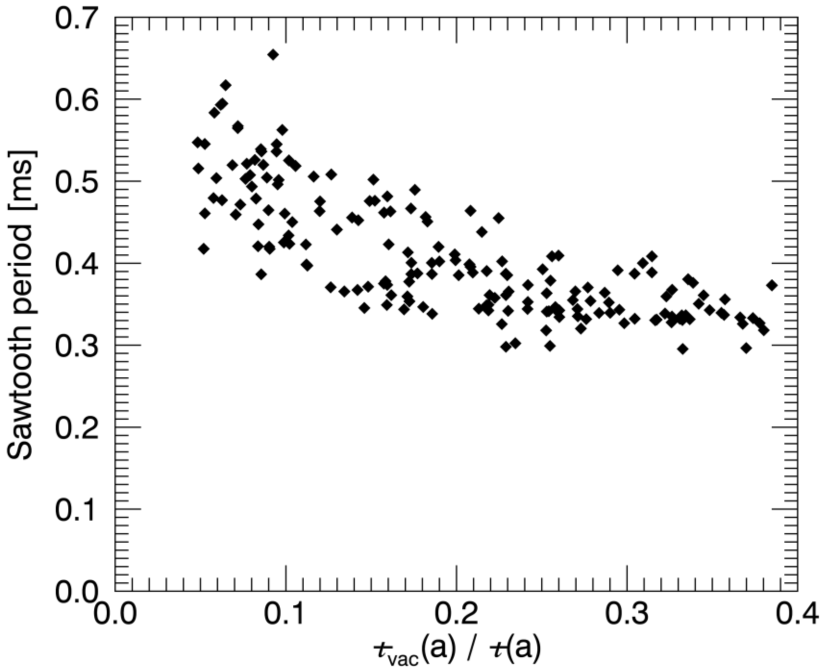
Sawtooth period and amplitude both decrease with application of higher 3D shaping

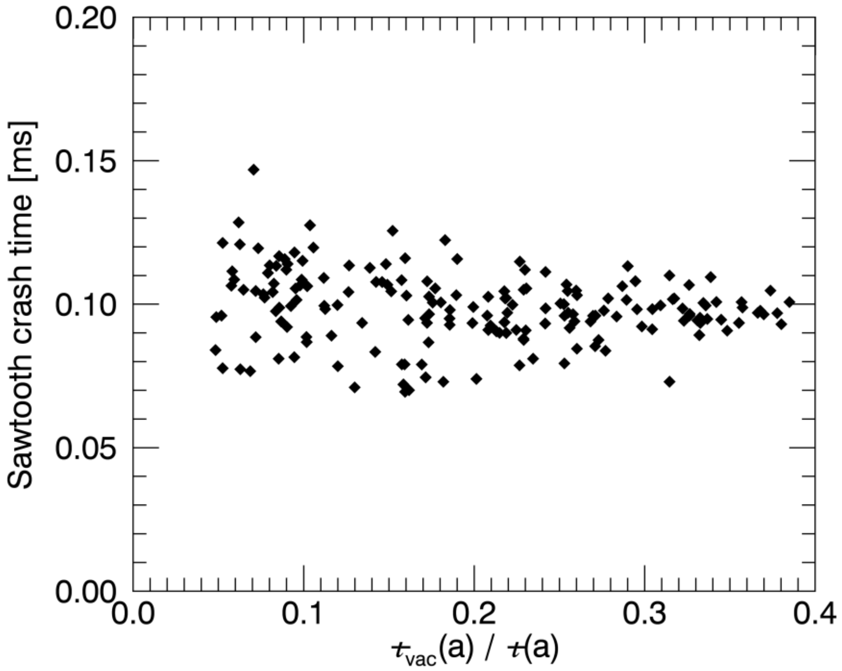


Sawtooth period systematically decreased by 3D magnetic shaping

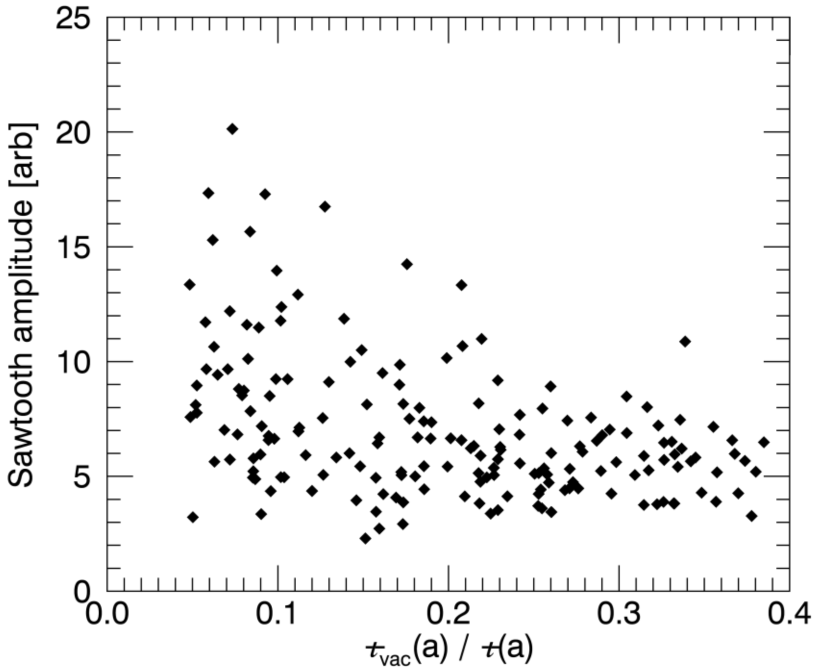


Sawtooth crash time appears to be unaffected by the amount of 3D shaping





Large amplitude sawteeth not observed at high levels of 3D magnetic shaping



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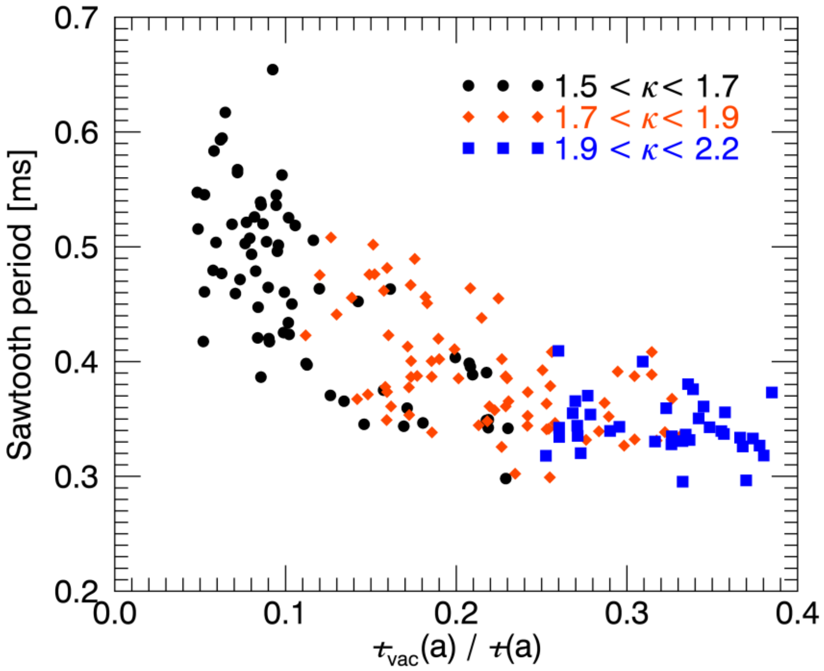
Elongation destabilizes m/n = 1/1 mode in tokamaks

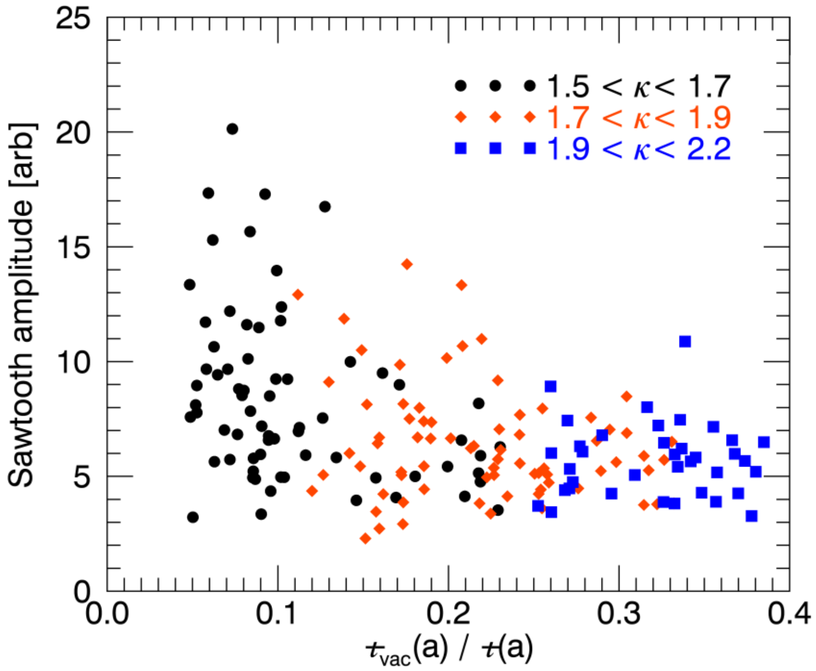
- For axisymmetric plasmas $\kappa = b/a$
- To understand the possible effect of 3D elongation on our sawtooth observations we employ a mean elongation, κ, computed by VMEC[1]
- This definition of κ reduces to the conventional definition of b/a if applied to an axisymmetric torus
- κ calculated on the last closed flux surface as a proxy for κ at the q=1 surface

1. ArchMiller et al., Phys. of Plasmas 21, 056113 (2014)

Shorter period sawteeth observed at higher levels of mean elongation



Decreased sawtooth amplitude also correlated with increasing mean elongation



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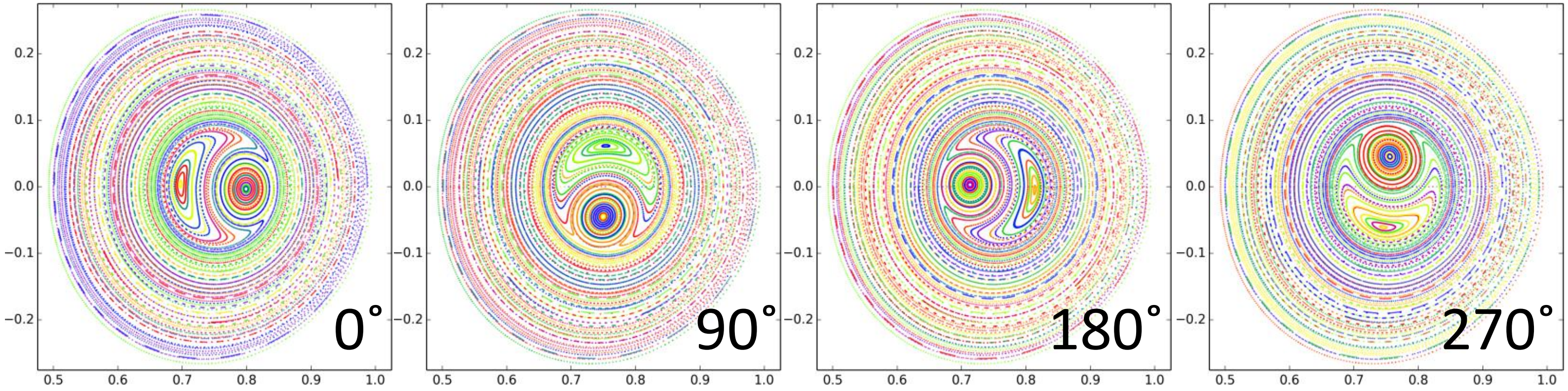
Resistive MHD simulation of CTH sawteeth and $m/n = 1/1$ mode activity underway using NIMROD

2D

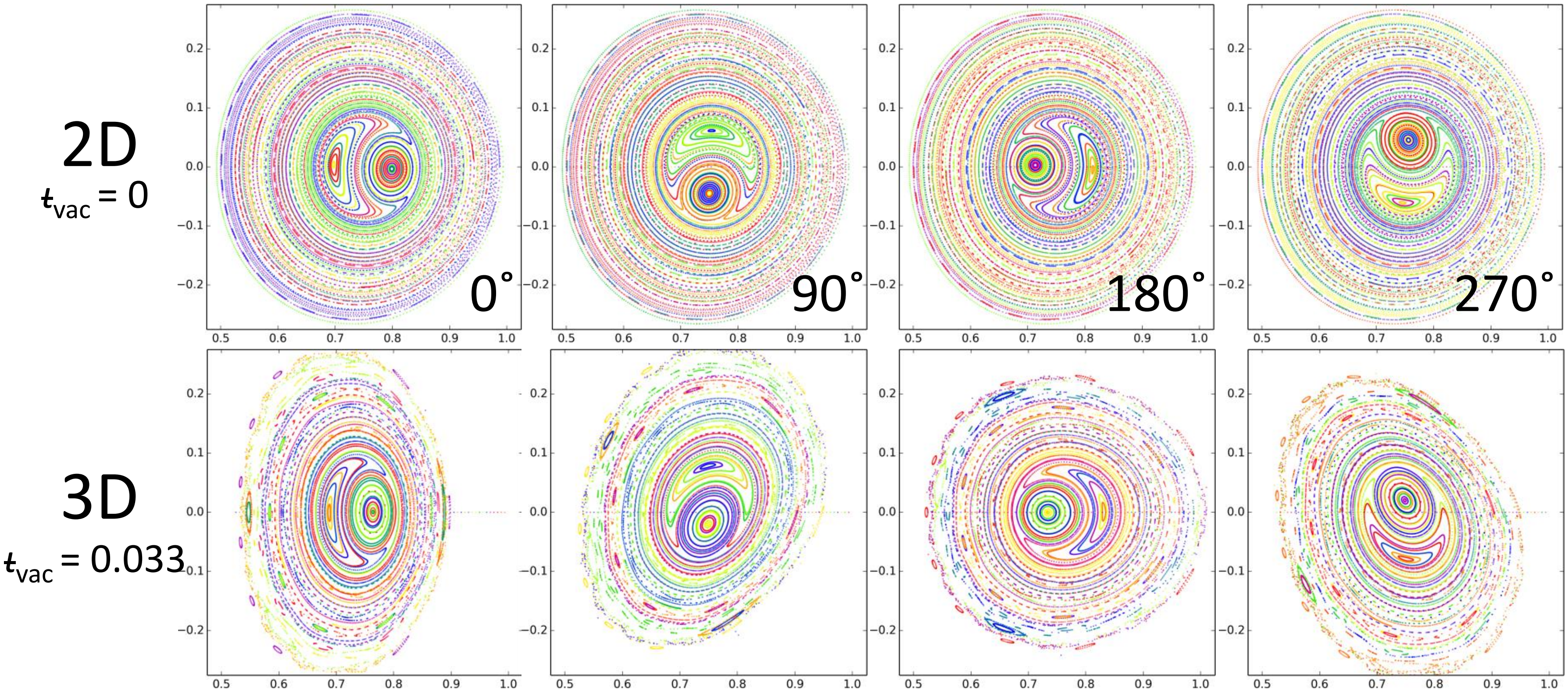
$\iota_{vac} = 0$



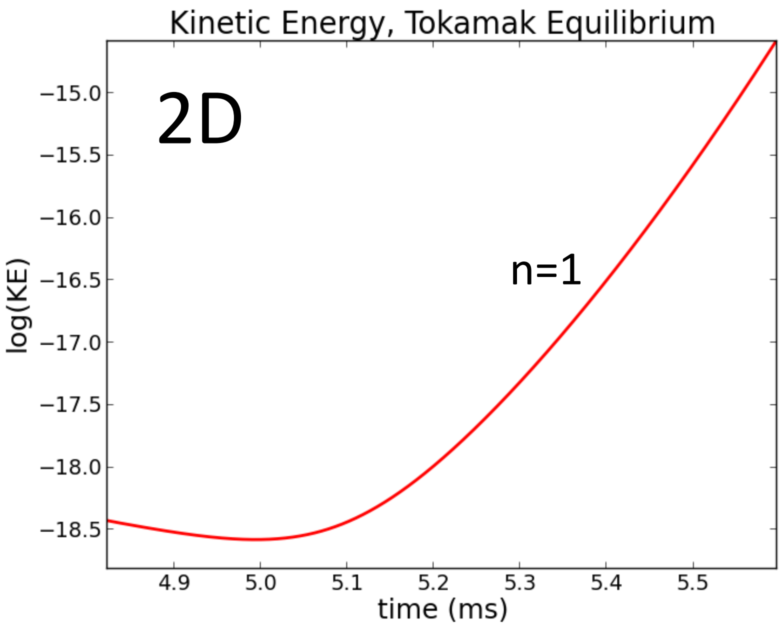
- Axisymmetric plasma simulated with similar parameters to CTH

work of N. Roberds

Fully 3D case exhibits a strongly shaped large amplitude 1/1 island and enhanced stochasticity

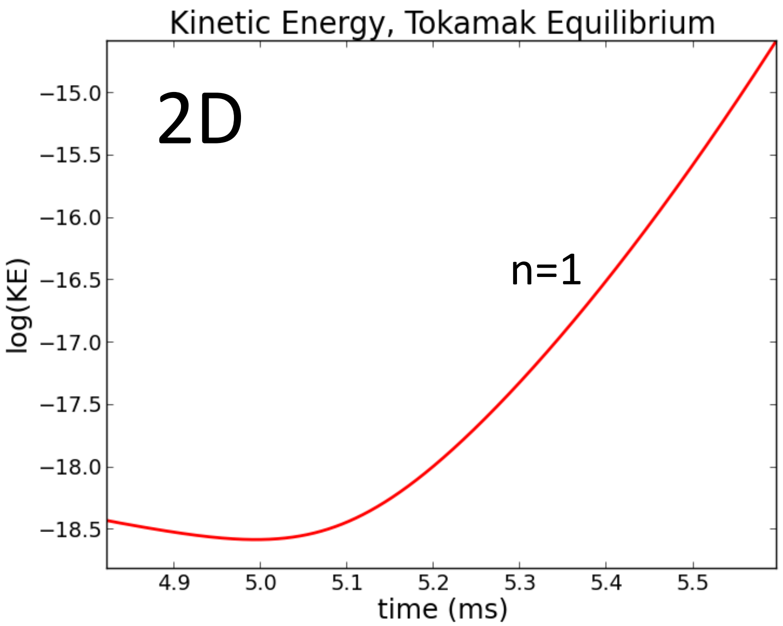


Linearly unstable MHD eigenfunction composed of a single n=1 mode in an axisymmetric configuration



For the axisymmetric case a single growing n = 1 mode is observed

Linearly unstable MHD eigenfunction has a rich toroidal harmonic content due helical shaping



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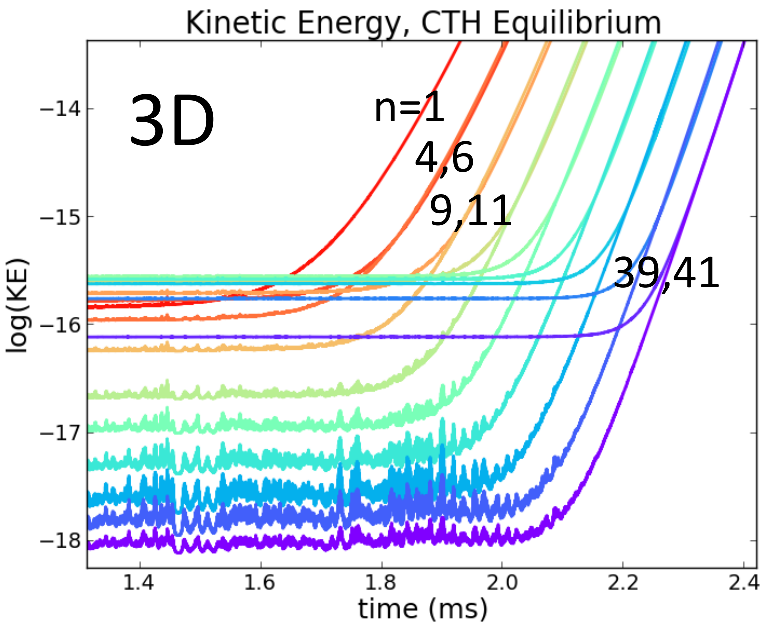
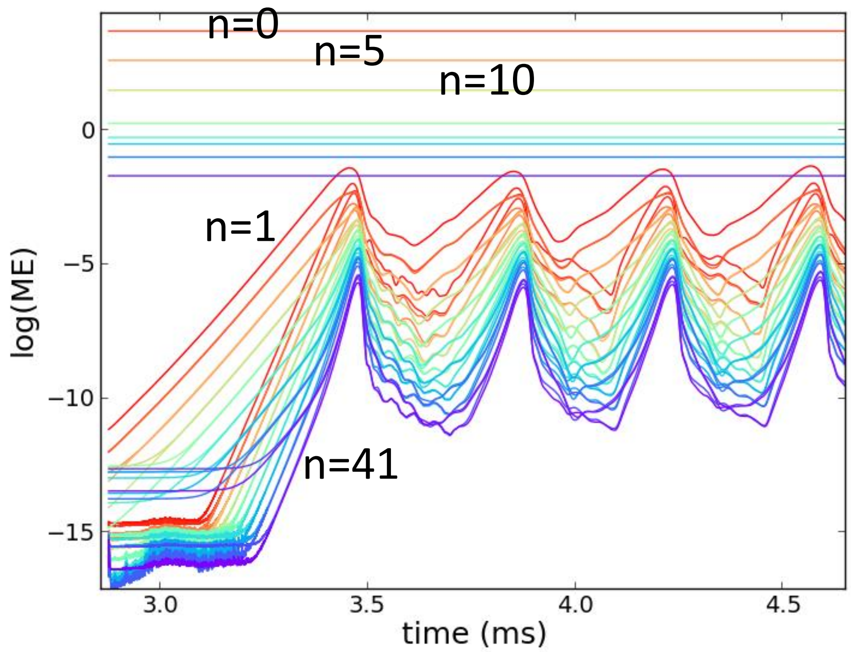


With stellarator symmetry, the eigenfunction contains harmonics with $jN_{fp} \pm 1$[1]

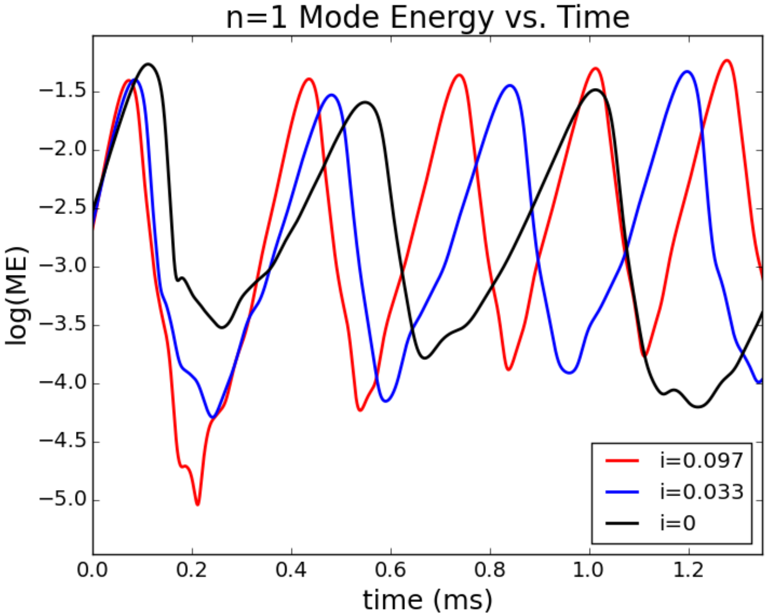
1. *D Spong, PoP 22, 2015*

NIMROD simulations reproduce sawtooth cycling consistent with experiment



- Equilibrium represented by the Fourier numbers 0, 5, 10, ...

NIMROD simulations with higher levels of stellarator transform produce shorter period sawteeth

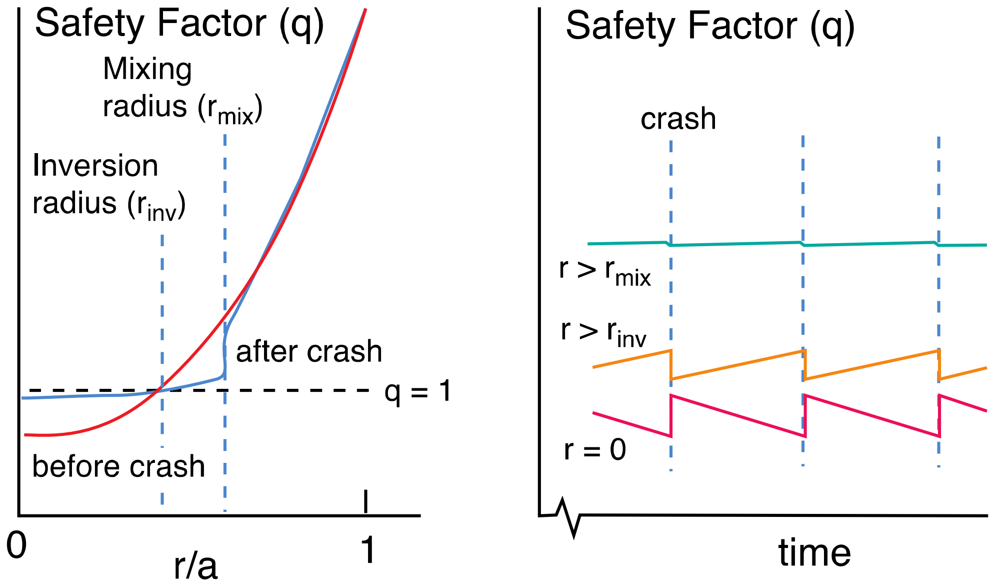


t_{vac}	τ_{saw} $[ms]$
0	0.52
0.0134	0.48
0.0333	0.37
0.097	0.28

Summary

- The observed sawtooth period and amplitude decreases with increased 3D shaping using stellarator transform
- The sawtooth crash time is not strongly correlated with the amount of 3D stellarator field
- The decreased sawtooth period and amplitude are correlated with increasing fractional transform and mean elongation
- NIMROD resistive MHD simulations capture similar trend on the effect of 3D equilibrium shaping with sawtooth cycle period as seen in experiment

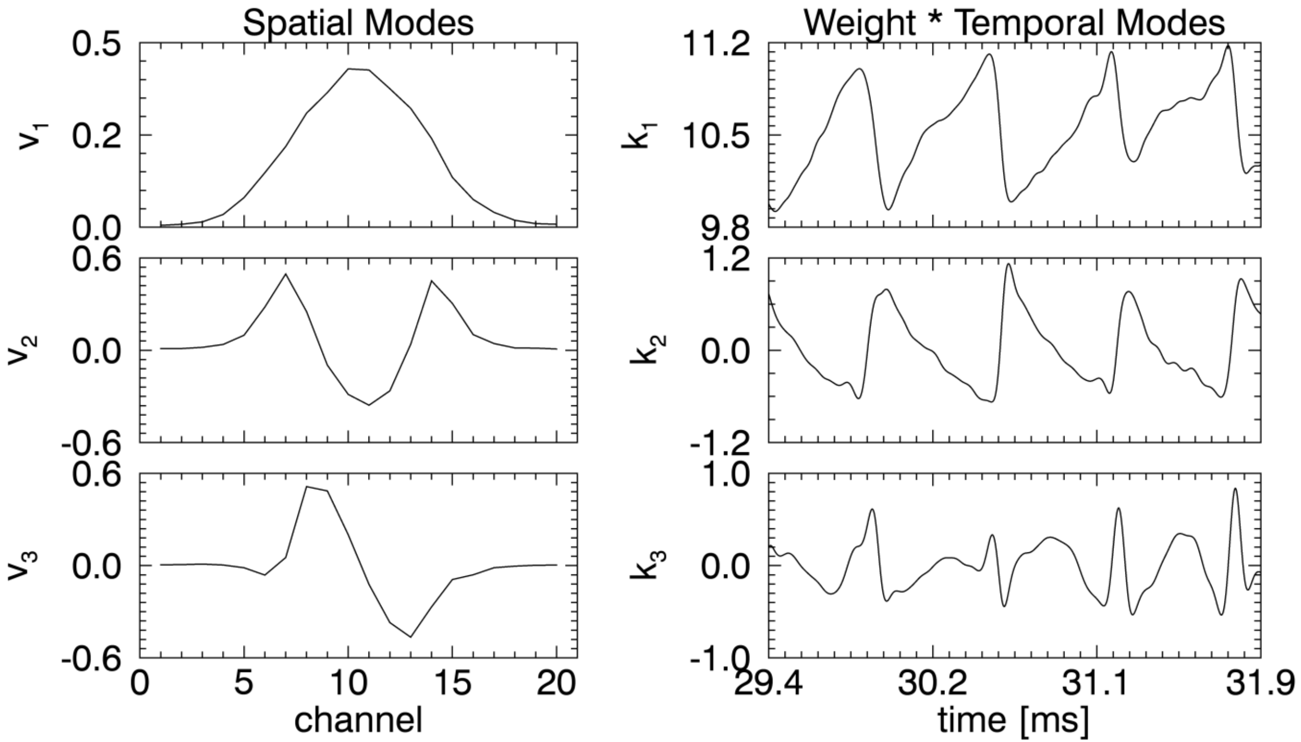
Safety factor profile inside inversion surface also flattens with *q* close to 1 after crash



- Non-ideal MHD physics important for m/n=1/1 mode evolution
- Both complete and partial reconnection of the flux inside the q =1 surface observed experimentally

Image: ITER Physics Expert Group, Nuc. Fusion 39, 12 (1999)

Biorthogonal decomposition provides an empirical mode basis to characterize the sawteeth behavior



No unique generalization of the elongation of a non-axisymmetric torus

- CTH is non-axisymmetric
- Kappa was calculated though VMEC by computing[1]:
  - Plasma Volume
  - Toroidally averaged cross-sectional area
  - Surface area of the plasma
- VMEC then determines the major radius, R_0, semi-minor axis, a, and elongation, κ
- This technique reduces to the conventional definition if applied to an axisymmetric torus
- Mean elongation varied from 1.5 to 2.2

$$V = (2\pi R_0)\pi a^2 \kappa$$

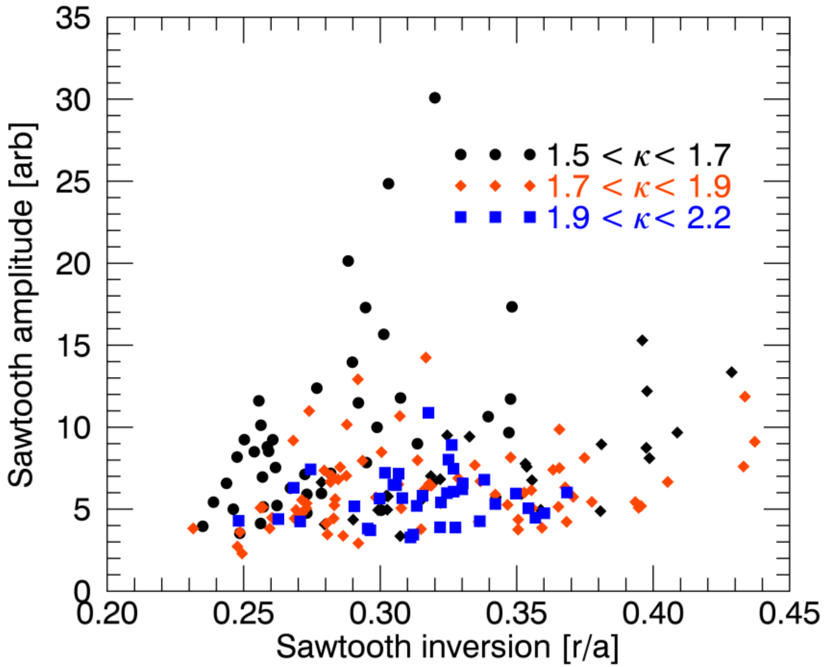
$$A = \pi a^2 \kappa$$

$$A_{surf} = (2\pi R_0)\, 2\pi a\, \tilde{C}(\kappa)$$

$$\tilde{C}(\kappa) = \frac{4E(1-\kappa^2)}{2\pi}$$

1. ArchMiller et al., Phys. of Plasmas 21, 056113 (2014)

Large sawteeth only observed in plasmas with lower ellipticity



- Smaller sawteeth observed over a range of normalized radius

The change in sawtooth period is due to an decrease in time between crashes