# Status, Plans, and Issues regarding Sawtooth Simulation

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CEMM Meeting

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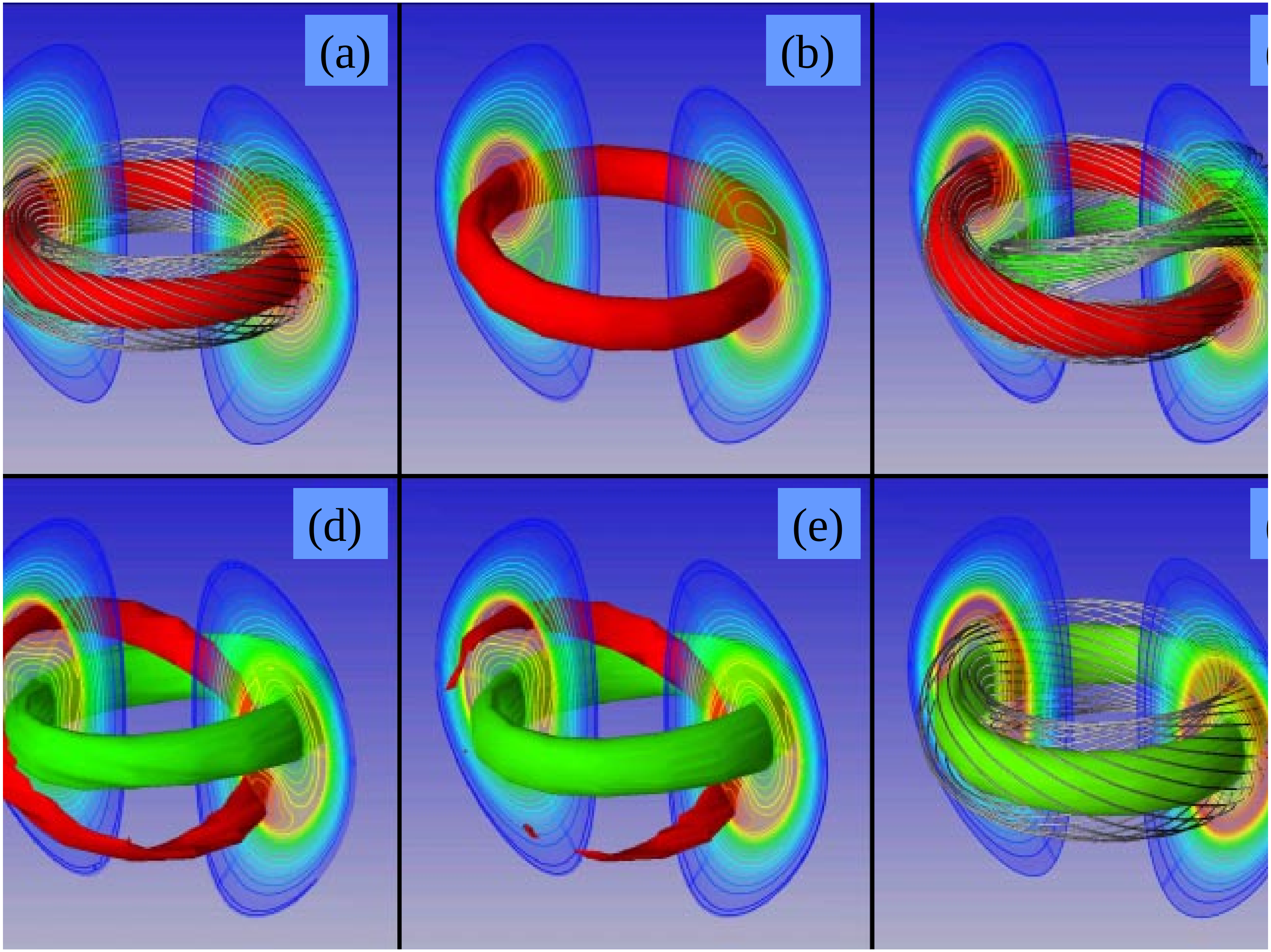
SEAVIEW C

Long Beach Hyatt




AVS movie of M3D calculation courtesy of W.Park and S.Kla

## Summary of Experimental Situation-1:

- Some recent experiments on JET and JT-60 with zero current density in the core have seen "axisymmetric" n=0 sawteeth [Hawkes, 2001].
  - However, the vast majority of experiments with the current peaked in the core see helical n=1 sawteeth.

- Many experiments have measured $q(0) < 1$ using several different techniques, and very small change in q(0) during the sawtooth. These include TEXTOR[Soltwisch,1995], TFTR [ Yamada,1994], MTX [Rice,1994], JET [Wolf, 1993], PBX-M[Levinton, 1989], TOKAPOLE II [Moyer,1989], TEXT[West,1987] and DIII [Wroblewski, 1991].
  - These experiments are in contradiction to ideal MHD [Levinton, 1994].

- There are other measurements reported of $q(0) = 1$ in DIII [Wroblewski,1993], ATC, ASDEX, TCA [Coltish, 1992], and TEXT [Wroblewski,1988].

## Summary of Experimental Situation-2:

•The sawtooth period has been shown to scale approximately with the central plasma resistivity [Park,1990], or a hybrid of the heating and resistive time [McGuire 1980].

- It has also been shown to be a function of the shape of the plasma cross section [Reimerdes, 2000].
- The period can be lengthened by heating [Snider,1989], [Campbell,1988].

- Many experiments report that details of the Kadomtsev model are incorrect.
    - q(0) is measured to stay below unity during the crash,
    - the crash time for the temperature is considerably faster than predicted for the Kadomtsev model [Yamada,1994], [Wesson,1991], [Edwards 1986]
    - often there is only a partial crash [Nagayama,1996], [Levinton,1994], [Wolf,1993], [Janicki,1990] ,[Westerhof,1989] , [McGuire,1987].
    - There is often no precursor to the collapse [Campbell,1986].

- The sawtooth is normally associated with the q=1 surface. However [Chang,1996] reports on a “q=2” sawtooth due to double tearing.

## Summary of Theoretical Situation-1:

- The basic ideal MHD theory says that a circular cylindrical plasma is always unstable to an internal kink mode when q(0) < 1. [Shafranov, 1970].

- It was later shown [Bussac,1975],[Zakharov, 1978] that a circular toroidal plasma could be stable to the ideal kink for a limited region of pressure, even when q(0) < 1. However, ellipticity is strongly destabilizing [Wahlberg, 1988], [Lutjens,1992], but triangularity is again stabilizing [Manickam, 1984].

- The pure ideal mode saturates at a low amplitude with a singular current sheet [Rosenbluth,1976], [Waelbroeck,1989] and thus resistive and other non-ideal effects, possibly including electron inertia [Wesson,1990] are clearly important.

- The basic reconnection model by [Kadomsev,1976] shows the sawtooth is a reconnection event with q(0) < 1 before the event, and q(0) = 1 after reconnection.

- This basic theory does not explain how q(0) got to be less than 1, or what triggers the start of the reconnection (crash). Nor does it correctly explain the crash time, or why q(0) remains less than one during the crash, or why there are often partial crashes.

- There is some speculation that the trigger problem can be explained by the q-profile going through unity off-axis [Parail, 1983], [Wesson,1986], but this doesn't explain why q(0) is measured to be less than 1 throughout the cycle.

## Summary of Theoretical Situation-2:

- The Hall term and electron pressure gradients in Ohm's law greatly speed up the crash time and can lead to explosive growth [Zakharov, 1993], [Wang,1993], [Rogers,1997].
- FLR theory shows that the reconnection layer should be the order of the ion-gyroradius [Basu,1982], [Pegoraro,1989], [Porcelli,1991].
- Density and temperature gradients at the q=1 surface are stabilizing [Zakharov,1993], [Rogers,1995], both linearly and nonlinearly, and with non-singular current layers. It follows from these that there is a strong dependence of stability on the local shear and other gradients at the q=1 surface [Berk,1991], [Rogister,1990], [Zakharov,1993].
- Several papers imply that stochasticity caused by the (1,1) mode interacting with the toroidal variation of the equilibrium [Lichtenberg, 1991] or driving higher-n ballooning modes unstable [Nishimura,1999], or becoming unstable to secondary tearing modes [Biskamp,1987] causes the fast crash.
- High-energy particles and thermal trapped particles affect the stability. [Porcelli,1996] There are stable and unstable regimes.

## Summary of Computational Situation-1:

- Early calculations using reduced MHD and/or exaggerated parameters reproduce the basic Kadomtsev model [Waddell, 1976],[Sykes,1976], [Aydemir,1989].

- Modifications have been made to this basic model to give:
  - compound sawteeth [Denton,1986], [Kleva,1987] ,
  - quasi-interchange modes [Wesson,1987], [Aydemir,1988], [Vlad,1989]
  - stabilization through heating of the m=1 island [Park,1987], and
  - the effects of neo-classical resistivity [Park,1990],
  - hyper-resistivity [Aydemir,1990],
  - finite pressure [Park,1991].

•It has been demonstrated that an ideal (1,1) mode can saturate and cause toroidally localized high-n ballooning modes to go unstable [Park,1995], [Lutjens,1997], [Nishimura,1999]

## Summary of Computational Situation-2:

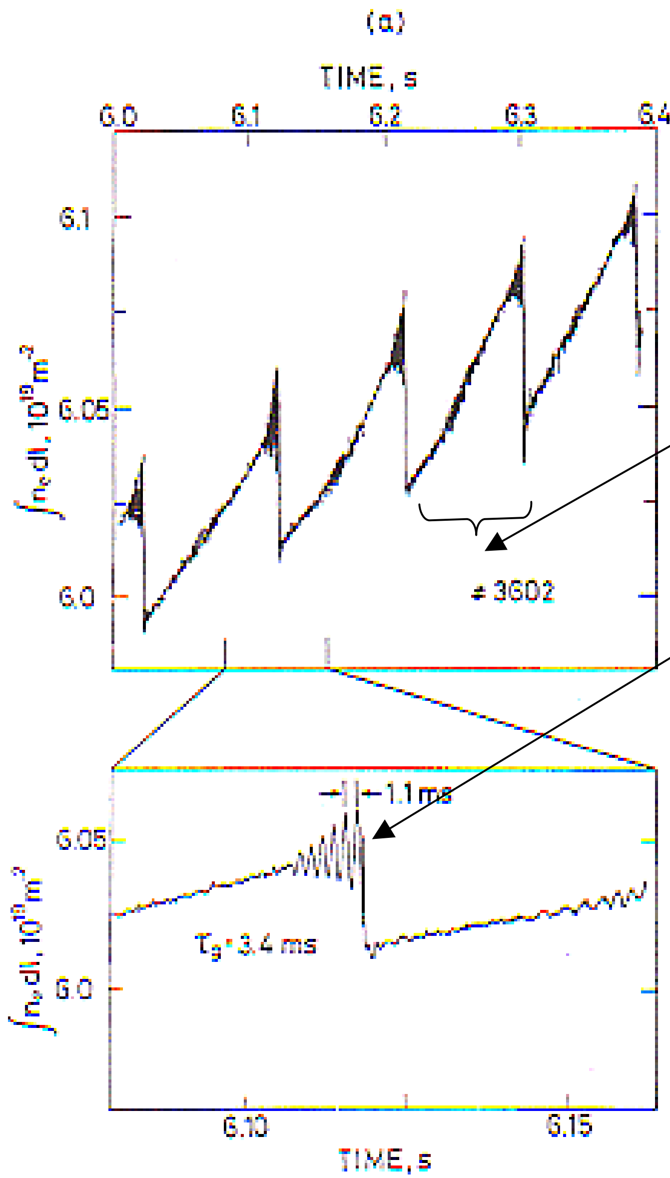
• It has been shown that the full 2-fluid equations can lead to ion diamagnetic drift that can stabilize the (1,1) mode [Sugiyama, 2000].

• The 4-field 2-fluid physics model with hyperresistivity has been shown to lead to accelerated nonlinear growth of the crash. [Aydemir,1992]

• It has also been shown that toroidal modulation of the m=1 resistive mode drives sidebands, and different magnetic island chains with m up to 10 overlap, leading to an annular stochastic region. This can expel the electron temperature in less than 100 μsec, removing the drive for the instability, and the central core could be pushed back without change in the value of q(0).[Baty, 1993]

•Similar sawtooth mechanisms can occur when $q_{min}$ crosses 2 [Chang,1996] or $1/q_{min}$ crosses zero [Huysmans, 2001] [Breslau, 2001]

# Elements of the Sawtooth:




terferometer data from typical JET discharge

- Sawtooth period
- Precursor and crash
- Reconnection and layer physics
- Coupling to other modes

## Outstanding questions:

1. Sawtooth period
    - How does the period scale with plasma and machine parameters?
    - Why is there a quiescent ramp phase ?
    - What is the trigger for the onset of the crash?
    - Contrast ohmic, auxiliary heated, and non-inductive
    - Effect of fast particles, thermal, non-thermal, passing, and trapped
    - Effect of period on Energy Confinement time

2. Sawtooth precursor and crash
    - What is the role of the ideal 1/1 mode?
    - How can you explain observed sawteeth with no precursor?
    - How does the crash time scale with plasma and machine parameters?
    - Rapidity of the onset of the collapse.
    - Mechanism for the rapid redistribution of the energy that accompanies the collapse.
    - Why both compound and simple sawtooth?

- How much magnetic reconnection occurs during the crash. i.e., how much does q(0) increase during the sawtooth?
- Role of the Hall term, whistler wave, ω*, viscosity
- Is layer width determined by ion Larmor radius or resistivity?
- Does the $c/\omega_{pe}$ length scale need to be resolved?
- Relative importance of collisional resistivity, electron inertia, hyperresistivity, Hall physics.

4. Coupling of the sawtooth to other modes.

- How does the mixing radius depend on plasma and machine parameters such as A, κ, δ, $\beta_P$ and $q_a$?
- Coupling to and destabilizing high n ballooning modes and resistive g-modes.
- Coupling to m > 1 ideal modes via toroidal coupling
- Trigger to NTM's
- Coupling to ELMs
- Mechanism and probability for inducing a disruption or IRE
- Energetic Particle Modes

## Essential Features of a Tokamak Sawtooth Simulation Model:

- Three-Dimensional toroidal geometry

- 2-fluid MHD Equations including density evolution and FLR effects (and Hall term?,  and electron inertia??)

- Parallel transport including effects of stochastic field lines

- Effect of fast particles, thermal, non-thermal, passing, and trapped

When, eventually, a better understanding of the dynamics of Sawteeth is achieved it may throw light on many other phenomena in Tokamak plasmas (such as the disruptive instabilities…and ELMs), but also perhaps on fast reconnection events in the Magnetosphere, the Solar Corona and elsewhere.

R.J. Hastie, August 1998