CEMM Planning Meeting

August 21, 2002

Room 07-120

General Atomics

Agenda

- Sawtooth Test Problem
- CEMM Meeting at APS Meeting
- CEMM SC2002 Display
- ISOFS September Workshop
- Extended MHD in the Integrated Modeling Initiative

Heat pulse propagation studies on DIII-D and the Tokamak Fusion Test Reactor

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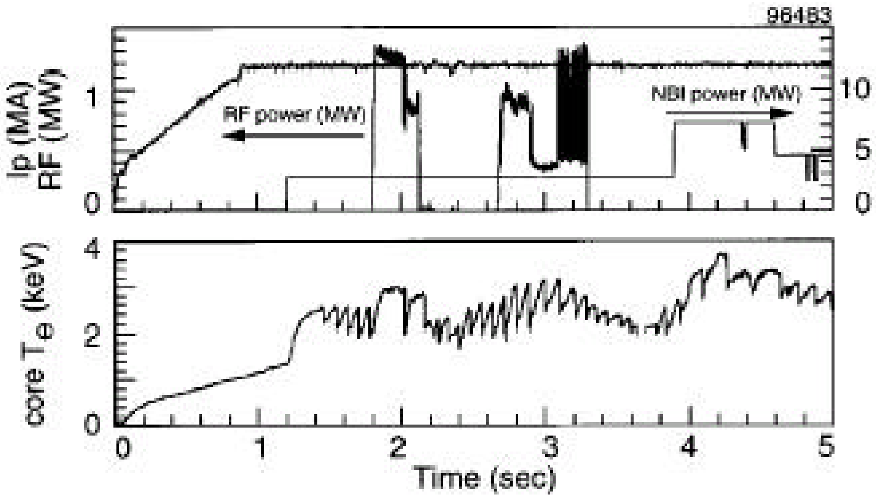
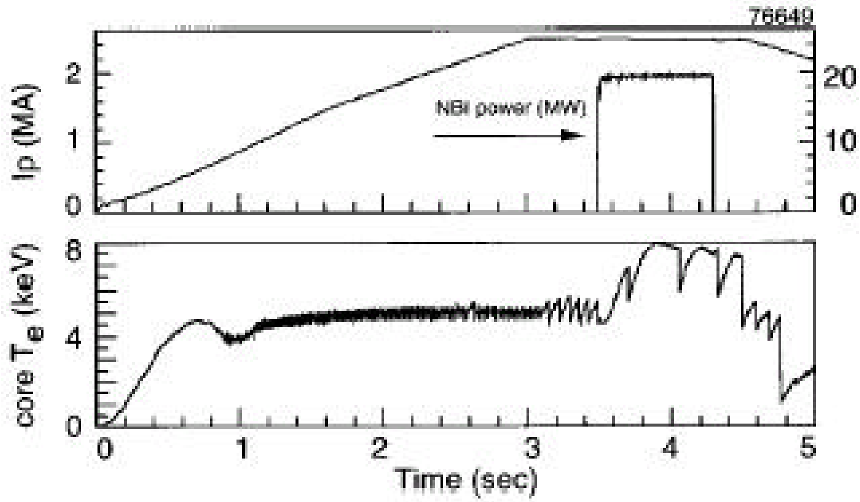
The sawtooth instability was discovered on the ST tokamak[7] and a heuristic model of the instability consistent with the limited experimental data of that time, was proposed by Kadomtsev.[8] Subsequently inconsistencies between the Kadomtsev model of the sawtooth and experimental measurements of the sawtooth instability were found.[9,10] Presently, no complete model of the sawtooth predicts the wide range of sawtooth behavior seen in many tokamaks. Section III presents data from DIII-D and TFTR showing that the sawtooth precursor behavior on DIII-D and TFTR is very similar, thus studies of the sawtooth induced heat pulse propagation on DIII-D and TFTR can be considered complementary. As well as contributing to the understanding of anomalous thermal transport, the observations of the ballistic heat pulse may also shed light on the sawtooth phenomena itself.



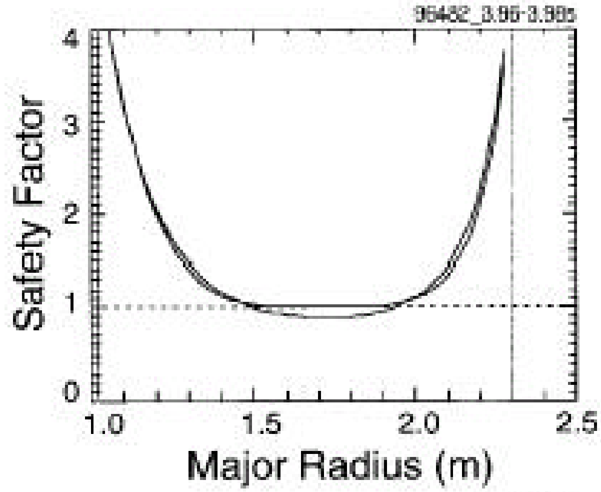
DIII-D

Sawtooth period was increased with ICRF and with NBI

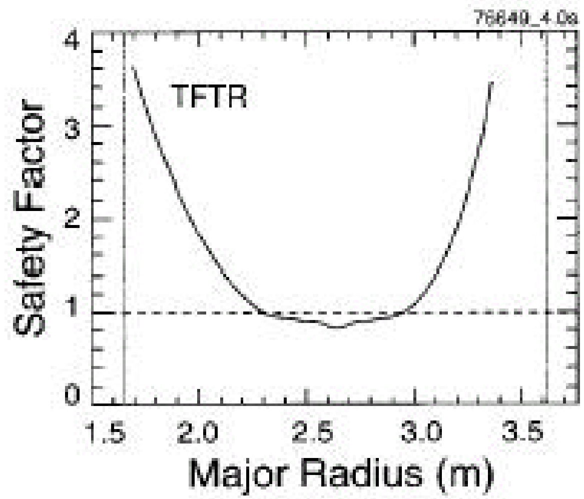


TFTR

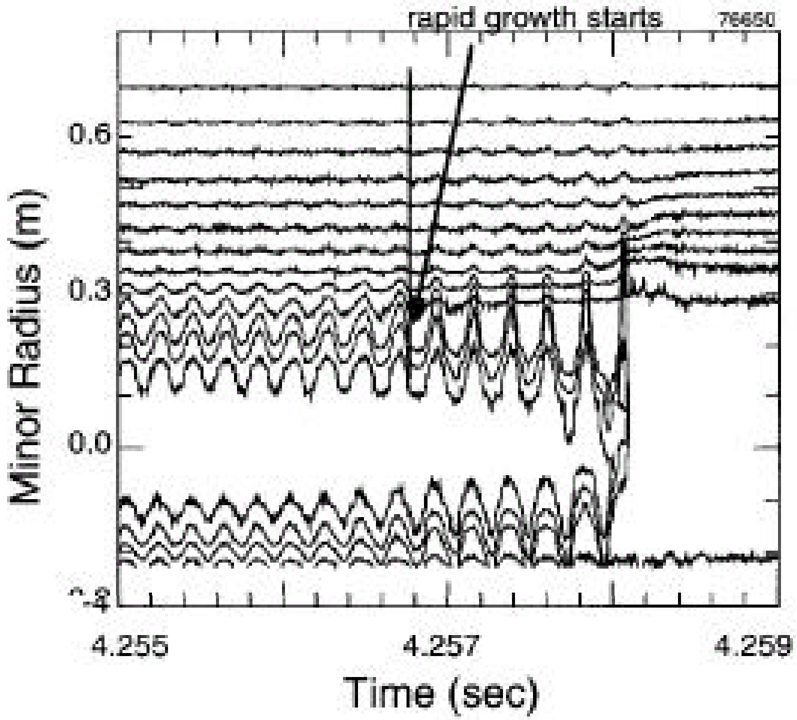
Sawtooth period was increased with NBI. Could be completely stabilized for edge Te high enough.



On DIII-D, MSE measurements show that q(0) jumps to unity during the sawtooth reconnection

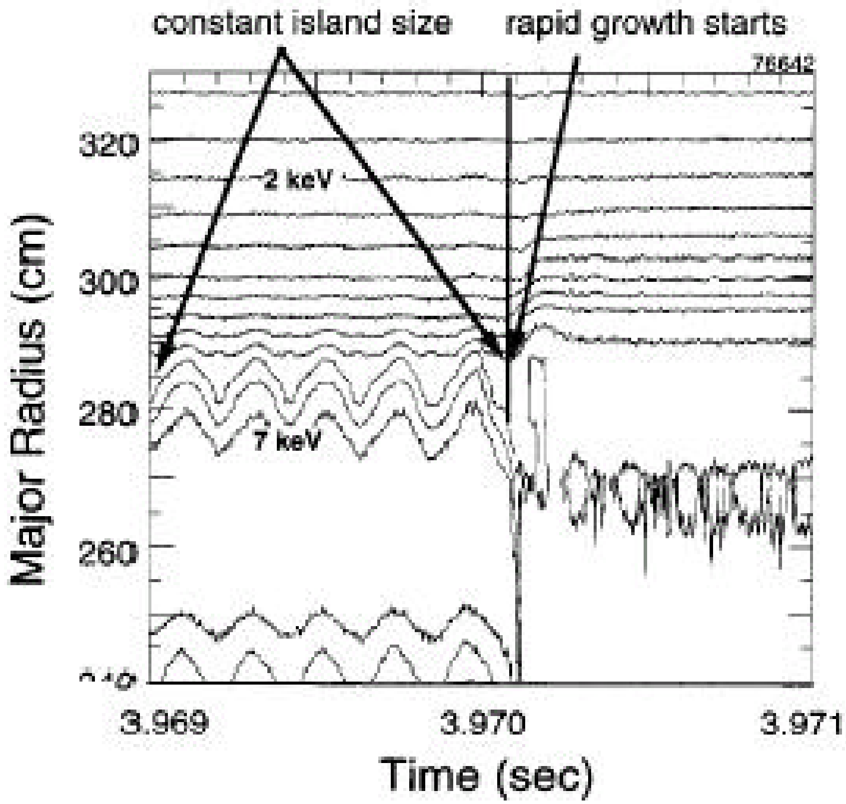


On TFTR, q(0) remains well below unity following the sawtooth (as in TEXTOR)



ECE measurements from TFTR. (contours every 0.5kev)

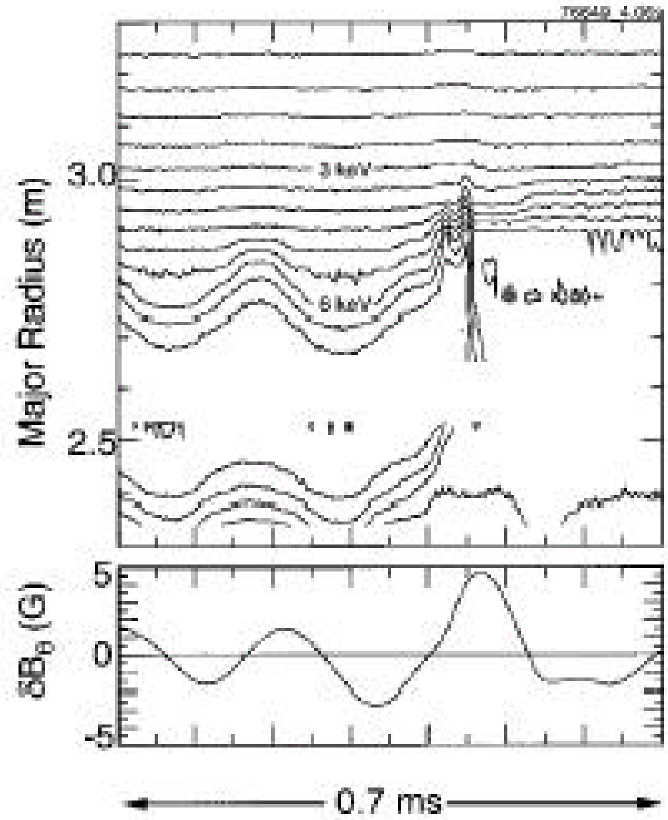
Sawtooth precursor island begins to grow 700 μsec before the crash



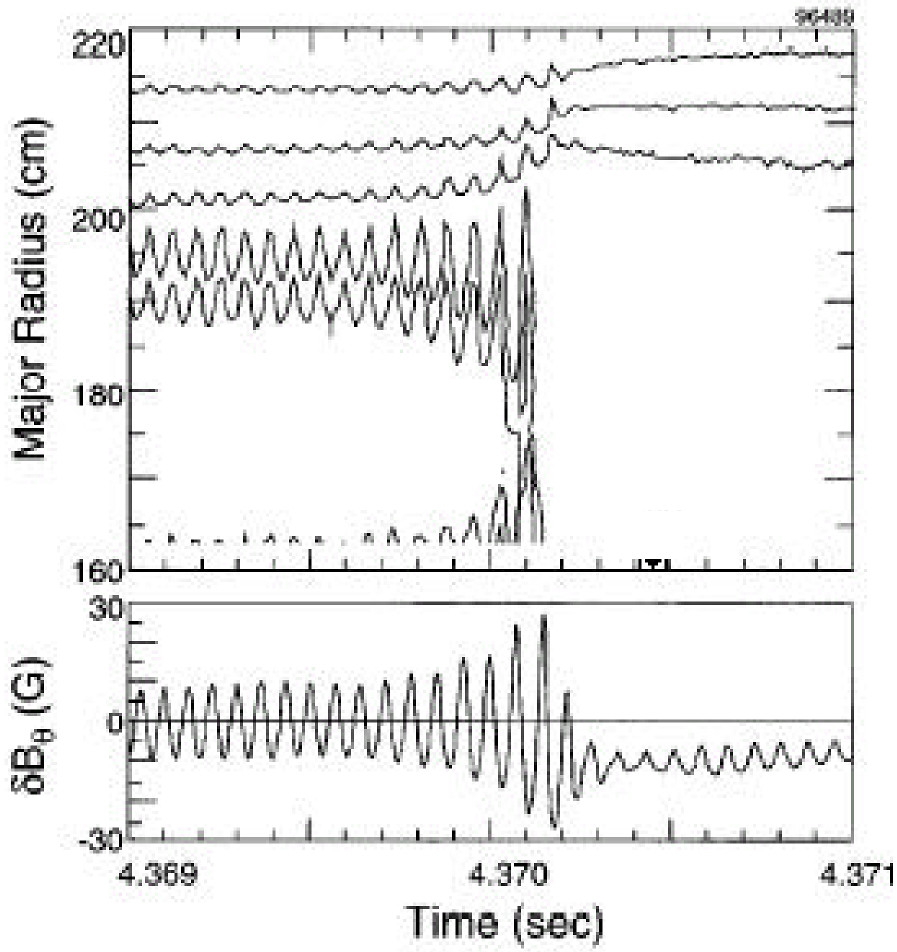
ECE measurements from TFTR. (contours every 0.5kev)

Sawtooth precursor island begins to grow 100 μsec before the crash

Sawtooth crash time can vary substantially in same shot or between shots.



A similar TFTR sawtooth shows a localized, intermediate-n ballooning mode during the final phase of the precursor growth.



Sawtooth crash on DIII-D. Behavior is very similar to that on TFTR. Note heat pulse that starts at the (1,1) growth time

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, Stratton, 2002, Breslau, *this meeting*].

    - However, the vast majority of [inductively driven] 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].

- There are other measurements reported of $q(0) = 1$ after the sawtooth crash 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], [Fredrickson,2000].

- Many experiments report that details of the Kadomtsev model are incorrect.
    - q(0) is measured to stay below unity during the crash in many experiments,
    - 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.

- The sawtooth radius can be very large and lead to discharge termination in Spherical Tokamaks [Gates, 2001]

Summary of Theoretical Situation-1:

- The basic ideal MHD theory says that a circular cylindrical plasma is always unstable to an ideal 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], and free boundary effects are destabilizing [Bondeson, Turnbull, Manickam].

- 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) often 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],
  - the effects of neo-classical resistivity [Park,1990],
  - hyper-resistivity [Aydemir,1990],
  - finite pressure [Park,1991].

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

Summary of Computational Situation-2:

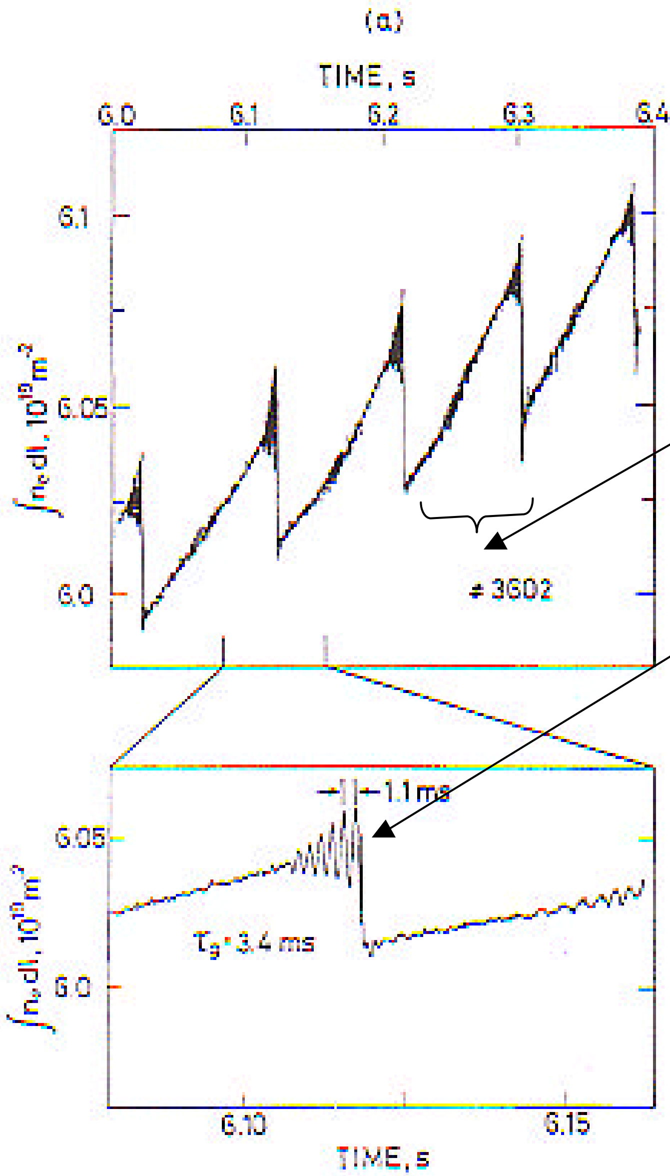
• It has been shown that the full 2-fluid equations can lead to ion diamagnetic drift that can stabilize the (1,1) mode [Sugiyama, 2000].

• The 4-field 2-fluid physics model with hyper-resistivity 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:



Interferometer 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?
   - Explain the rapidity of the onset of the collapse.
   - How does the crash time scale with plasma and machine parameters?
   - Mechanism for the rapid redistribution of the energy that accompanies the collapse.
   - Why both compound and simple sawtooth?

3. Layer physics and reconnection

- 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/ω_{pe} length scale need to be resolved?
- Relative importance of collisional resistivity, electron inertia, hyper-resistivity, 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, β_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

Alternate Approach: Instead of modeling a big device for short times with unrealistic parameters, model a small device using the actual parameters: CDX-U is a possible candidate

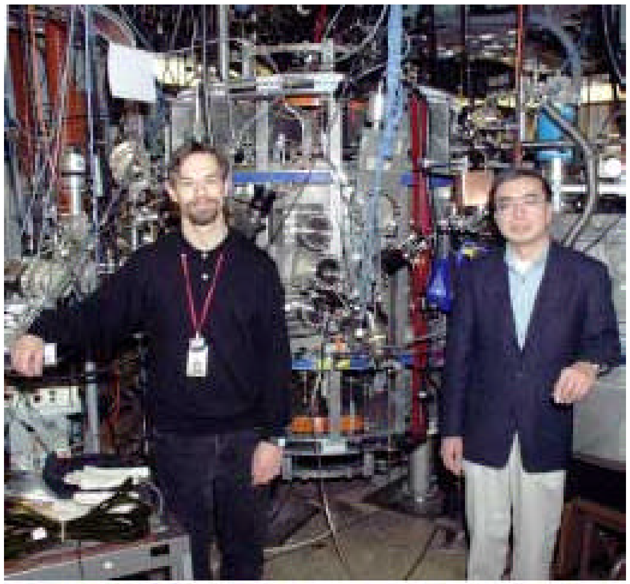


Fig 1: At the Current Drive Experiment Upgrade are Dick Majeski (left) and Bob Kaita, who co-headed the project.

CDX-U Plasma Parameters		
Parameter	**Description**	**Value**
R_0	Major radius	33.5 cm
a	Minor radius	22.5 cm
$A=R_0/a$	Aspect ratio	1.5
κ	Plasma elongation	1.5-1.7
B_T	Toroidal magnetic field	2300 gauss
$n_e(0)$	Central electron density	$\sim 4\times10^{13}$ cm^{-3}
$T_e(0)$	Central electron temperature	100 eV
I_P	Plasma current	70 kA
	Pulse length	25 ms
	Pulse flat-top	5-10 ms

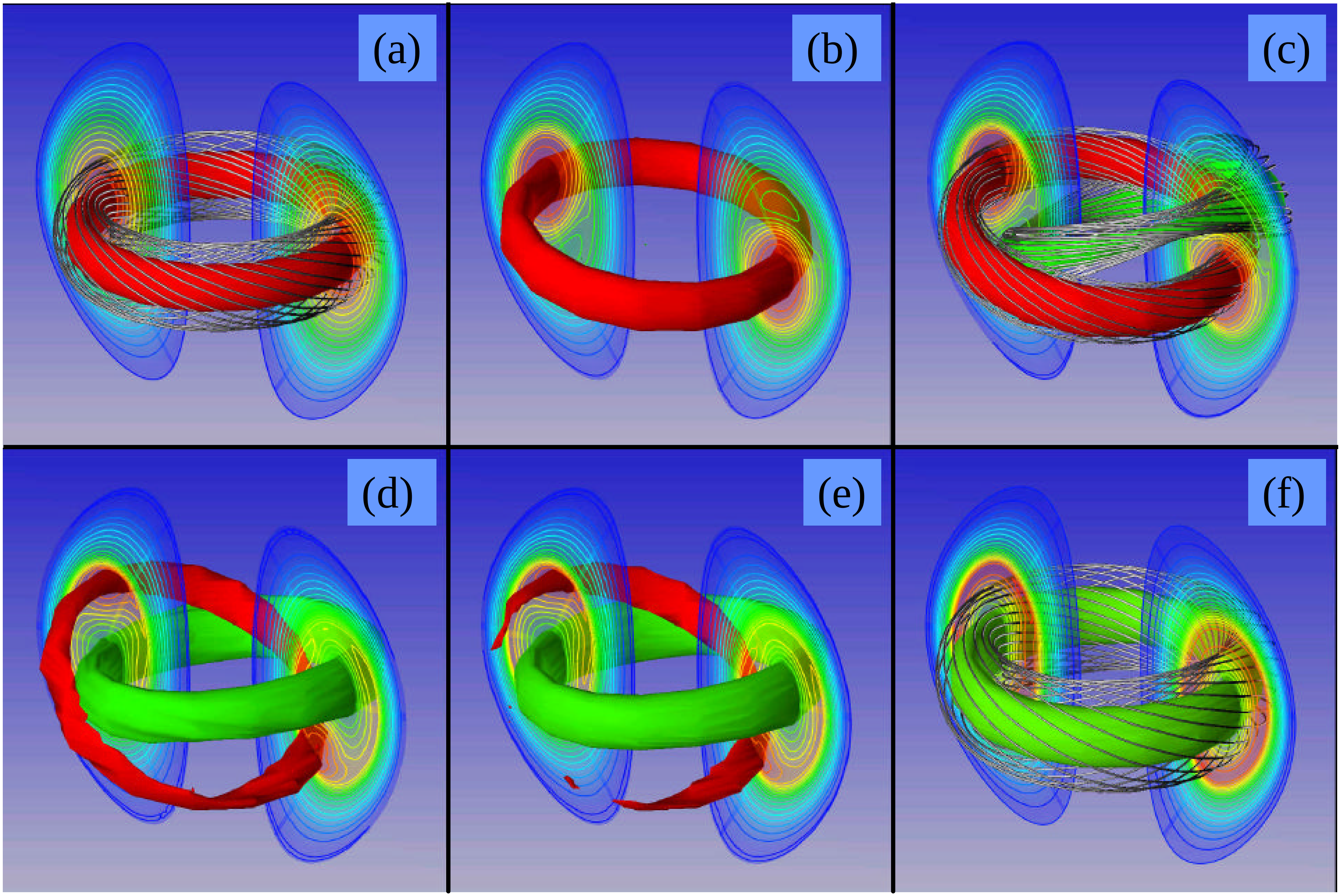
$(\rho^*)^{-1} = 40$ $\quad$ $v_A = 10^8$ cm/sec $\quad$ $T_{discharge} = .025$ ms $= 10^5\,\tau_A$

$S = 4 \times 10^4$ $\quad$ $\tau_A = a/v_A = 2. \times 10^{-7}$ s $\quad$ PLT 10 Chord soft-X-ray

12 point Thompson

“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

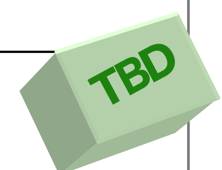


AVS movie of M3D calculation courtesy of W.Park and S.Klasky

Integrated Simulation and Optimization of Fusion Systems Workshop

September 17,18, 2002

San Diego, CA

Fundamentals APPLICATIONS EXAMPLE Focused Integration Initiatives	[Fundamentals] - RF Heating and CD - Neutral Beams - Alpha Particles - Neutral Gas - Pellet Injection SOURCES	[Fundamentals] - PIC-based - Vlasov-based - Electron Physics - Core + Edge TURBULENCE	[Fundamentals] - 2-fluid - Hybrid PIC+fluid - Full Kinetic Ions - 2D + 3D Equilibria X-MHD	[Fundamentals] - n, T, v, J, E_r evolution equations - Geometries: Axisymmetric & non- - Grad-Hogan *t* evolution 1 1/2 D TRANSPORT	[Fundamentals] -ab initio defect/ impurity interactions - Bond Order Potentials - 3D Dislocation Dynamics - Fracture Mechanics MATERIALS	[Fundamentals] - Synthetic Diagnostics INTERPRETATION & ALGORITHMS	[Fundamentals] - Parallel Data SOFTWARE ARCHITECTURES
PLASMA EDGE - First wall - Pedestal Physics - Edge Localized Modes - Open Field Lines - Divertor Ablation	- Wall Interaction - Neutral Gas - Atomic Physics	- Edge Turbulence Code (fluids based, and kinetics based) -Incl/ Capabilities for Open **B**-field Lines	- 2D or 3D Equilibria w/ Open Field Lines - ELM Physics	- Wall Models	- Sputtering and Vaporization - Corrosion and Compatibility -Helium Embrittlement	- Expt. Data Packaging - …	Define code modules Identify shared computation modules External data representations
TURBULENCE on the TRANSPORT TIMESCALE - Gyrokinetic Ions - Electron Physics - Evolve density, T	- RF H & CD - Neutral Beams	- PIC-based - Vlasov-based - Electron Physics - Core + Edge	- 2D & 3D Equilibria	- 1 1/2 D Solvers - Anomalous Heating and Diffusion	- Penetration - *Zeff*		Data location and transport services Metadata systems for large data management Design external interfaces for modules
ISLAND GROWTH - Sawtooth Growth - Neoclassical Tearing	- NTM Feedback - RF Stabilization of Island Sawteeth	- Kinetic Ion Model -Transport in Island Geometry - Fluid Electrons	- 3D Evolving (x,t) Equilibria - Island Growth - Alpha-particle - driven Multi-Mode Resonances	- Model of Remainder of the Plasma	- *Zeff*		Select systems for - code archiving and management - configuration and building - testing frameworks
WHOLE DEVICE MODELING - Entire Discharge - Evolving (2D, 3D) Equilibria - Core + Edge - External Circuits	- Simplified Models of All Sources	- Simplified Models of Profile Transport (e.g., GLF23,MMM95) -Edge Model -Alpha-particle Scalar Convection -Alpha-particle Thermal Transport	- Simplified Models of Sawteeth and Islands - 2D and 3D Equilibria	- Circuit Equations & Feedback Systems - External Structures - Access to Expt. Data	- Penetration - *Zeff*		
OPERABLE CODE CAPABILITY							

Draft: ISOFS Workshop

September 17, 2002

0900 - 0930	Intro + Overview of Report 1
0930 - 1030	Example Integrated Initiatives
1030 - 1045	*Break*
1045 - 1110	1: Sources, *D.Batchelor*
1110 - 1135	2: Turbulence, *?????*
1135 - 1200	3: X-MHD, *D.Schnack*
1200 - 1330	*Lunch*
1330 - 1355	4: 1 1/2 D Transport, *W.Houlberg*
1355 - 1420	5: Materials, *??????*
1420 - 1440	*Break*
1440 - 1710	Cross-Cutting I: FOCUSED INTEGRATION INITIATIVES *[Examples]* - Plasma Edge; session/ discussion led by *R.Stambaugh* - Turbulent Transport session/ discussion led by *R.Cohen* - Island Growth; session/discussion led by *S.Jardin* - Whole Device; session/ discussion led by *?????*
1710 - 1730	Wrap-up - summary for day
1730 - 1930	RECEPTION

September 18, 2002

0900 - 0915	Welcome
0915 - 0945	"Interpretation & Algorithms" *[invited talk(s)]*
0945 - 1015	"Architectures" *[invited talk(s)]*
1015 - 1030	*Break*
1030 - 1200	Cross-Cutting II (a): - Interpretation & Algorithms - Architectures
1200 - 1330	*Lunch*
1330 - 1430	Cross-Cutting II (b): - Architectures - Interpretation & Algorithms
1430 - 1500	Summary Drafting
1500 - 1515	*Break*
1515 - 1535	1: FII Summary - Plasma Edge, *R.Stambaugh*
1535 - 1555	2: FII Summary – Turbulent Evolution, *R.Cohen*
1555 - 1615	3: FII Summary - Island Growth, *S.Jardin*
1615 - 1635	4: FII Summary – Whole Device, *???????*
1635 - 1655	5: Architectures
1655 - 1715	6: Interpretation & Algorithms/ User Interfaces
1715 - 1730	Wrap-up

Summary and recommendations:

- Belova paper demonstrates equivalence of the 2-forms of the gyroviscous cancellation allowing formulation either in terms of guiding center velocity V or ion velocity V_i
- Nature of approximation in neglecting gradient terms in ion-momentum equation (HM) should be clarified
- SP neglect of higher-order polarization drift terms ($V_* \rightarrow V_{di}$) removes Hall term in Ohm's law and hence remove whistler waves. Effect on applications should be clarified.
- Energy conservation is an outstanding problem since there is no agreed upon expression for $\Pi:\nabla V$
- Need conservative expression for $\nabla \bullet \Pi$ including gradients and curvature terms in B: (for both GV and N_e and N_i parts)
- CEMM goal should be to develop and document "standard" sets of equations: compare and contrast