

Reduced Stability Models Used in Integrated Modeling Simulations of Tokamaks

Glenn Bateman¹

with contributions from

**A.H. Kritz¹, F. Halpern¹,
T. Onjun² and A.Y. Pankin³**

¹Lehigh University Physics Department, Bethlehem, PA 18015, USA

²Sirindhorn International Institute of Tech., Pathumthani 12121, Thailand

³SAIC, San Diego, CA 92121, USA

Workshop Toward an Integrated Plasma Simulation
SWIM

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Large Scale Instabilities Considered Within Integrated Modeling Simulations

- **Edge Localized Modes (ELMs)**

- Dynamic pedestal and ELM models used in JETTO and ASTRA codes
- Periodically removes pedestal, limits pedestal height

- **Neoclassical tearing modes (NTMs)**

- ISLAND module currently used in the BALDUR code
- Changes profiles, reduces confinement, can cause disruptions

- **Sawtooth oscillations**

- Porcelli trigger and Kadomtsev reconnection models
- Periodically mixes central plasma profiles, spreads heating profile

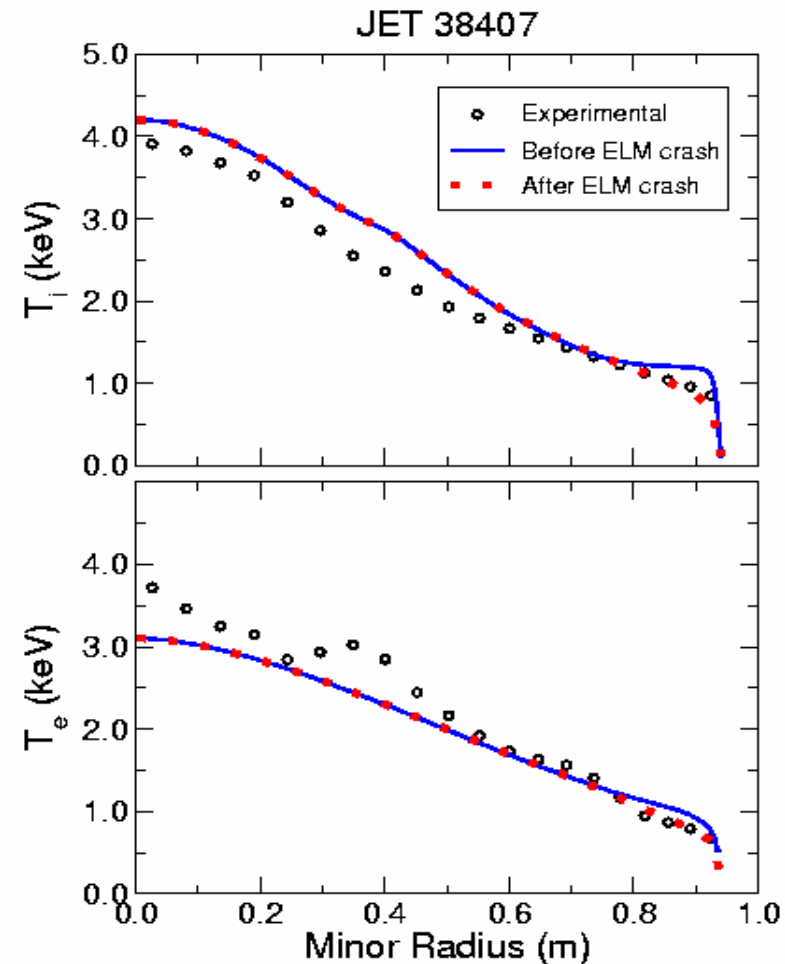
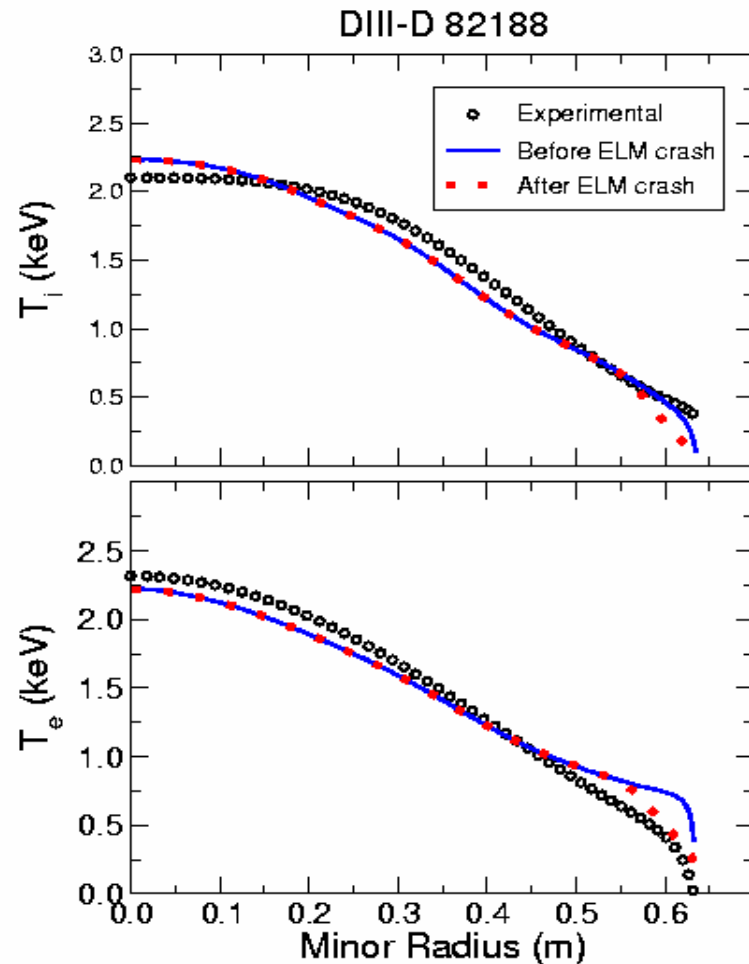
- **Vertical instability**

- Part of the disruption model in the TSC code
- Can produce large forces on walls due to “halo currents”

Comparison Between Models Used in JETTO and ASTRA Codes for Pedestal and ELMs

	Model in JETTO	Model in ASTRA
Transport through pedestal:	Ion thermal neoclassical at top of pedestal for all channels of transport	Flow shear stabilization of ITG/TEM and resistive ballooning modes + ETG + neoclassical ion transport
Width of pedestal:	Prescribed width or scaling proportional to ion thermal Larmor radius	Width determined self-consistently from flow shear stabilization
ELM trigger:	MHD instability calibrated using HELENA and MISHKA ideal MHD codes	MHD instability. Recently, trigger model developed using BALOO, ELITE & DCON codes
ELM crash:	Transport transiently increased by factors of 300 (thermal) and 100 (particle)	Profiles changed abruptly between time steps using empirical energy loss scaling

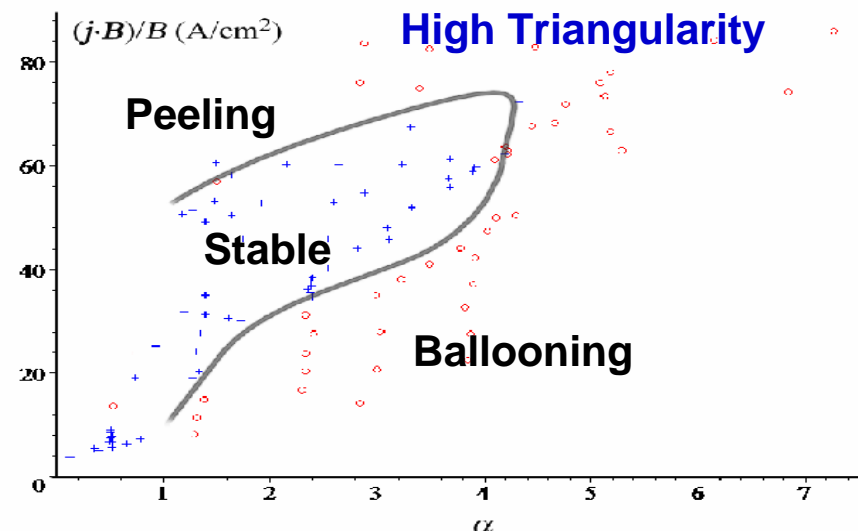
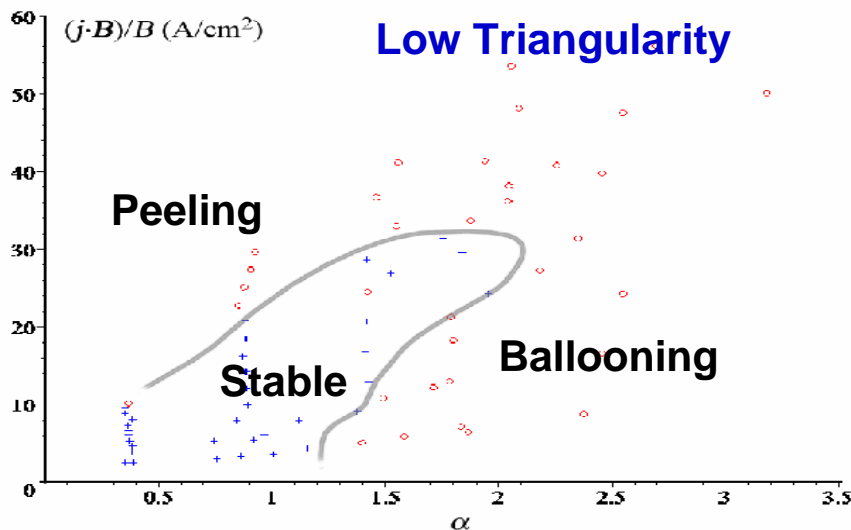
Simulation of Profiles, Pedestal, and ELMs



- Lehigh model for transport, pedestal and ELMs used in ASTRA simulations of DIII-D and JET discharges

Improved MHD ELM Trigger Stability Criteria

- Recently, BALOO, ELITE, and DCON ideal MHD stability codes used to parameterize the ELM trigger in ASTRA
 - BALOO for high n modes, ELITE for intermediate and high n modes, and DCON for low n modes
 - Two DIII-D equilibria were considered — low and high triangularity
 - The lower and upper stability boundaries were parameterized by polynomials and ASTRA simulations were carried out
 - A.Y. Pankin *et al.*, Czech Journal of Physics 55 (2005) 367



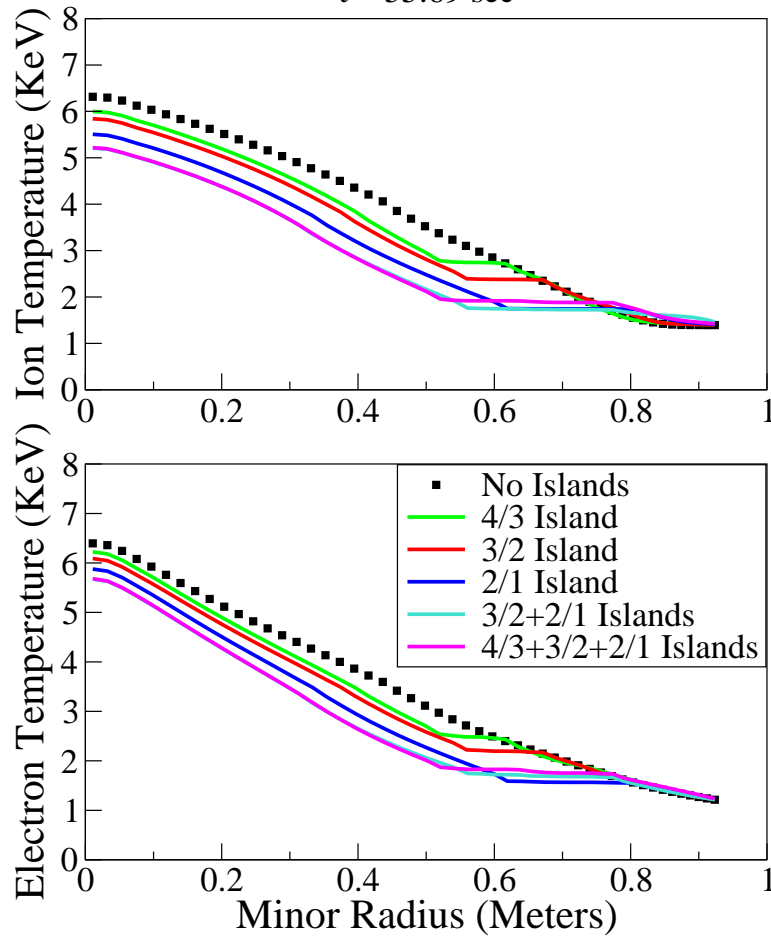
Neoclassical Tearing Mode ISLAND Module

- Magnetic islands driven by neoclassical saturated tearing modes can produce increased radial transport and disruptive instabilities in tokamak discharges
- The ISLAND module computes multiple island widths driven by saturated neoclassical tearing modes
 - ISLAND module in NTCC Module Library: <http://w3.pppl.gov/NTCC>
 - C. Nguyen, G. Bateman and A.H. Kritz, *Phys. Plasmas*, 11, 3460 (2004)
 - Currently used in BALDUR simulations of tokamaks
 - Fast enough to use in long simulations (300 second ITER simulations)
- Quasi-linear, steady state method in the ISLAND module
 - Derivation based on perturbation of an axisymmetric equilibrium
$$\vec{J}^1 \times \vec{B}^0 + \vec{J}^0 \times \vec{B}^1 = \nabla p^1 \quad \nabla \cdot \vec{B}^1 = 0 \quad \mu_0 \vec{J}^1 = \nabla \times \vec{B}^1$$
 - Uses Hamada-like coordinates for arbitrary aspect ratio, plasma cross-sectional shape and β

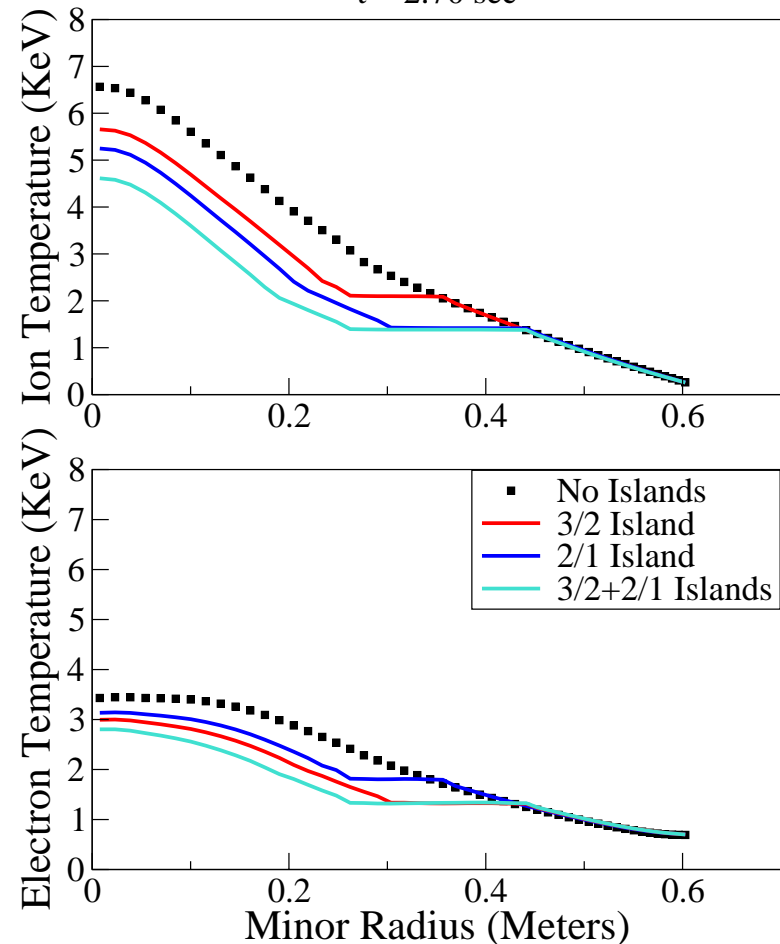
Effect of NTMs on Temperature Profiles

- BALDUR simulations of JET and DIII-D discharges in which temperature profiles are affected by NTM islands

JET 33131
t = 55.69 sec



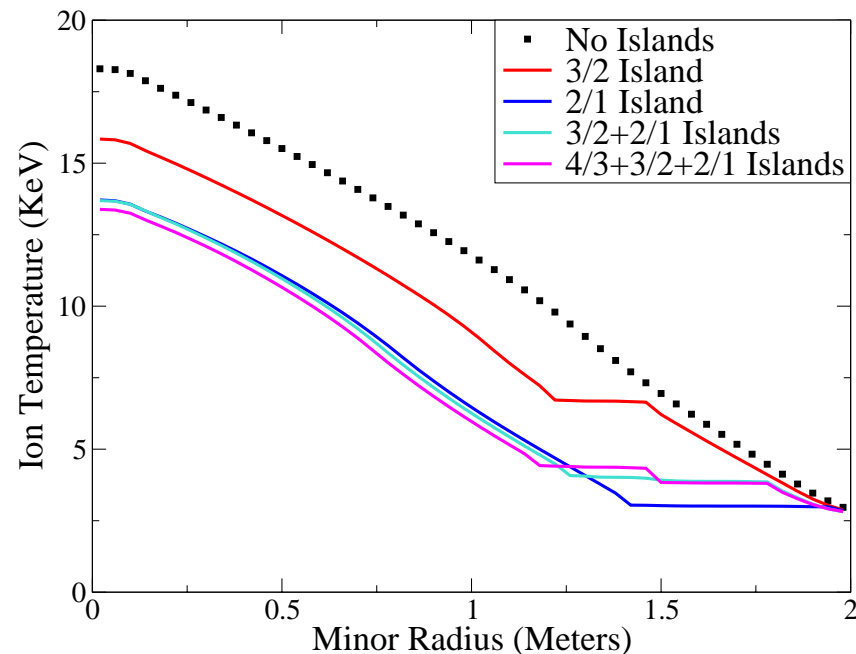
DIII-D 77559
t = 2.70 sec



Effect of NTM Saturated Islands in ITER

- **BALDUR simulations of ITER:**
 - **Self-consistent treatment of magnetic islands and sawtooth oscillations**
 - **Standard H-mode scenario with predicted static pedestal**
 - **G. Bateman, T. Onjun and A.H. Kritz, Plasma Phys. Control Fusion 45 (2003) 1939**
- **Fraction of plasma radius covered by magnetic islands consistent with estimates made by C. Hegna at 2002 Fusion Snowmass meeting**
- **Sawteeth with large mixing radius might seed islands**

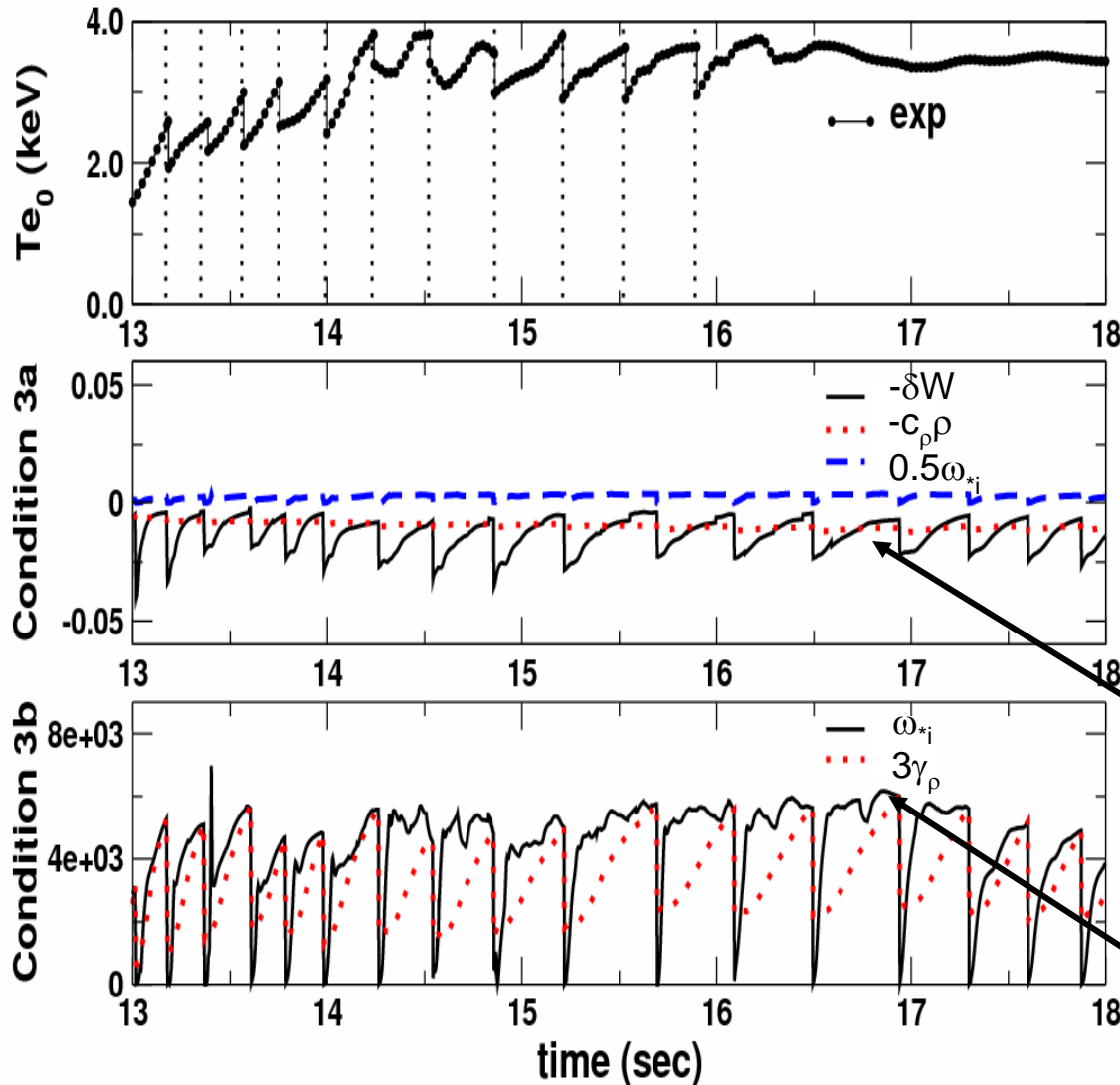
Scenario	W_{43}/a	W_{32}/a	W_{21}/a	$T_{i,0}$	Q	β
No Islands	-	-	-	18.3	10.6	2.5
3/2	-	0.13	-	15.8	6.2	2.0
2/1	-	-	0.25	13.7	2.8	1.4
3/2+2/1	-	0.10	0.14	13.6	2.6	1.5
4/3+3/2+2/1	0.06	0.07	0.15	13.3	2.4	1.4



Sawtooth Trigger and Crash Models

- **Porcelli model used to trigger each sawtooth crash**
 - Three criteria tested at $q=1$ surface for onset of $m=1$ instability
 - Kink mode stabilized by fast ion orbital precession
 - Ideal kink mode stabilized by diamagnetic rotation
 - Diamagnetic stabilization of $m=1$ resistive tearing mode
 - F. Porcelli et al., Plasma Phys. and Controlled Fusion 38, 2163 (1996)
- **Porcelli model used for partial magnetic reconnection**
 - Produces $q=1$ within an annular region after each sawtooth crash
 - No predictive model yet for width of annular $q=1$ region
- **Kadomtsev model used for mixing energy density, particle density and fast ion density within sawtooth mixing region**
 - B. Kadomtsev, Sov. J. Plasma Phys. 1 (1975) 389 — still works well
 - It is assumed that fast ions are mixed within sawtooth mixing region, but not ejected from the plasma

Sawtooth Criterion 3 for JET 33140



- Experimental data with vertical dotted lines marking sawtooth crash times

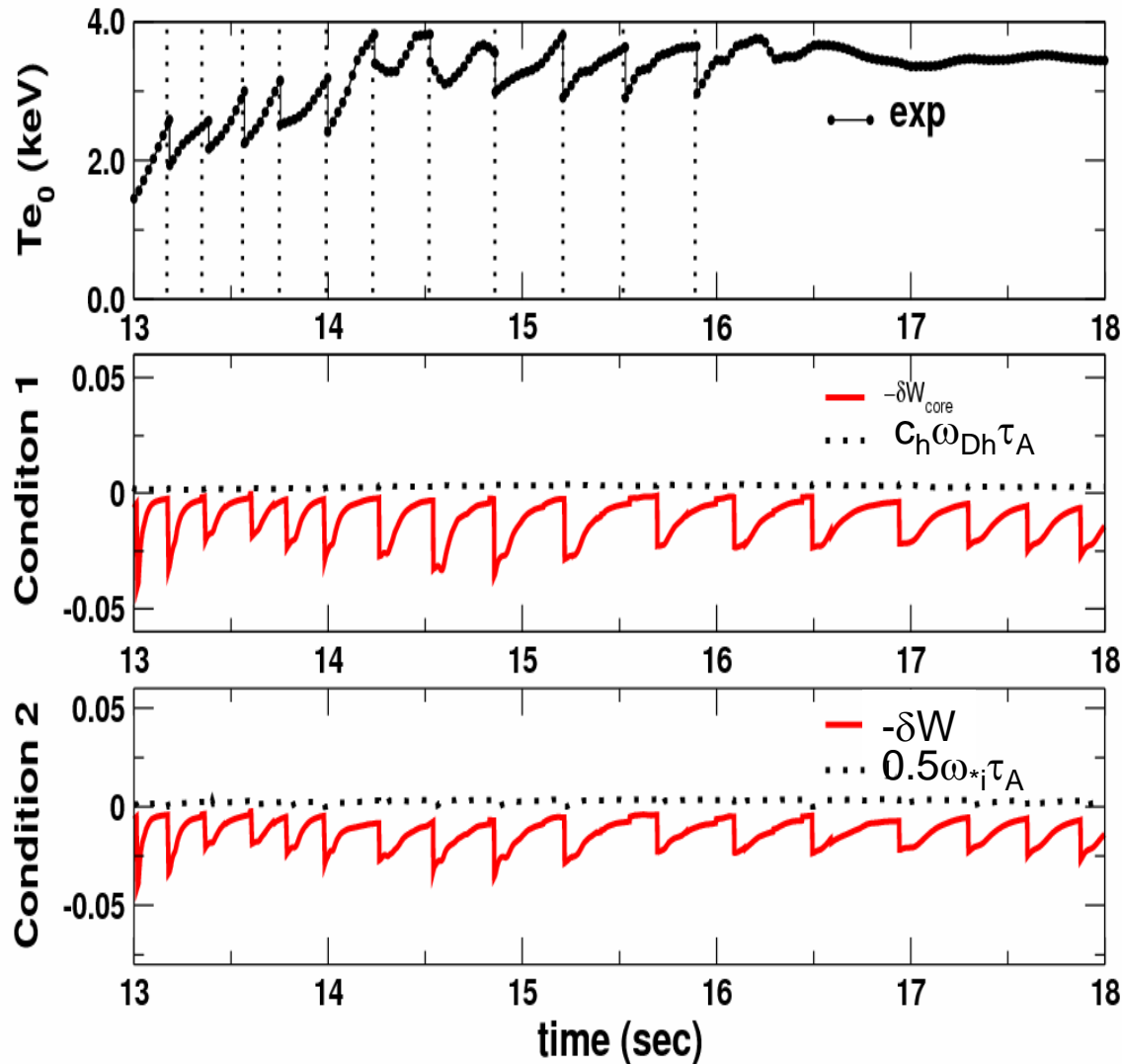
- In this simulation, all the sawteeth are triggered as a result of criterion 3 (tearing modes)

- Two parts of criterion 3 need to be satisfied for sawtooth crash to occur

a) $-c_{\rho}\rho < -\delta W < 0.5*\omega_{*i}$
(black line between the red and blue)

b) $\omega_{*i} < 3*\gamma_{\rho}$
black red

Sawtooth Criterion 1 and 2 for JET 33140



Experimental data with vertical dotted lines marking sawtooth crash times

In this simulation, sawteeth are not triggered by fast ions (criterion 1)

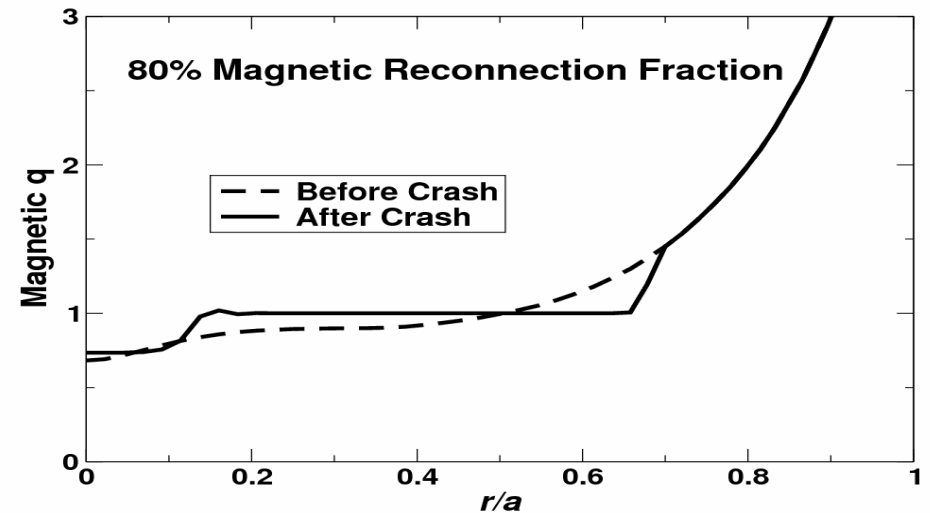
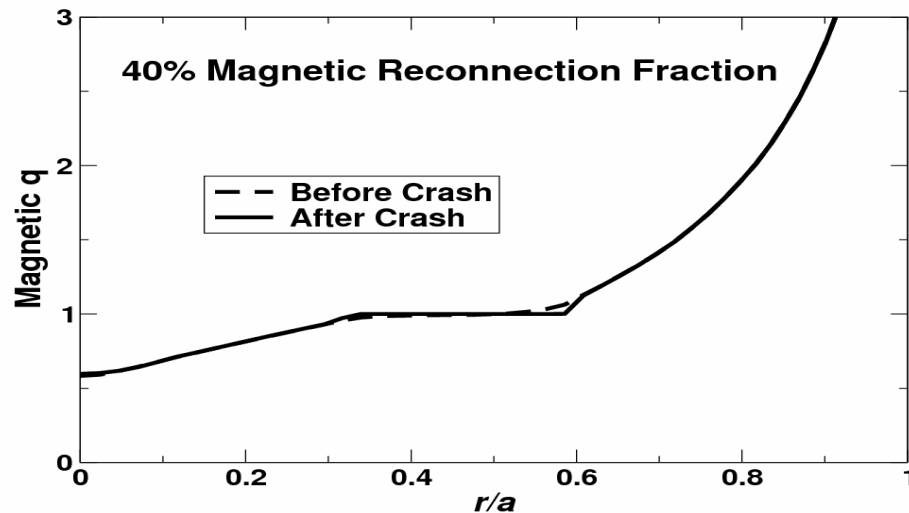
$$-\delta W_{\text{core}} < C_h \omega_{Dh} \tau_A$$

Red curves do not cross black dotted lines

In this simulation, sawteeth are not triggered by the ideal mode with diamagnetic stabilization (criterion 2)

$$-\delta W < 0.5 \omega_i \tau_A$$

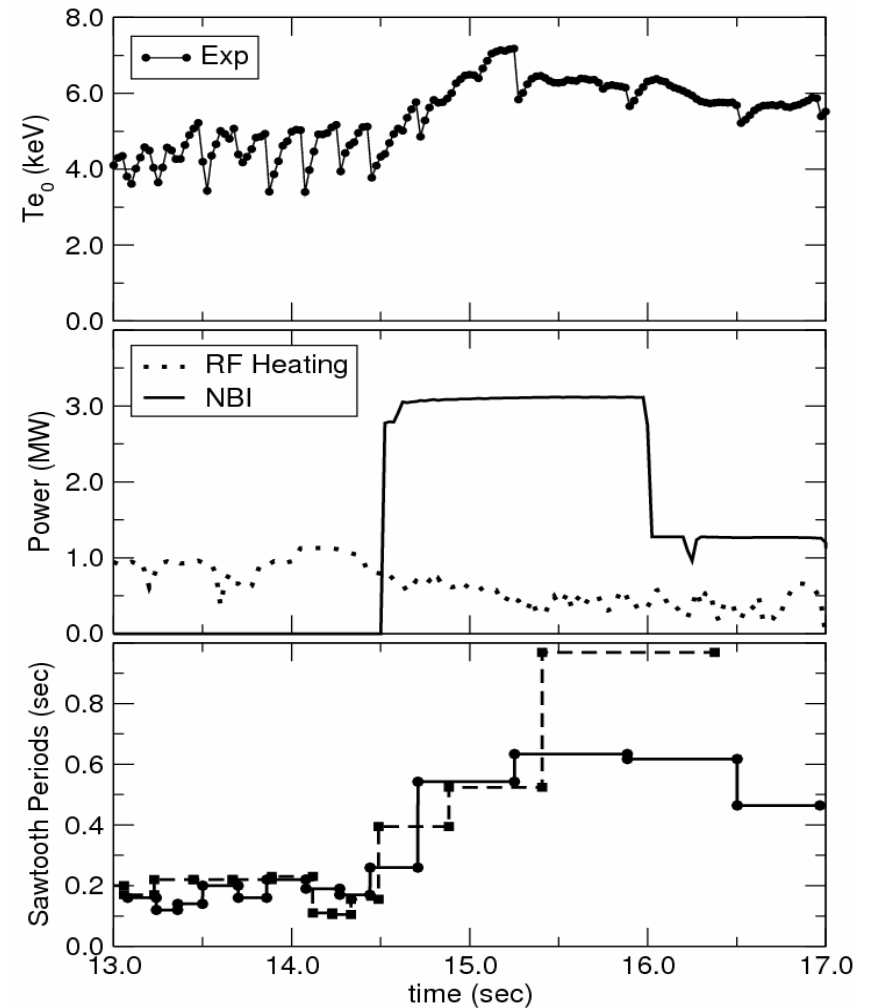
Magnetic q Profiles Before and After Crash



- Magnetic q -profile is flattened at $q=1$ in annular region
- “Magnetic Reconnection Fraction” is defined as the fraction of the mixing radius over which $q=1$ after sawtooth crash
- When testing for the next sawtooth crash, the $q=1$ radius is taken to be at the center of the $q=1$ annular region
- Current density diffusion restores magnetic shear within annular region during the sawtooth cycle

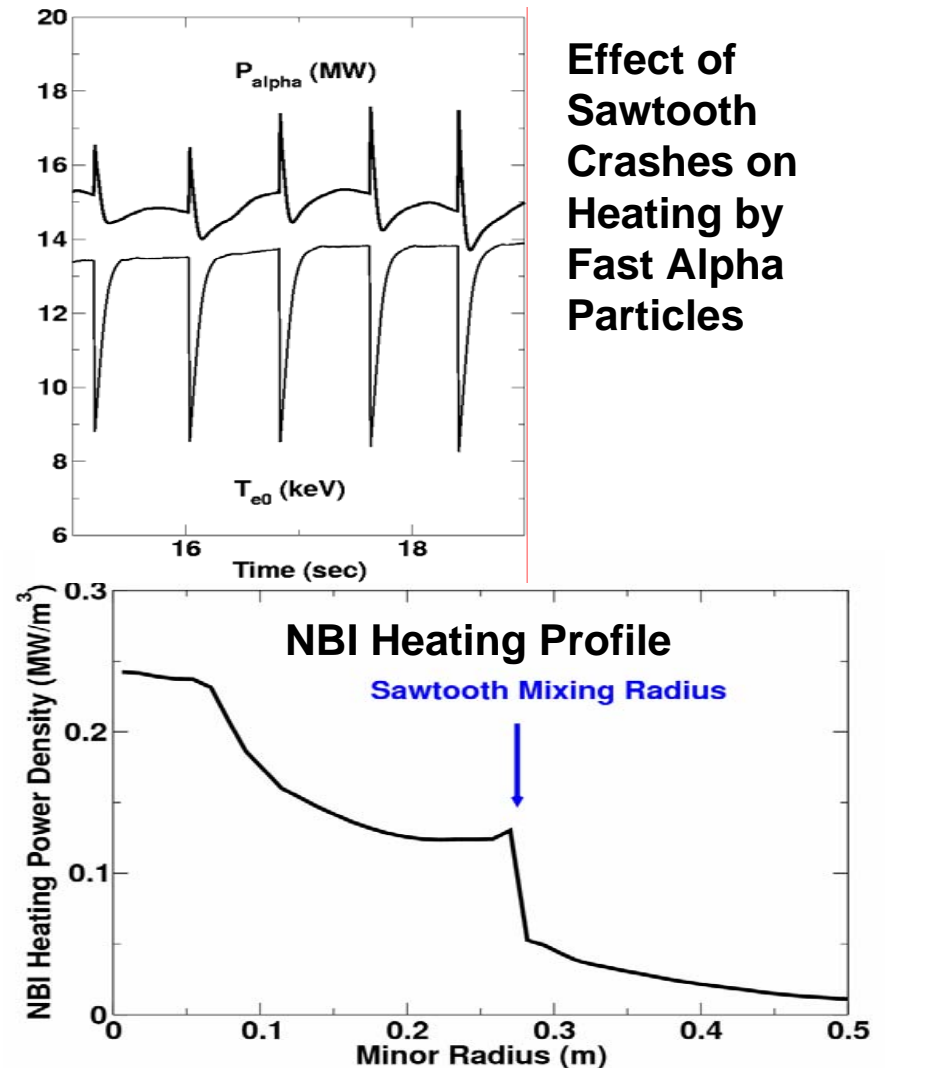
Sawtooth Period Generally Increases With Increasing Heating Power

- JET 33131 shown at right
 - Central electron temperature from experimental data in top panel
 - Frequent sawtooth crashes extend to less frequent crashes as heating power is increased
 - Heating power in central panel
- Sawtooth period levels from experiment and simulation shown as a function of time in lower panel
 - 80% magnetic reconnection used in simulation
 - Each line segment show the sawtooth period (vertical axis) between beginning and end of each sawtooth cycle



Examples of Coupling Between Different Physical Phenomena

- Sawtooth oscillations affect most central plasma profiles
 - Sawtooth crashes transiently change slowing down time for fast ions
 - Sawtooth crashes cause redistribution of fast ions
 - Spreads out heating profiles
- Edge conditions affect core temperature & density profiles
 - Particularly true for profiles controlled by stiff transport
 - H-mode pedestal height strongly affects profiles and confinement



How Reduced Stability Models can be Improved

- **Model needed for the effect of each ELM crash**
 - How are the plasma edge profiles changed by an ELM crash?
 - Where does the pedestal current density go during an ELM crash?
 - How much current density goes to the wall or into the plasma?
- **Improved models needed for sawtooth trigger and crash**
 - Can a predictive model be developed for the fraction of magnetic reconnection during each sawtooth crash?
 - Improved sawtooth trigger model needed for hot, low collisionality plasmas with large fraction of fast ions
 - Are fast ions ejected from plasma by sawtooth crashes?
- **Neoclassical tearing mode models must be improved:**
 - Must include effects of differential island rotation
 - Can initiation of seed islands be predicted?
 - Do islands become electrostatically charged as fast ions in islands are accelerated to high energies with wide banana orbits?