The Internal m=1 Mode

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The Internal m=1 mode[1]

- Why do we care about m=1 modes in ITER ?
- The Porcelli-Boucher-Rosenbluth (PBR) Model
- Verification of the PBR Model
- Shortcomings of the PBR Model
- Excitation of other modes
- Prediction of inversion radius
- Status and plans for 3D Extended-MHD modeling
- Activities planned for the Fusion Simulation Project: Simulation of Wave Interaction with MHD (SWIM)
- Discussion

[1]Emphasis on progress since Snowmass

Why do we care about m=1 modes in ITER?

- In normal operation, sawteeth are expected in ITER with $r_1/a \sim 42\ \%$ with a period of 20-40 sec.
- These large sawteeth could excite other modes (NTM), and might lead to increased disruptivity, and ash accumulation.
- It is possible to increase the frequency and decrease the period of these large sawteeth by applying ECRH or ICRH near the q=1 surface.
- It is prudent to develop predictive models to design such a system for ITER as an operational tool.

The Porcelli-Boucher-Rosenbluth (PBR) Model (1996):

In a plasma with $q_0 < 1$, the sawtooth is triggered when one of the following criteria satisfied:

$$-\delta \widehat{W}_{core} > c_h \omega_{Dh} \tau_A \quad (1)$$

High-energy trapped particles do not complete many orbits within a perturbation time

$$-\delta \widehat{W} > 0.5 \omega_{*i} \tau_A \quad (2)$$

(global) Internal kink mode not stabilized by diamagnetic effects

$$0.5 \omega_{*i} \tau_A > -\delta \widehat{W} > -c_\rho \widehat{\rho} \qquad (3a)$$

$$and \quad \max(\gamma_\rho, \gamma_\eta) > c_r (\omega_{*i} \omega_{*e})^{1/2} \quad (\text{or } s_1 > s_{crit}) \qquad (3b)$$

Resistive (or semi-collisional ion-kinetic, or collisionless) internal kink mode not stabilized by kinetic layer effects

$c_h, c_\rho, c_r,$ (order unity)

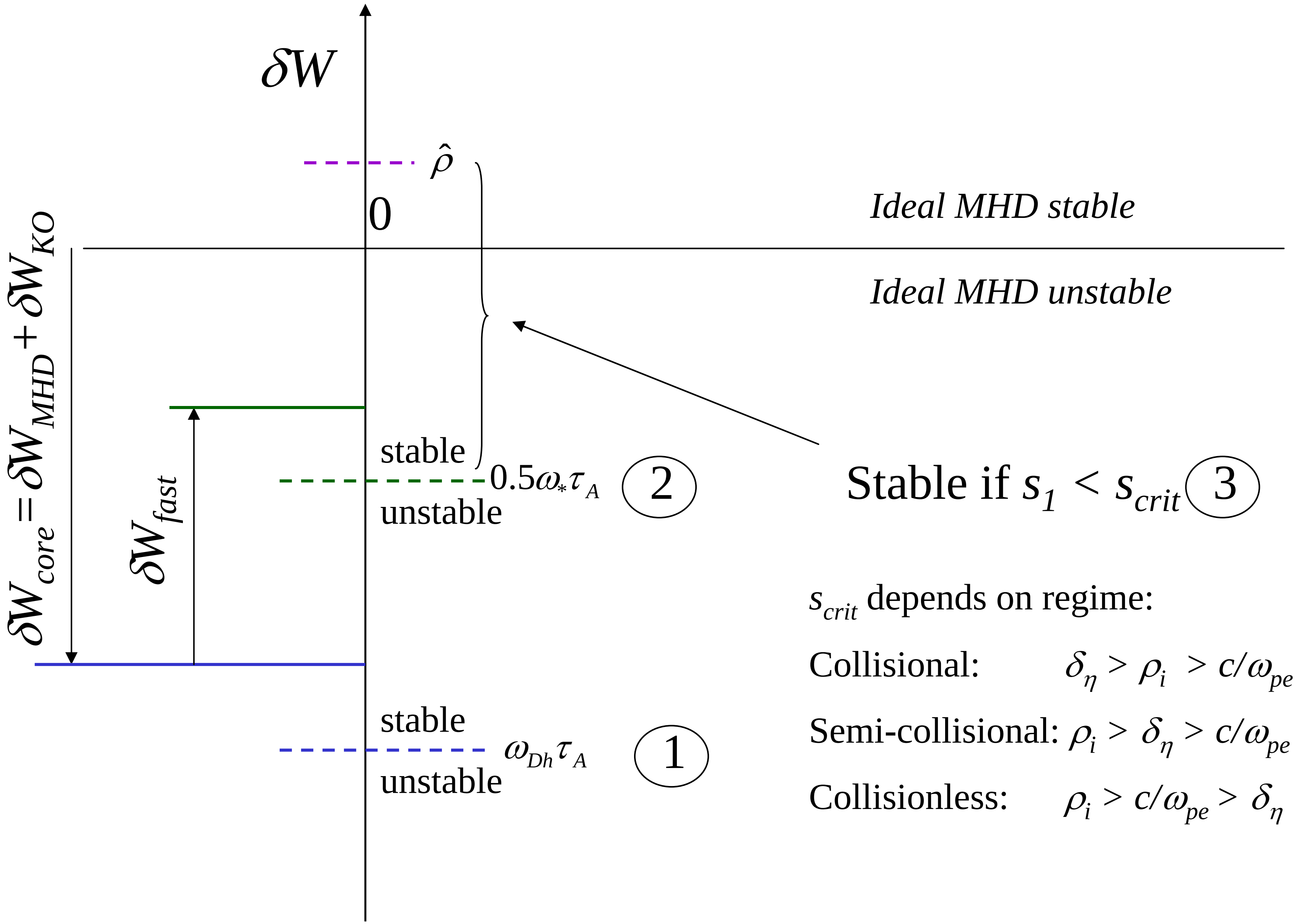
Incomplete or complete relaxation: reconnection starts as in Kadomtsev. As island reaches a critical width w_{crit}, widespread magnetic turbulence develops.

$$\delta W_{core} = \delta W_{MHD} + \delta W_{KO}$$

$$\delta W = \delta W_{core} + \delta W_{fast}$$

They give approximate forms for the δWs, but others have replaced these with more exact forms (recommended)

The Porcelli-Boucher-Rosenbluth criteria:



s_{crit} depends on regime:

Collisional: $\delta_\eta > \rho_i > c/\omega_{pe}$

Semi-collisional: $\rho_i > \delta_\eta > c/\omega_{pe}$

Collisionless: $\rho_i > c/\omega_{pe} > \delta_\eta$

Verification of the PBR Model

- JET: experimental evidence for localized CD shortening the periods of fast-ion-induced long sawteeth on JET: Fast ions from minority ICRH stabilize, ICCD near q=1 destabilizes. Interpreted as change in shear s_1, and thus reduction in $\delta W_{fast} \sim 1/s_1$ (Criteria 1)
  - Eriksson, PRL **92** 235004 (2004)
- JET: PBR model gives sawtooth period to within 20% as period varies by factor of 5 during NBI ramp. Agreement with Criteria (1) and both (3a) and (3b): Complete reconnection model.
  - Angioni et al PPCF **44** 205 (2002)

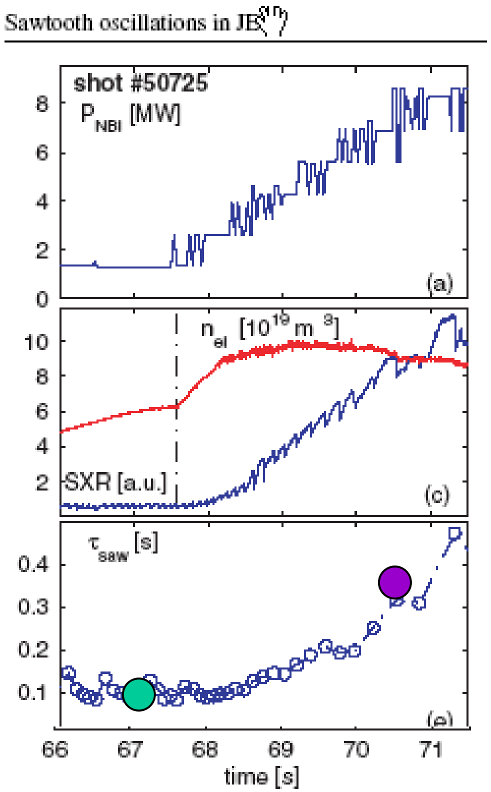
- TCV: experiment and modeling showing stabilization of sawtooth with ECH on TCV. Good agreement with Porcelli model: resistive MHD stabilized by ω* effects. Unstable for $s_1 > s_{1crit}$. (Criteria 3b) Complete reconnection. Co-CD and heating are destabilizing inside q=1.
  - Angioni, et al NF **43** 455 (2003)
- TCV: experiments with ECRH in different shaped plasmas show qualitative agreement with Criteria (2) for "bad shapes" (high κ, low δ) and qualitative agreement with Criteria 3b for "good shapes" (low κ, high δ) when more accurate expression for δW_{MHD} was used
  - Reimerdes, et al. PPCF 42 629 (2000)

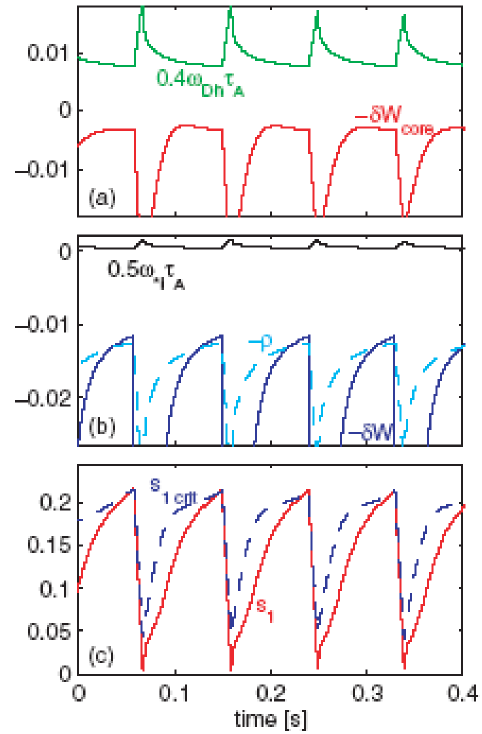
- FTU: semi-collisional analogue of $s_1 > s_{1crit}$. (Criteria 3b) correlates very well with onset of sawteeth in both ohmic and ECRH heated plasmas .
  - Cirant et al, Plasma Phys. Control Fus. 41 B351 (1999)

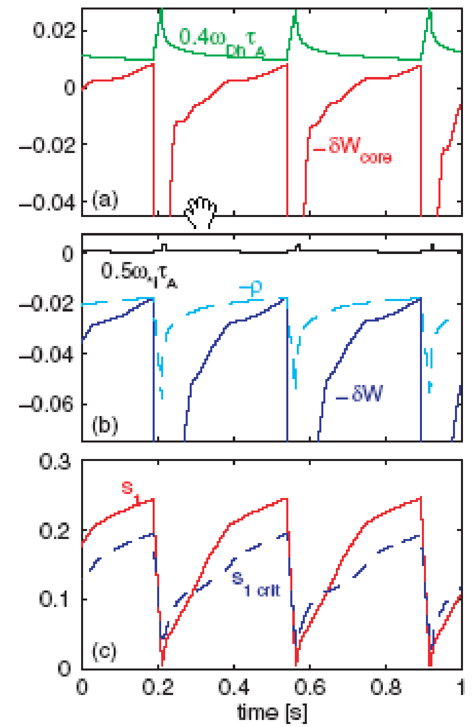
- ASDEX: decrease ST period with co-ECCD central dep, increase with off-axis co-ECCD: qualitative agreement with (Criteria 3b)
  - Muck, PPCR 47 1633 (2005)

- TFTR: collisionless analogue of $s_1 > s_{1crit}$. (Criteria 3b) correlates very well with onset of sawteeth in supershot discharges with peaked density profiles .
  - Levinton et al Phys. Rev. Lett. **72** 2895 (1994)

Example of detailed comparison of PBR model with JET ramp-NBI experiments.





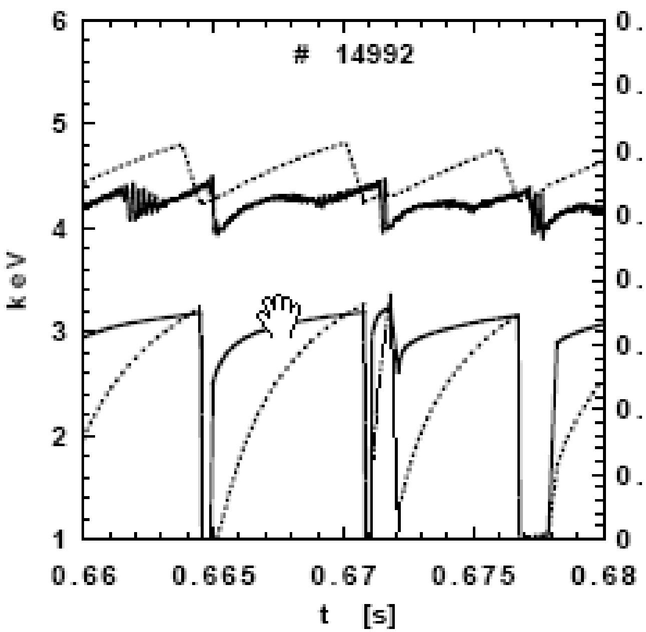


t=67, τ~0.1 ● t=70.5, τ~0.35 ●

"The simulated sawtooth periods …are found in every case to be …within 20%..[of the] experimentally observed sawtooth periods..[where]…the period at the end of the NBI power ramp-up can be up to 5 times longer than…at the beginning of the ramp."

C. Angioni, et al, PPCF **44** (2002) 205

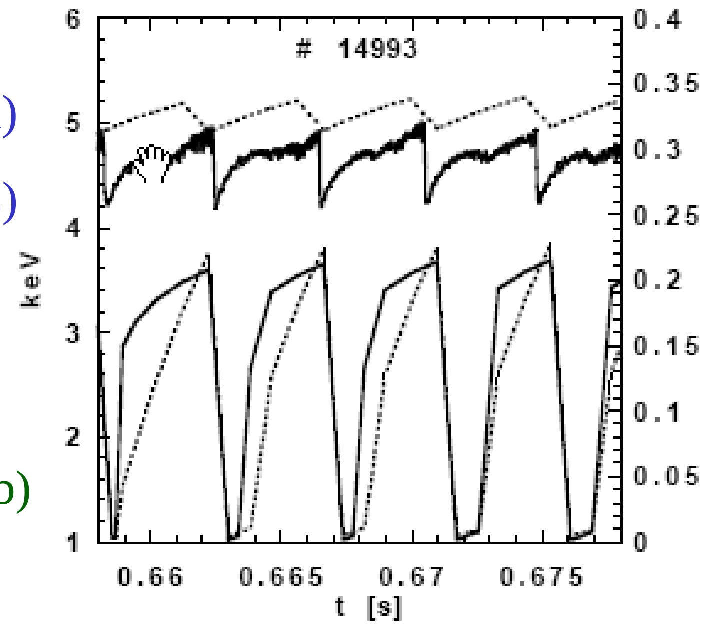
Comparison of simulated and experimental sawtooth periods in FTU during ECCD



Exp (solid)

Sim: (dots)

Critical shear criteria (3b)



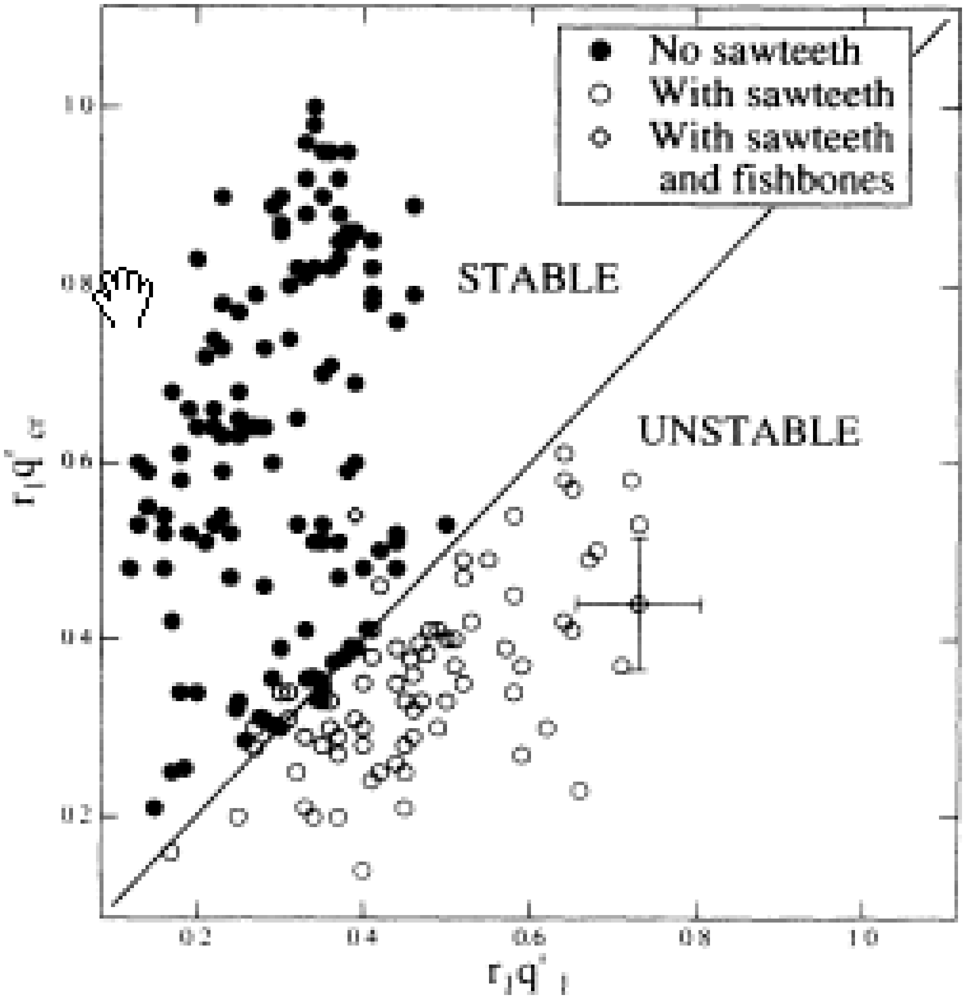
Co-ECCD in FTU

Counter-ECCD in FTU

Same power of ECRH is applied near q=1 surface

Porcelli et al., **41** (2001) 1207

TFTR: Correlation of the critical shear criteria (3b) with the presence or absence of sawteeth.



Levinton, Zakharov, et al, PRL 72 2895 (1994)

Summary of the experimental tests of the PBR model

PBR Criterion tested

Experiment	**Heating**	**(1)**	**(2)**	**(3a)**	**(3b)**	**regime**
JET	ICRH	x				Semi-collisional
JET	NBI	x		x	x	Semi-collisional
TCV	ECH		x[1]		x	Resistive
FTU	ECH				x	Semi-collisional
ASDEX	ECH				x	Semi-collisonal
TFTR	NBI				x	collisionless

[1]NOTE: used more accurate formula for δW_{MHD}

(Wahlberg 1998 *Phys. Plasmas* **5** 1387)

Shortcomings of the PBR Model

- JET: Necessary to do more detailed calculation of fast-particle stabilization term: shaped plasmas, rotation, and beam ion distribution.
  - T Graves, PRL, 92 185003 (2004), Graves, Phys Plasmas **10** 1034 (2003) Graves, Phys Plasmas 12 090908 (2005)
- Analytic form for Alpha-particle stabilization not accurate for ITER shapes when compared to detailed numerical results.
  - Fu, et al, to appear in Phys Plasmas (2006)
- ASDEX-U: during the crash phase, reconnection is incomplete and a large island persists that fully reconnects on a slower timescale after the crash. Consistent with a recent sawtooth reconnection model
  - Letsch, Nuc. Fus. 42 1055 (2002)
- TCV: different types of incomplete reconnection during intense ECH experiments. Period in general agreement with theory:
  - Furno, et al Nuc. Fus. 41 403
- Stabilizing effect of precession of circulating alpha-particles should be added to PBR expression. Also, circulating particles can help stabilize nonideal modes.
  - Kolesnichenko, et al Phys. Plasmas 12 022501 (2005)
- Crash time and details about the crash physics are not addressed.
  - (see H. Park, et al., submitted to Phys Fluids 2006)

Overall conclusion is that the basic PBR model is valid, but the individual terms need to be evaluated carefully:

$$-\delta \widehat{W}_{core} > c_h \omega_{Dh} \tau_A \qquad (1)$$

$$-\delta \widehat{W} > 0.5 \omega_{*i} \tau_A \qquad (2)$$

$$0.5 \omega_{*i} \tau_A > -\delta \widehat{W} > -c_\rho \widehat{\rho} \qquad (3a)$$

$$and \quad \max(\gamma_\rho, \gamma_\eta) > c_r (\omega_{*i} \omega_{*e})^{1/2} \quad (\text{or } s_1 > s_{crit}) \qquad (3b)$$

$$\delta W_{core} = \delta W_{MHD} + \delta W_{KO}$$

$$\delta W = \delta W_{MHD} + \delta W_{KO} + \delta W_{fast}$$

May require numerical evaluation of δW_{MHD} , δW_{KO} , δW_{fast} at each timestep in a transport code (which is becoming increasingly feasible as computers get faster)

Excitation of other modes:

- Tore Supra: Reconnection associated with monster sawtooth crash causes large current density gradient which drives resistive (3,2) mode linearly unstable.
  - Maget, et al. PPCF **47** 357 (2005)

- JET: Discharges with significant ICRF generally have a low threshold for triggering of NTM (monster sawtooth)
  - However, when the resonance position ..has been carefully chosen to destabilize sawteeth (just outside q=1), the β_{Nonset} is increased significantly over its value with NBI-only.
    - Westerhof, et al, Nucl. Fusion **42** 1324 (2002)

Prediction of sawtooth inversion radius:

- Transport codes such as PRETOR, ASTRA, TSC, are able to predict this adaquately
- Experimentally, for ohmic shaped plasmas, the relation

$$\rho_{INV} \sim \left(A_{INV} / A_p \right)^{1/2} \sim 1/q^* \equiv \langle J \rangle / J_0 \, q_0$$

seems to hold. Weisen, Nuc. Fus. 42 136 (2002)

Need for 3D Modeling

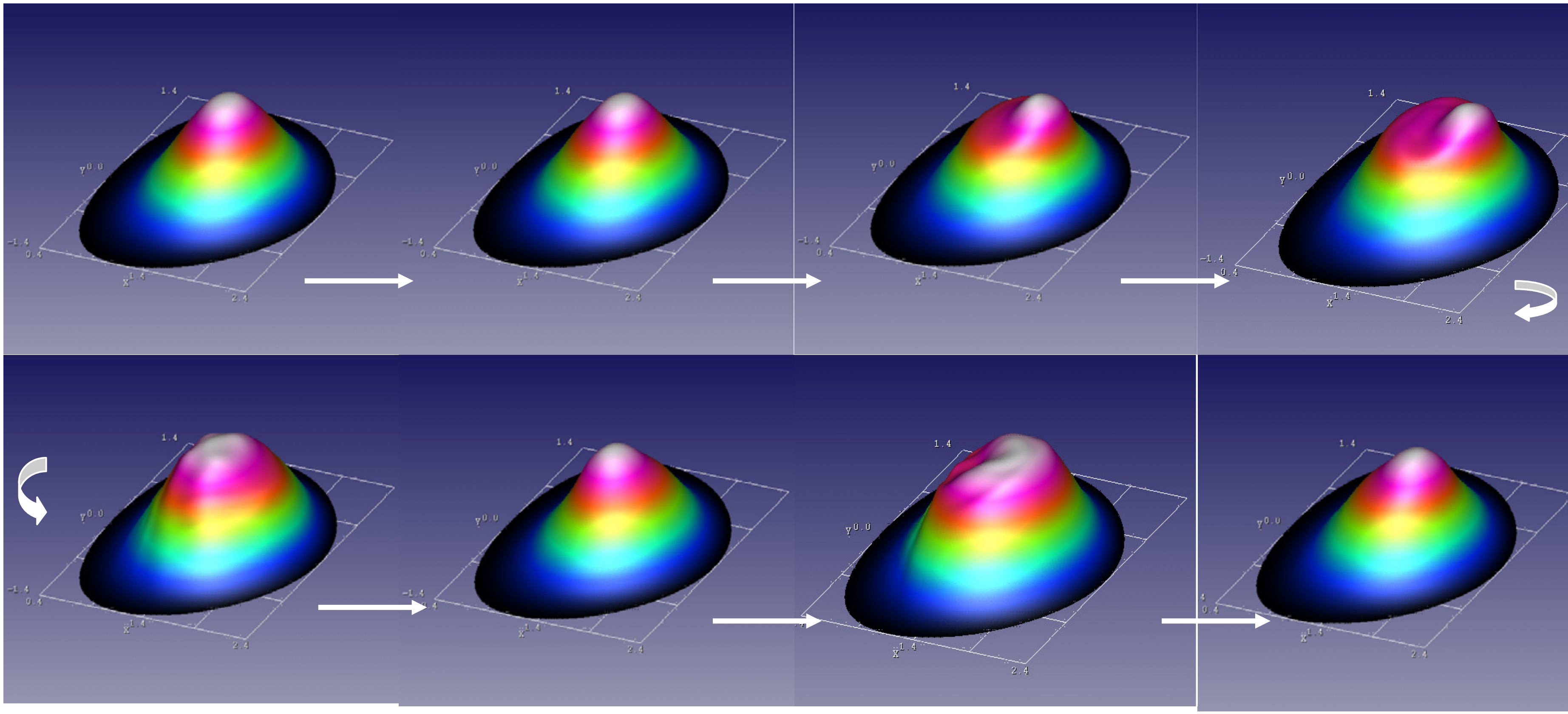
- Even though the PBR model agrees fairly well with existing experiments, there is no guarantee that it will successfully predict sawteeth in ITER
  - The δW_{fast} and δW_{KO} terms will be proportionally larger, and these have not been tested as well as the other terms involving shear

Status and plans for 3D modeling

M3D and NIMROD have started on a program to model the sawtooth in existing experiments, using the actual parameters of the experiment. It has the following objectives:

- Code verification and validation and NIMROD/M3D comparison
- Test the validity of the PBR model and improve as necessary
- Understand better the interaction of the m=1 mode with other modes such as NTMs and ELM
- Quantify the effects of non-Maxwellian distribution function (α-particles)
- Interface with the SWIM project to produce a predictive tool for calculating the effect of RF (de)stabilization of the m=1 mode

Campaign to model sawtooth in CDX-U using actual parameters of that discharge

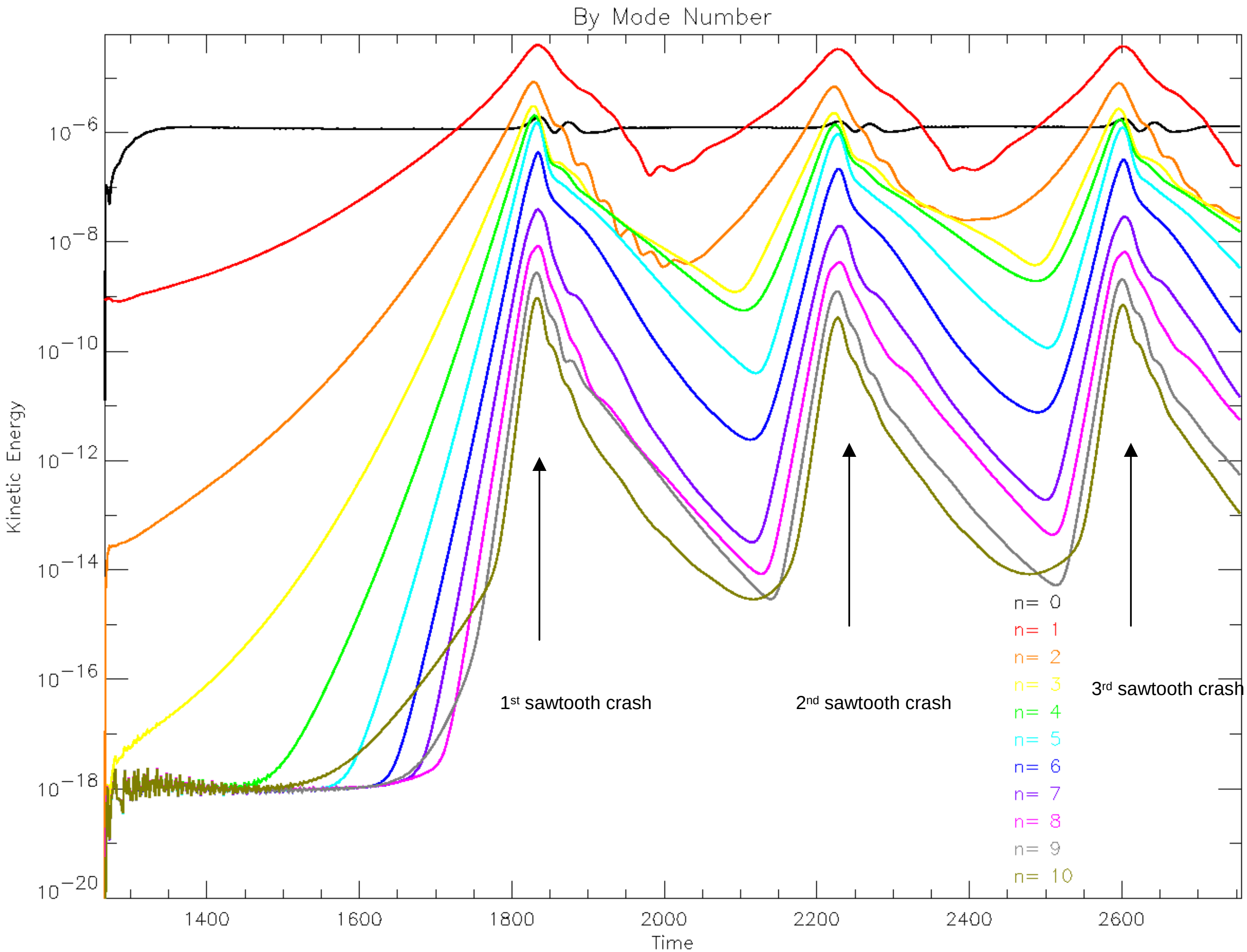


After first crash

After second crash

Breslau
M3D

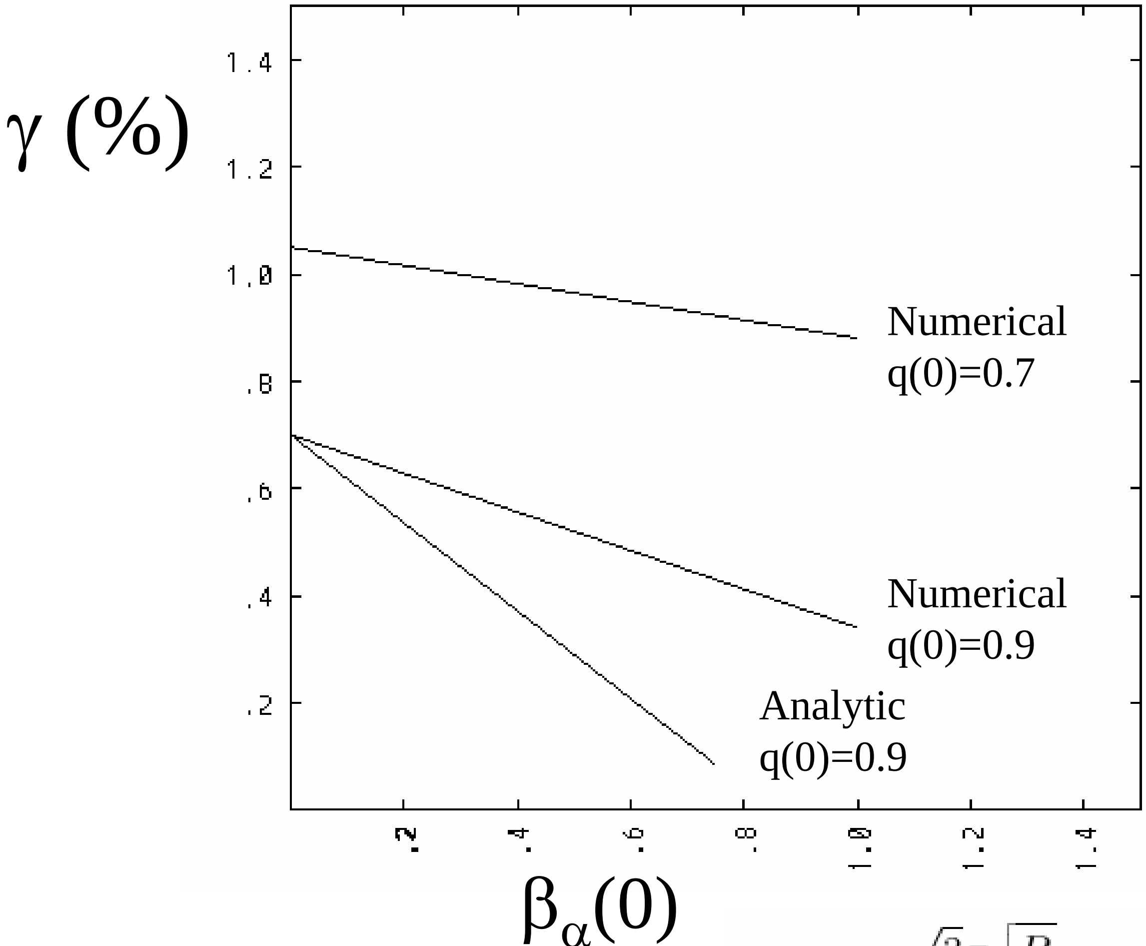
Three Sawtooth Cycles



Sawtooth period 1 ≈ 395 τ_A ≈ 100 μs;
Sawtooth period 2 ≈ 374 τ_A
Reference CDX sawtooth period ≈ 125 μs

Breslau
M3D

M3D finds that Alpha Particles in ITER are less stabilizing as compared to the analytic result

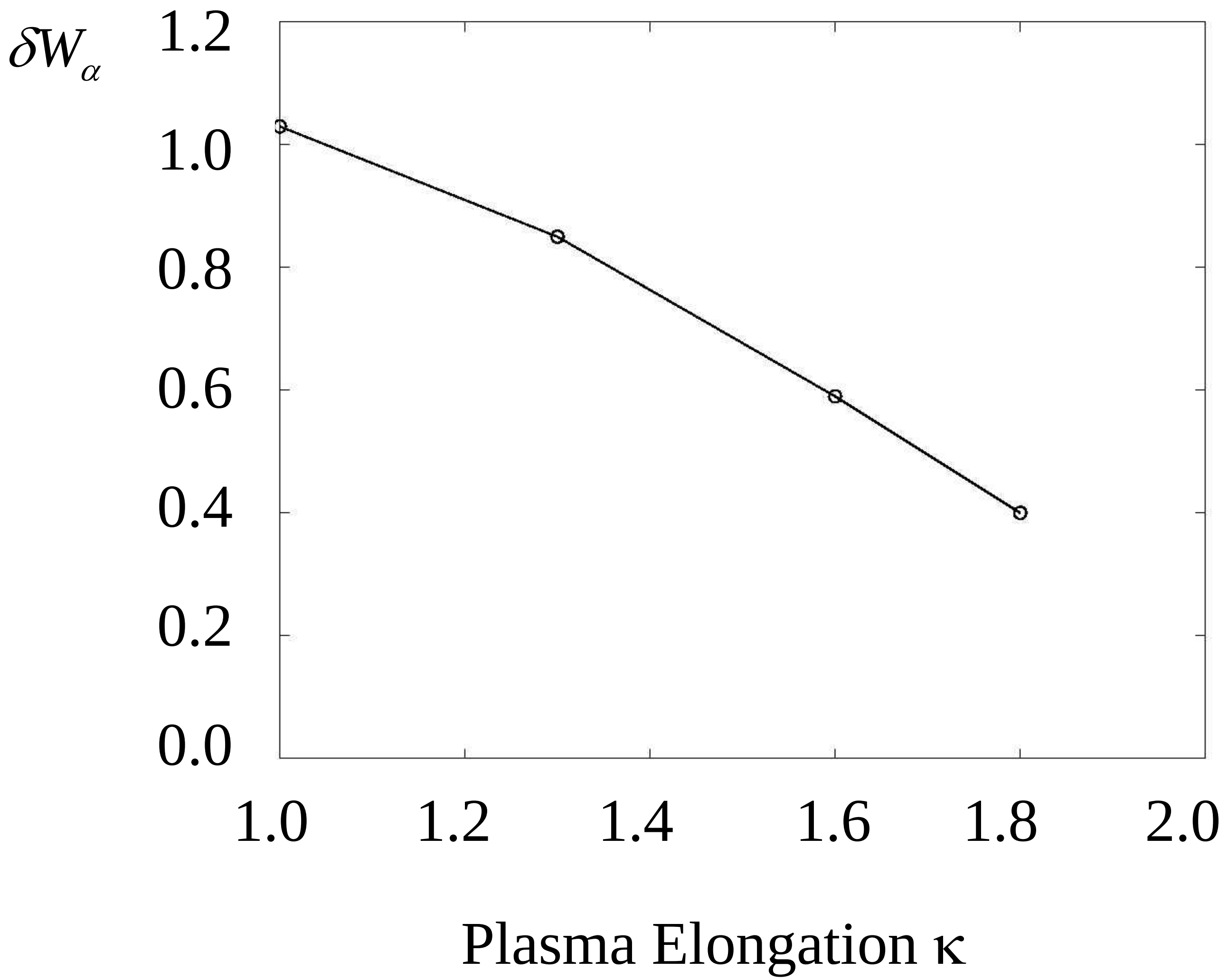


G. Fu

$$\delta W_{\alpha} = \frac{\sqrt{3}\pi}{8 s_1}\sqrt{\frac{R}{r_1}} \int_0^{r_1} dr[(0.6+3.2(1-q-0.5s))(\frac{r}{r_1})^{1.5}\frac{d\hat{p}_{\alpha}}{dr}]$$

McClements et al. Nucl. Fus. 35 1761

M3D finds that plasma shaping reduces alpha particle stabilization significantly



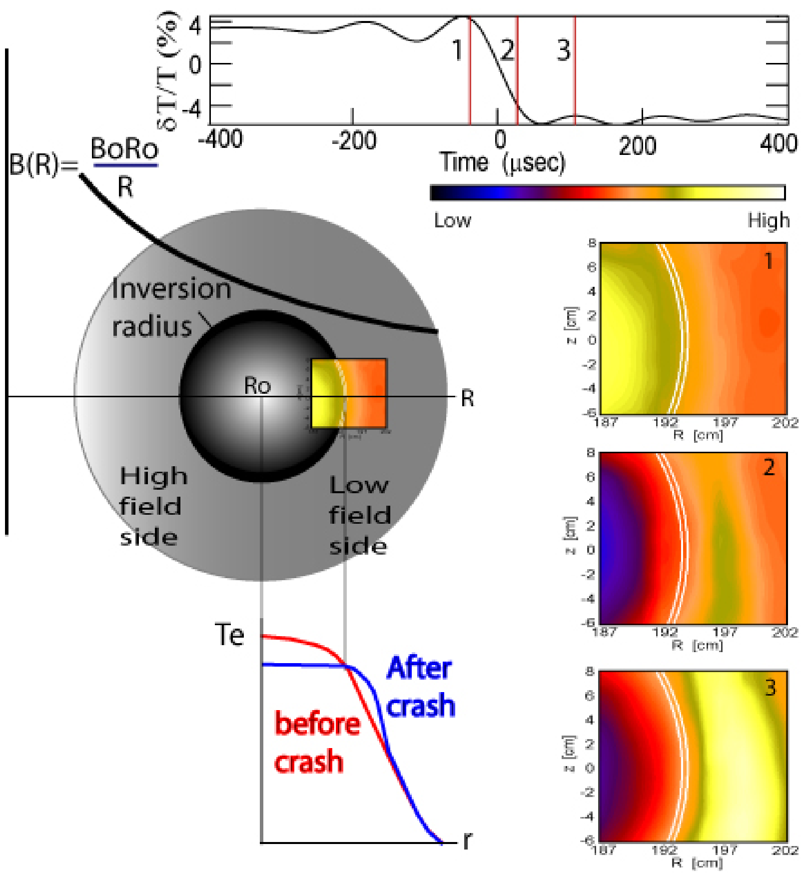
Fu

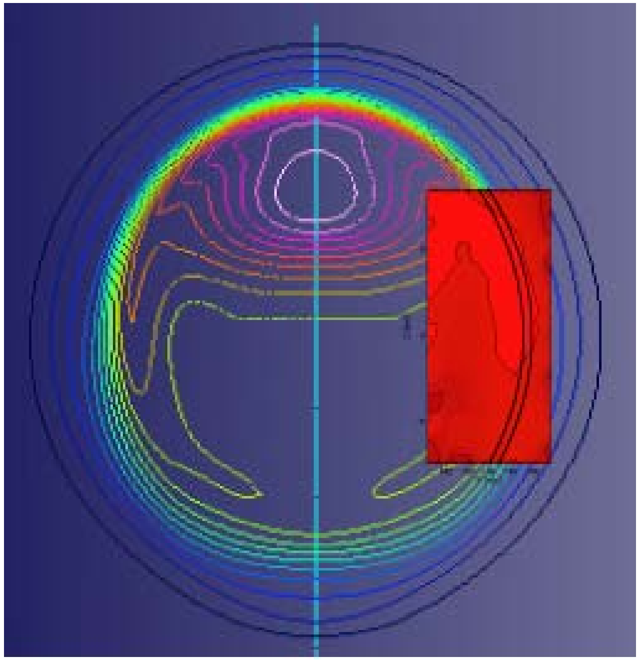
Other Relevant M3D results:

- Fishbone is stable in ITER
- Verified importance of Kruskal-Oberman term:
  - For an ITER case, the internal kink mode growth rate is reduced by half due to thermal ion kinetic effects.
  - The thermal ion kinetic effects are as stabilizing as fusion alpha particles.

Fu

New 2D images of electron temperature fluctuations during sawtooth with high temporal and spatial resolution from TEXTOR





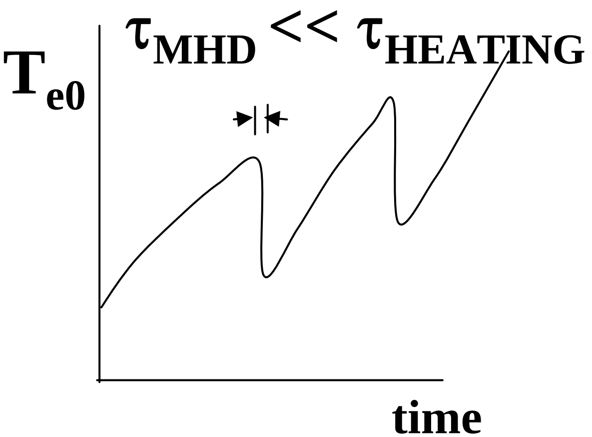
Overlay of 2D image with M3D simulation

H. Park

The newly funded FSP, Simulation of Wave Interaction with MHD (SWIM) will target m=1 mode

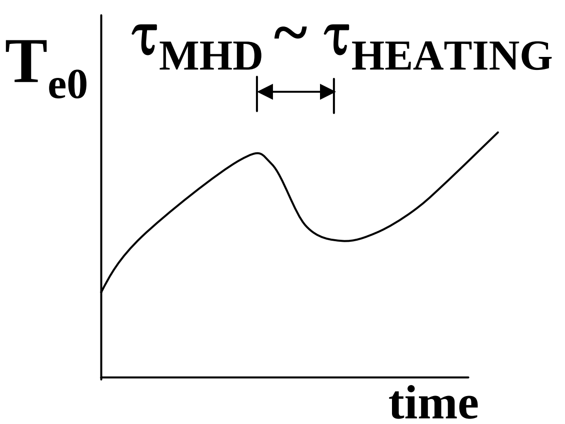
Fast phenomena – separation of time scales

- Response of plasma to RF much slower than fast MHD motion
- RF drives slow plasma evolution, sets initial conditions for fast MHD event
- Example: sawtooth crash



Slow phenomena – no separation of time scales

- RF affects dynamics of MHD events ⇔ MHD modifications affect RF drive plasma evolution
- Deals with multi-scale issue of parallel kinetic closure including RF – a new, cutting edge field of research
- Example: Neoclassical Tearing Mode



SWIM approach these regimes in two *campaigns* of architecture development and physics analysis and validation: now in progress. Goal is to develop most complete RF/FP/MHD packages working together.

Discussion Topics

A. Recent Developments:

1. What major BP-related developments have occurred in this area since the Snowmass 2002 study?

B. Implications and Outstanding Issues:

2. What issues remain to be resolved for a successful BP experiment in ITER?
3. What are the consequences of resolving these issues, or not, in the next ~10 years?
4. What issues should be resolved by a successful BP experiment?

C. What should the U.S. fusion community do:

5. What contributions can/should the U.S. fusion program make to resolving these issues?
6. How should the BPO be structured to best help the community make these contributions?