Macroscopic Stability Breakout Group

Breakout Group Leaders
C. C. Hegna and G. A. Navratil

6 questions to be addressed

- **A. Recent Developments:**
  - 1. What major BP-related developments (in theory, modeling, experiment and technology) 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?

Agenda

8:30 - NTMs

- Gates - 20 minutes
- LaHaye - 10 minutes

9:30 - External Kink and RWMs

- Sabbagh - 20 minutes

10:30 BREAK

10:45 - m = 1/sawteeth

- Jardin - 20 minutes
- Sugiyama - 10 minutes

12:00 LUNCH

1:00-3:00 JOINT SESSION WITH EDGE BREAKOUT GROUP

1:00 - Pedestal/ELMs

- Snyder - 20 minutes
- Fenstermacher - 10 minutes

2:00 - Disruptions

- Whyte - 20 minutes
- Wesley - 10 minutes

3:00 BREAK

3:15 - Error Fields and Critical Rotation

- LaHaye - 15 minutes
- Reimerdes - 15 minutes

3:45 - 3D Equilibrium & Response

- Zarnstorff - 15 minutes

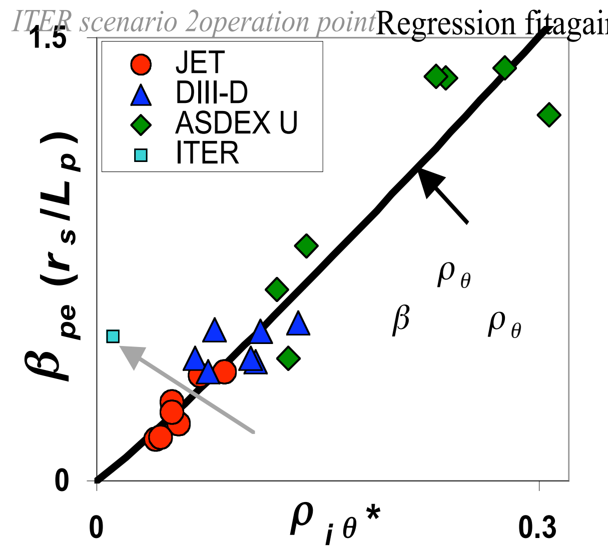
4:15 - ICC BP Issues

- Sarff - 20 minutes

5:15 - USBPO Discussion

Neoclassical Tearing Modes may significantly limit ITER operation

In ITER, NTMS are predicted to be less stable than present day devices.
If left unmitigated, the low-beta limit set by a 2/1 NTM could prevent ITER form achieving its goals.



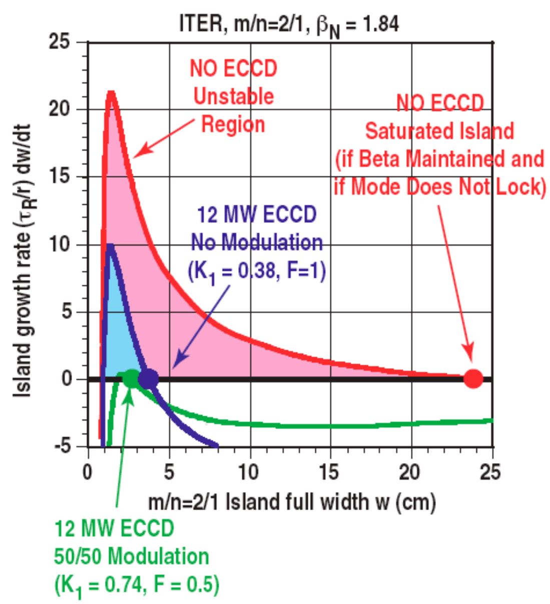
Since Snowmass,

- Demonstration of complete stabilization of m/n = 2/1, 3/2 NTMs with unmodulated ECCD and improved β.
- Consensus on the physics of the neoclassical polarization effect.
- Control techniques on seed producing Instabilities - producing small sawteeth with RF

Neoclassical Tearing Mode Control Techniques Require Validation

Outstanding issues

- Demonstrate ECCD stabilization for $q_{95} \sim 3$ with rotation similar to that expected for ITER - planned for DIII-D in '06-'07
- Improved modeling requirements - Seeding physics, self-consistent of island rotation, small island modeling, coupled RF-neoclassical closures - SWIM project, model for FIR, Hybrid scenario
- Test of modulated ECCD suppression; test of broad vs. narrow ECCD localization - DIII-D '06-'07



External Kink/Resistive Wall Mode Physics

We cannot rely on plasma rotation for ITER operation in the wall stabilized regime

- Is resistive wall mode control essential to ITER?
  - For basic pulsed, low β_N operation, no.
  - For steady-state Q ~ 5 plasma goal, probably yes.
  - For establishing basic plasma physics and the RWM control in ITER essential for DEMO, yes.

Since Snowmass,

  - RWM stabilized by plasma flow
  - Dynamic error field correction sustains rotation and allows sustained access to high ideal β_N
  - Resonant Field Amplification (RFA) discovered and explains the rotation damping above the no-wall limit
  - RWM-induced plasma rotation damping is global and non-resonant - consistent neoclassical toroidal viscosity theory
  - Multi-mode (32 modes) control achieved on the EXTRAP-T2R reversed field pinch
  - Coupling of ELMs to RWMs

The physics of Resistive Wall Mode control requires further study

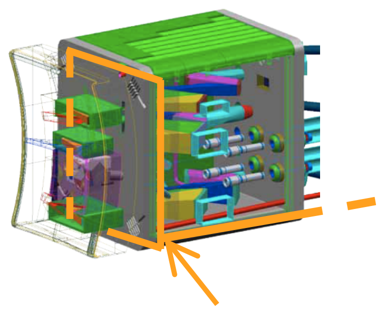
Issues

- Demonstration RWM stabilization in low rotation plasmas - Optimization of algorithm, control coil geometry, noise reduction, etc. DIII-D and NSTX ‘06-’07; HBT-EP
- Importance and stabilization of n > 1 instabilities - seen on NSTX - planned activities for DIII-D and NSTX ‘06-’07
- Establishment of the stabilization physics for predictive scaling of rotation threshold for ITER - ITPA activity - DIII-D, NSTX, JET
- Effect of coil modularity - sideband excitation of other MHD modes - e. g., NTM destabilization?

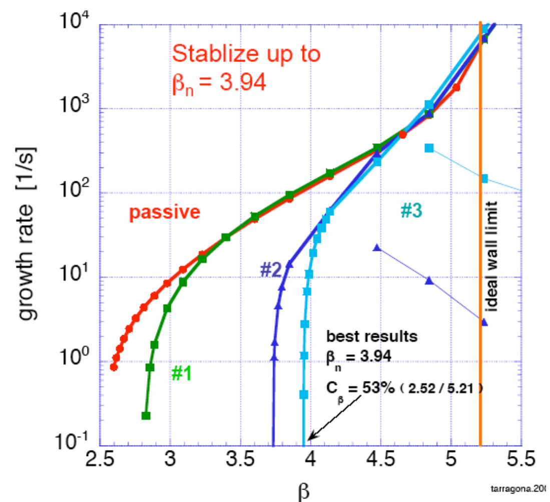
External Kink/RWM physics

US experimental facilities are uniquely equipped to lead the world effort on RWM physics and mode stabilization.

- Unique US program contributions
  - Design of optimal control coil geometry for ITER
  - Port plug coils are a necessity for the US community to do its RWM program on ITER



• **Internal RWM coils would be located inside the vacuum vessel behind shield module but inside the vacuum vessel on the removable port plugs.**



7 RWM Coils mounted behind the blanket in every other port except NBI ports. (assumes 9 ms time constant for each blanket shield module)

Large m = 1 Modes/Sawteeth are expected in standard ITER operation

In normal operation, sawteeth are expected in ITER with r/a ~ 42% with a period of 20-40 s.

These sawteeth could excite other modes (NTMs) and lead to enhanced disruptivity and energetic particle loss

After Snowmass

- The Porcelli-Boucher-Rosenbluth (PBR) model agrees fairly well with existing experiments, but there are issues in evaluating the individual terms in the theory and extrapolating to ITER plasmas.

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

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

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

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

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

(global) Internal kink mode not stabilized by diamagnetic effects

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

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

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

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

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

Inproved understanding of m = 1 mode stability requires advances in theory

Critical issues

- The PBR sawtooth model is only approximate
  - Coefficients are not well determined and only partially benchmarked
  - Detailed physics model is incomplete
  - $-\delta W$ and energetic particle contributions are expected to be much larger than in present day tokamaks
- Need accurate predictions of burning plasma parameters
  - Implementation in transport code needs to be improved for accurate predictions MHD instability triggers and growth rates
- Other physics effects: rotation, two-fluid and mode rotation, and coupling

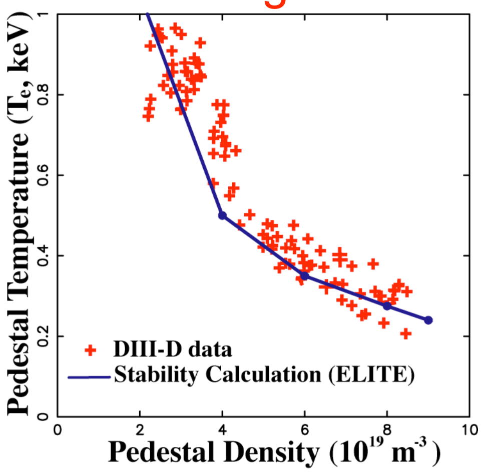
Unique US contributions

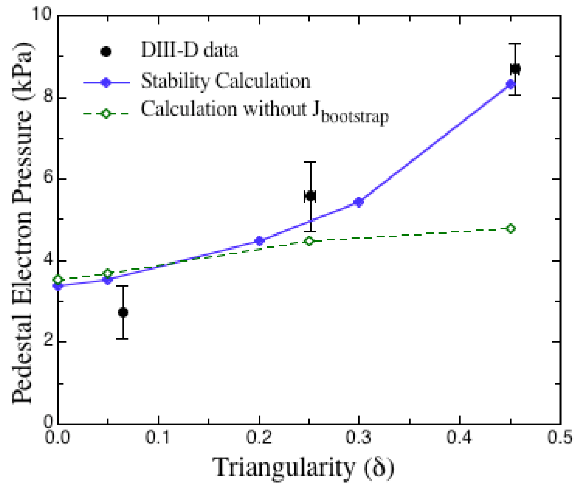
- Simulation of Wave Interaction with MHD (SWIM) project to target these issues
- Significant data exists on tokamak sawteeth for validation of theoretical predictions

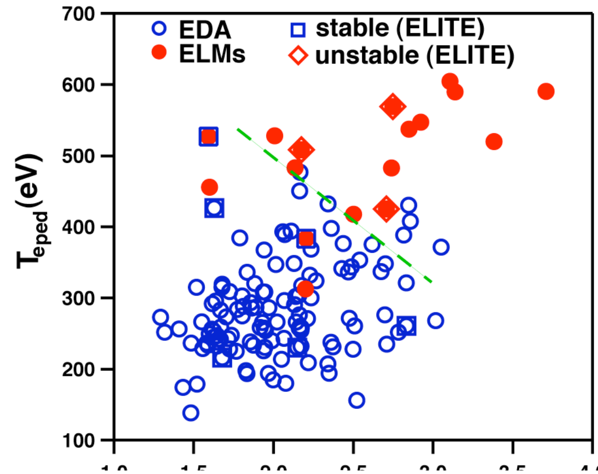
Understanding ELM physics is crucial for ITER

ITER and most BP devices operate in H-mode -

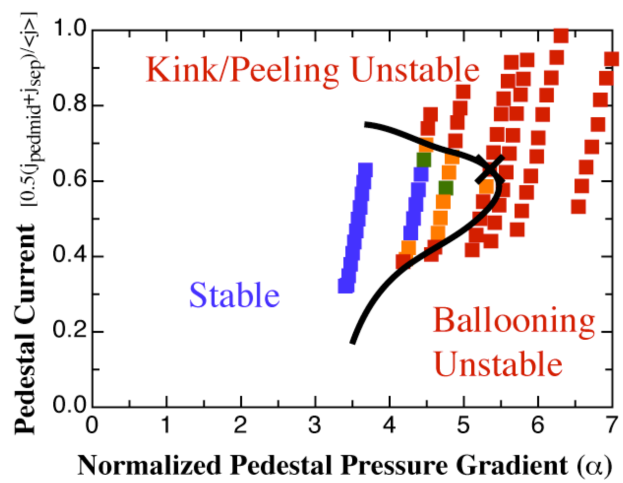
Large ELMs are not tolerable in ITER







DIII-D Shot 119748, Pedestal Stability just before ELM



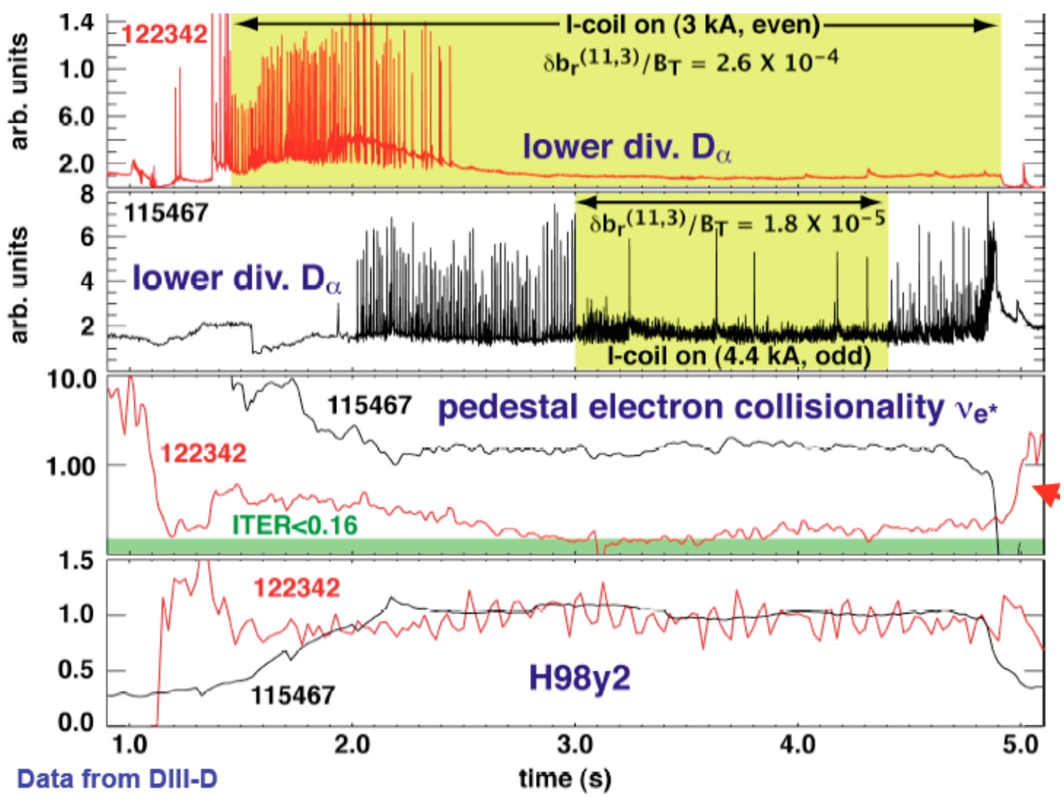
"Standard" ELMs caused by intermediate wavelength (n~3-30) MHD instabilities

- –Tested on multiple tokamaks both directly and in database studies
  - •Role of bootstrap current largely confirmed but awaiting fast measurements
  - •C-Mod EDA regime holds pedestal below P-B limits
- –Edge stability analysis becoming fairly routine on some machines

ELM Control techniques have developed in recent years

Since Snowmass

– The most important development is a method to suppress ELMs using resonant magnetic perturbations (RMPs). - DIII-D



What is the plasma response to RMP fields?
--- particle transport most affected?
--- scaling control at low vs. high collisionality?

ELM/Pedestal Physics

Issues

- Physics of setting the pedestal width
- Robust mechanism for creating small ELMs with reliable avoidance of larger events
- Physics understanding of ELM dynamics and heat deposition
- Physics of passive ELM-free operation (QH, EDA)
- Robustness in the presence of alphas

Unique US contributions

- US experiments lead pedestal stability efforts
- Strong suite of analysis tools
  - Advanced edge simulation projects - (CPES, ESL)
- Impact the RMP ELM control for ITER

Disruption avoidance and/or mitigation will be a topic of central issue in the operation of ITER

ITER will be the first MFE experiment where the avoidance and mitigation of disruption damage must be an integral part of ALL plasma operations

Since Snowmass

- Significant progress using high pressure gas jets to mitigate disruptions on C-MOD, DIII-D and JET

Issues

- Develop and benchmark resistive MHD numerical codes - NIMROD, M3D - inclusion of neutral/atomic physics, radiation, gas flow, etc.

US Opportunities

- Work with ITPA on cross-machine comparisons
- Enhance cross-discipline approach to whole disruption issue
  - MHD control, detection, avoidance and mitigation
- Predictive modeling

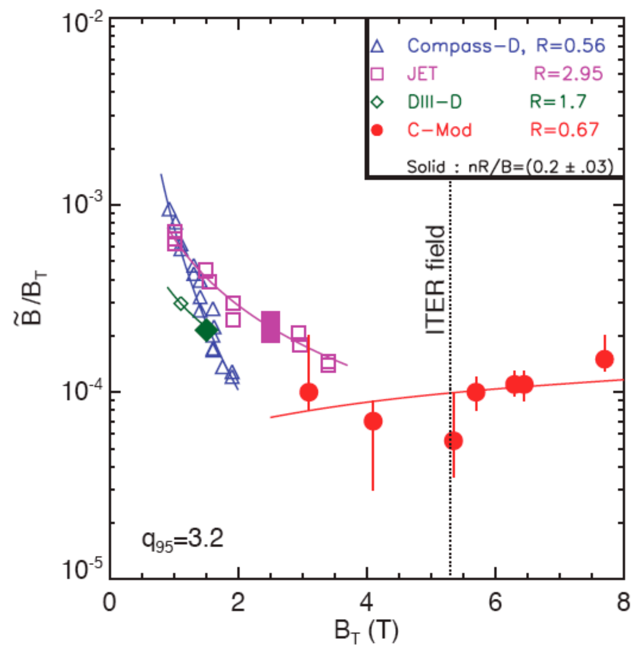
The penetration of error fields is generally an issue in low density Ohmic tokamak operation

Since Snowmass

– The tolerable error field for mode locking in ITER is still uncertain. But, recent C-MOD data suggest that the critical locking threshold is $\delta B/B_t \sim 10^{-4}$. This is much more optimistic than earlie DIII-D projections

Issues

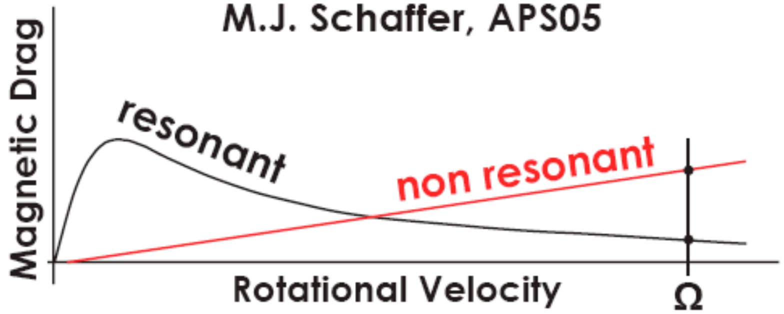
– No predictive theory



(C-Mod data $\frac{B_{21}}{B_T}$ at constant $\bar{n}R/B$,
B_{pen}

CONJECTURE: NON-RESONANT Magnetic Perturbations May Be Important in Plasma Braking and Mode Locking

- **Plasma starts in rotating state, so magnetic drag < driving torque**
- **Rotating plasma shields resonant fields ($B_{rmn} \approx 0$ at resonance surface)**
  - Resonant drag acts mainly in neighborhood of resonant surface
  - Peaks at low speed, decreases at high speed
- **Non-resonant fields not shielded**
  - Drag acts throughout plasma
  - Increases with speed



- **The "Slippery Slope" to a Locked Mode can START with non-resonant drag, even though locking eventually depends on a large resonant drag at end**
- **Experimental "Locked Mode Scaling" with δB and n_e DEPENDS ON INITIAL DRAG**
  - IT WILL NOT DEPEND ON JUST $\delta B_{resonant}$
- **Magnetic error correction must include BOTH resonant AND non-resonant components**

Importance of 3D equilibrium effects are recognized in a variety of macroscopic stability issues

3D Magnetic Perturbations are increasingly used to control tokamak stability and performance

- Compensations for error fields
- Resistive wall mode feedback
- ELM stabilization

Issues

- Need to develop analysis of effect of 3D perturbations on equilibrium to understand effects on stability and transport
  - Ripple transport
  - Stellarator equilibrium - PIES, VMEC, M3D, NIMROD
  - Expand plasma response in ideal stability eigenfunctions
  - Direct fitting to measured external 3D plasma generated B

Need to extrapolate to 3D perturbations to ITER burning plasmas

Innovative Confinement Concepts connections to burning plasma physics

For many issues, the benefits (in both directions) will occur through validation of MHD theories and codes which can be applied to other configurations (I. e., understanding the basic physics).

Issues - Some MHD issues common to many concepts

- Wall stabilization, resistive wall modes
- Neoclassical effects on tearing modes
- Alpha-driven instabilities
- Kinetic effects
- Flow shear stabilization
- Diagnostics & computational tools
- Profile control (not strictly MHD, but related to next item)
- Coupling of transport & stability: self-consistent profiles, nonlinear effects, etc.

The ICC portfolio is more than alternate solutions

- Experimental test bed for understanding primary configuration variables, e.g.,
  in toroidal confinement:
  - Aspect ratio (FRC, ST, Spheromak)
  - External transform (Stellarator)
  - Toroidal field strength (FRC, RFP, Spheromak,)
  - Opportunity for strong synergy between tokamak and all ICCs
- Cross-concept (configuration space) predictive capability could ***define*** the optimum configuration.

Predictive science valid over a wide range of configuration space will most convincingly allow an “alternate” substitution for DEMO, even if the substitution is not very different from a present-day concept.

On USBPO Organization

- The proposed Topic Group for Macroscopic Plasma Physics is appropriate
  - But, increasingly there will be issues of overlap that will require significant joint work with other topical groups, e. g., energetic particle effects on MHD, plasma boundary physics, …
- Interfacing of ICC activity with USBPO
  - Supporting role of physics contributions in the near term, e. g., RWM stabilization in RFPs, 3D equilibrium issues, …
  - Looking beyond ITER and alternate solutions to ITER issues, e. g., DEMO incorporation of ICC innovations
  - ICCs will want dedicated ITER experiments to inform ICC burning plasma physics issues

Our USBPO Recommendation

- Form a task group to spearhead the design of ITER coils for control of RWMs and ELMs.
  - Joint effort from the MHD and Boundary topical groups.