Feedback Control of MHD kink instabilities on the HBT-EP tokamak

David A. Maurer

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J. Bialek\textsuperscript{1}, J. Bodeo\textsuperscript{2}, A. H. Boozer\textsuperscript{1}, C. Cates\textsuperscript{1}, L. Chousal\textsuperscript{2}, R. Fitzpatrick\textsuperscript{3}, D. Guskin\textsuperscript{1}, R. James\textsuperscript{1}, T. H. Jensen\textsuperscript{4}, O. Katsuro-Hopkins\textsuperscript{1}, A. Klein\textsuperscript{1}, R. Le Francois\textsuperscript{1}, Y. Liu\textsuperscript{1}, M.E. Mauel\textsuperscript{1}, G. A. Navratil\textsuperscript{1}, S. F. Paul\textsuperscript{5}, T. S. Pedersen\textsuperscript{1}, M. Shilov\textsuperscript{1}, and N. Stillits\textsuperscript{1}

\textsuperscript{1} Columbia University  
\textsuperscript{2} University of California at San Diego  
\textsuperscript{3} Institute for Fusion Studies  
\textsuperscript{4} General Atomics Corporation  
\textsuperscript{5} Princeton Plasma Physics Laboratory
Outline

• Introduction: Importance of high pressure plasmas to fusion and motivation for active control
• MHD limits to high-pressure operation: kink modes
• HBT-EP passive and active control systems
• Passive and active HBT-EP control experiments to reach higher pressure and current operation
• Optimizing kink mode feedback systems: ideal wall performance
Goal:  *Improve Performance of Fusion Systems via MHD Instability Control*

**Approach:** Understand the basic physics of macroscopic, performance limiting MHD instabilities and their active and passive control.

Use this knowledge to improve operational pressure limits and hence power output for future fusion energy systems.

Study physics of these issues in a flexible small machine test bed environment with MHD relevant plasmas and apply knowledge and tools developed to larger fusion experiments (*DIII-D, NSTX, FIRE, ITER*)
Basic External Kink Instability

Kink modes limit high plasma pressure performance in current and future large tokamaks

kinking motion gives rise to a perturbed force that acts to enhance the kinking motion

Fast timescale motion \( \sim 10^{-6} \) sec (active feedback not possible)
A Close Fitting Conducting Wall Can Stabilize the Ideal Kink

Resistive walls allow magnetic flux leakage on slow timescale ~ msec

NO Wall

No wall → fast kink unstable

WITH Wall

Flux compression gives restoring force that stabilizes the fast kink mode

Flux leakage allows growth of slow kink (resistive wall kink mode)
Timescale slow enough for feedback control
HBT-EP Is A Unique Test Bed For Experimental Studies And Model Benchmarking of RWM Control Physics

HBT-EP Experimental Geometry

Shells retracted: $b/a = 1.52$

Shells inserted: $b/a = 1.07$

HBT-EP Passive Wall Stabilizer

- Independently (movable) positionable Aluminum and Stainless shell segments
- Complicated geometry needs accurate 3D quantitative representation
- Fully adjustable wall time constant by varying plasma-shell segment distance

HBT-EP Active Control Coils

- Three "smart shell" control and sensor coils per stainless steel shell segment
- Total of thirty independent control/sensor loops for radial flux cancelation
- Recently added new coil set with 40 control coils and 20 new Bp sensor coils
Ideal (fast) Kink Suppression Using a Conducting Wall

Stabilization of the External
Ideal Kink with Wall Stabilization

Wall Retracted

Wall Near Plasma

- All AI plates inserted above
- Similar stabilization observed with half of the AI plates inserted
Feedback Control System for Resistive Wall Kinks

- Three control and sensor coils per SS passive plate as shown
- Thirty independent control/sensor pairs for radial flux cancelation ("smart shell")
Feedback Successful At Suppressing Resistive Wall Kink and Inhibiting Induced Disruption

Feedback allows higher current/lower $q^*$ and higher pressure operation. Plasmas disrupt later due to internal tearing mode growth.
Optimized Feedback: Approaching the Ideal Wall limit

• Theory and modeling tell us that minimizing the control coil-resistive wall coupling (mutual inductance) while increasing control coil-plasma coupling leads to better feedback performance

• And minimizing sensor coil-control coil coupling increases performance

• New goal is “optimized” system with both of these features able to perform at the ideal wall limit
VALEN Optimization of Feedback Control

New Control Coils Located in the Gaps Between the Passive Plates with $B_p$ Sensors Predicted to Reach Ideal Wall Limit

- 20 new control coil pairs at 5 distinct toroidal and 4 poloidal locations on outboard side of tokamak
- 20 new companion $B_p$ sensors on plasma facing side of SS passive plate
- Initial mode control experiments in progress
Optimized Feedback Control Coil System

New control coils mounted on thin 0.25 mm stainless steel shim stock to minimize wall coupling.

New poloidal sensors on plasma facing side of stainless steel plate (not shown).

New mode control experiments have begun by mapping poloidal sensors in toroidal angle 72 degrees to make up $B_p$ sensor to $B_r$ control coil phasing using existing analog circuitry.
Initial Tests of Optimized Feedback Phasing Underway

**Target RWM**

**Suppression**

**Amplification**

- **negative feedback**
- **positive feedback**
Summary

- High plasma pressure and current operational limits due to MHD kink modes can be surpassed using a combination of passive wall stabilization and active feedback control.

- HBT-EP experiments have demonstrated:
  - Wall stabilization of the ideal kink using a segmented wall
  - Feedback control of the RWM and disruption suppression
  - Implementation and initial experiments with an optimized feedback configuration
  - Benchmarking of the VALEN RWM control code