STRUCTURE AND FEEDBACK STABILIZATION OF RESISTIVE WALL MODES IN DIII-D


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ABSTRACT

• Resistive wall modes (RWM) limit the performance of DIII-D discharges when beta exceeds the no-wall ideal stability limit. These n=1 global kink modes grow on the slow time scale of magnetic diffusion through the surrounding conductive vacuum vessel wall.

• Active feedback stabilization experiments in 2000 suppressed RWMs for periods 50 times longer than the resistive penetration time of the wall.

• Experiments in 2001 have demonstrated dramatic improvements in active control capability, owing largely to an extensive new set of magnetic sensors installed inside the vacuum vessel after the 2000 campaign.

• The new magnetic sensors, together with existing external sensors and a toroidal array of x-ray cameras, have also afforded better characterization of the previously observed mode structure.
Resistive wall modes (RWM) have been under study on DIII-D for several years. Experiments on active magnetic feedback stabilization of these modes began in 1999. Internal and external magnetic loops and probes, arranged in toroidal arrays, detect slowly growing n=1 magnetic perturbations from RWMs. Feedback stabilization commands are generated from magnetic sensor data, using a variety of algorithms, and sent to three power amplifiers. Each amplifier energizes a pair of active coils with the proper current and phase for controlling growth of the mode.
Most experiments in 2000 used Smart Shell logic, where the feedback system attempts to null the net radial flux through the sensor loops.

Other experiments used Explicit Mode Control logic, where the feedback system attempts to suppress the residual flux from the mode after subtracting contributions from the active coils.
DIII–D HAS EXTENSIVE RESISTIVE WALL MODE DIAGNOSTICS

- Thirty external $\delta B_r$ loops and 18 internal $\delta B_r$ loops measure toroidal and poloidal structure of radial field perturbations from RWMs.
- Four pairs of diametrically opposed internal $\delta B_p$ probes measure poloidal field perturbations on the vacuum vessel midplane.
- Identical x-ray cameras at three toroidal locations show RWM internal structure.

![Diagram of DIII–D diagnostic setup](image)
CODES PREDICT INDUCED CURRENTS IN CONDUCTING WALL

GATO-VALEN
J. Bialek et al.

GATO-VACUUM
M. Chance et al.
δB_r LOOPS MEASURE RWM HELICAL STRUCTURE AT WALL

- This figure shows typical data from the 30-loop array of external δB_r sensors and resulting mode analysis for a discharge without feedback.
- All three toroidal arrays show similar but phase shifted behavior.
- This helical structure is in agreement with expectations.

![Graph showing δB_r loops](image)
CODES PREDICT RWM INTERNAL STRUCTURE

- Plasma displacements predicted by MHD stability codes are mainly poloidal but with net radial components.
- Toroidally separated soft x-ray cameras can observe non-axisymmetric radial displacements.
X-RAY ARRAYS MEASURE RWM INTERNAL STRUCTURE

- Chord-by-chord comparisons of soft x-ray intensities from toroidally separated poloidal arrays are used to find relative radial displacements between the two toroidal locations at minor radii corresponding to the x-ray sight lines.
INTERNAL STRUCTURE FROM X-RAYS AGREES WITH GATO

- Soft x-ray determination of the radial profile of relative radial displacements between two toroidal locations shows kink-like internal structure.
- Normalized radial displacements near the plasma midplane are in general agreement with results from the GATO stability code.
X-RAY AND $\delta B_r$ DATA SHOW EXPECTED PHASE RELATION

- Amplitude and phase of $\delta B_r$ from midplane saddle loops are used to find relative difference in $\delta B_r$ between 195° and 45° toroidal locations for comparison with relative displacements deduced from x-ray arrays.
- Maximum $\delta B_r$ is expected to be 90° clockwise (viewed from above) from maximum radial displacement.
- Results confirm expected 90° toroidal phase difference.
MODE STRUCTURE IS RETAINED DURING ACTIVE FEEDBACK

- In this example of Smart Shell feedback using internal midplane $\delta B_r$ loops, RWM mode amplitude is held at moderate level for ~100 ms.
- Internal radial displacement is well correlated with differences in $\delta B_p$ from internal probes and phase-shifted $\delta B_r$ from external midplane saddle loops.
MODE GROWTH IN GATED-OFF PERIOD DEMONSTRATES CONTROL

- In this example of long-duration (>50 $\tau_w$) active stabilization, mode is controlled until feedback is gated off, then grows.
- Control is re-established when feedback is switched back on.
VALEN PREDICTS BETTER CONTROL WITH INTERNAL SENSORS

- VALEN code calculations, with Smart Shell logic and no plasma rotation, predict:
  - Properly designed internal $\delta B_r$ sensors will enable greater control capability than that possible with external saddle loops.
  - Internal $\delta B_p$ sensors will offer even greater advantages because of insensitivity to radial fields from the active coils.
INTERNAL SENSORS ENABLE IMPROVED ACTIVE CONTROL

- This figure shows toroidal plasma rotation data for experiments using a rapid $I_p$ ramp to reliably trigger an RWM at $\sim$1400 ms in the absence of closed-loop feedback. (Toroidal rotation is a sensitive indicator of the presence of an RWM.)
- With Smart Shell feedback, internal $\delta B_r$ loops are more effective than external loops in controlling the RWM.
- Internal $\delta B_p$ probes with Explicit Mode Control feedback are far more effective than either internal or external $\delta B_r$ loops and Smart Shell feedback.
In plasmas with slow $I_p$ ramp, $\delta B_p$ feedback gives stable operation for almost a second at $\beta_N$ approaching twice the no-wall stability limit.
PRE-PROGRAMMING CURRENTS GIVES SIMILAR $\beta_N$ AND $f_\phi$.

- In a slow Ip ramp case, pre-programming active coil currents to match $\delta B_p$ feedback currents gives similar $\beta_N$ and $f_\phi$. 

![Graph showing $\beta_N$, $f_\phi$, $I_c$, and $I_p$ over time](image)
• Non-axisymmetric magnetic error fields exert a braking effect on toroidal plasma rotation.
• For plasma pressures above the no-wall ideal stability limit, RWMs grow when rotation stops.
• Closed-loop $\delta B_p$ feedback provides dynamic correction of magnetic error fields.
• When error fields are minimized, toroidal plasma rotation can be sustained by torque from neutral beams.
• Rapid toroidal rotation increases the effectiveness of the conductive wall in stabilizing Resistive Wall Modes.
SUMMARY

• Extensive new arrays of internal magnetic sensors, together with external sensors and toroidally distributed soft x-ray cameras, have been used to confirm the previously observed and theoretically predicted global kink nature of resistive wall modes.
• Closed-loop feedback stabilization experiments using the internal sensors support predicted improvements in mode control with respect to previously reported results using external sensors.
• With active control, plasmas have been sustained for almost a second at pressures approaching twice the no-wall limit.
• Closed-loop \( \delta B_0 \) feedback has allowed access to regime where sustained toroidal rotation increases effectiveness of resistive wall in stabilizing Resistive Wall Modes.