ABSTRACT

• Recent DIII-D experiments in plasmas with pressures at or above the no-wall ideal MHD stability limit have shown that rapid toroidal rotation can enhance the stabilizing effect of a surrounding conductive wall and delay the onset of resistive wall modes or, in some cases, prevent them altogether.

• When the braking arising from magnetic error fields is reduced, either by feedback or preprogrammed control of currents in correction coils, the plasma rotation can be sustained by torque applied by neutral beam heating.

• Stable operation has been achieved with pressures well above the no-wall limit for almost two seconds.

• These results are compared with cases where the input torque was reduced by using more nearly perpendicular beam injection or electron cyclotron heating.
The RWM has been studied on DIII-D for several years

- Extensive diagnostic sets characterize the Resistive Wall Mode (RWM).
  - Thirty external $\delta B_r$ loops and 18 internal $\delta B_r$ loops measure radial perturbations.
  - Four pairs of diametrically opposed internal $\delta B_p$ probes measure poloidal perturbations.
  - Identical x-ray cameras at three toroidal locations show RWM internal structure.
- Six picture-frame coils allow pre-programmed or closed-loop feedback control of 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.
  - The active coils are also used to correct magnetic error fields arising from imperfections in the toroidal and...
RWM IS A GLOBAL KINK WITH $\gamma \sim \tau_W^{-1}$

- Magnetic probe and x-ray measurements confirm RWM global kink structure.
- Measured helical structure at the VV wall and internal radial displacements are in agreement with modeling results.
- Growth time is of order of the flux penetration time of the DIII-D VV wall, $\tau_{W} \sim 6 \text{ ms.}$
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.
RWM KINK 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 $\sim 20 \tau_w$.
- 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.

![Graphs showing intensity, time, and magnetic field changes over time](image-url)
INTERNAL SENSORS ENABLE IMPROVED FEEDBACK 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.
By shot-to-shot optimization of currents in the active coils, static $n=1$ error fields can be minimized.

With optimized error field correction, plasma rotation is sustained for a longer period and onset of RWM is delayed.
EXPERIMENTS VALIDATE CALCULATED $\beta_N$ NO-WALL LIMIT

- Calculations show that the no-wall ideal MHD stability limit for normalized plasma pressure $\beta_N = \beta/(I_p/aB)$ is well represented by $\beta_N^{\text{no-wall}} \approx \lambda l_i$, where $l_i$ is the plasma internal inductance and $\lambda$ is approximately constant for similar plasma configurations. (A.D. Turnbull et al., RP1.003)

- For $\beta_N \sim \beta_N^{\text{no-wall}}$ non-axisymmetric magnetic error fields exert a braking torque on toroidal rotation.

- Magnetic braking experiments at different $\beta_N$ values confirm calculated no-wall limits.
  - For $\beta_N < \beta_N^{\text{no-wall}}$ the plasma is insensitive to error fields.
  - If pre-programmed error field correction is turned off when $\beta_N \geq \beta_N^{\text{no-wall}}$ plasma rotation stops and RWM grows.
  - If pre-programmed error field correction is maintained when $\beta_N \geq \beta_N^{\text{no-wall}}$ plasma rotation continues and RWM does not grow.
\( \delta B_p \) FEEDBACK GIVES LONG DURATION STABILIZATION

- In a plasma with slow \( I_p \) ramp, Explicit Mode Control feedback with \( \delta B_p \) sensors gives stable operation for almost a second (150 \( \tau_w \)) at \( \beta_N \) approaching twice the no-wall stability limit. In this case, error field correction was intentionally de-tuned before start of feedback.
PLASMAS WITH $\beta_{N\text{ no-wall}} \approx 4\ell_i$ ARE SIMILAR TO $\beta_{N\text{ no-wall}} \approx 2.4\ell_i$ CASES

- High performance, double null plasmas, with no $I_p$ ramp and $\beta_{N\text{ no-wall}} \approx 4\ell_i$, respond to error fields in much the same way as $\beta_{N\text{ no-wall}} \approx 2.4\ell_i$ cases.
  - For $\beta_{N} < \beta_{N\text{ no-wall}}$ the plasma is insensitive to error fields.
  - For $\beta_{N} \geq \beta_{N\text{ no-wall}}$ RWM grows unless error fields are minimized.

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PRE-PROGRAMMING CURRENTS GIVES SIMILAR $\beta_N$ AND $f_\phi$

- In a slow $I_p$ ramp case, pre-programming active coil currents to match $\delta B_p$ feedback currents from previous shot gives similar $\beta_N$ and $f_\phi$.
- This demonstrates that Explicit Mode Control feedback with $\delta B_p$ sensors provides dynamic optimization of error field corrections.
For $\beta_N \sim \beta_N^{\text{no-wall}}$ the plasma amplifies error fields. (J.T. Scoville et al., RP1.009)

- Pulsed $n=1$ error fields with no preferred helicity give rise to nonlinear, helical plasma response.
- Explicit Mode Control feedback with $\delta B_p$ sensors dynamically adjusts active coil currents so as to minimize plasma response to error fields.
ERROR FIELD CORRECTION ALLOWS $\beta_N > \beta_{N_{\text{no-wall}}}$ FOR ALMOST 2 S

- With error field correction by either shot-to-shot optimization or $\delta B_p$ feedback, long duration operation has been achieved at $\beta_N$ well above $\beta_{N_{\text{no-wall}}}$.
  - Active coil currents for the two correction methods are about the same.
  - When maximum $\beta_N$ is controlled, plasma is stable at $\beta_N > \beta_{N_{\text{no-wall}}}$ for $>280 \tau_W$.

![Graph showing $\beta_N$, $f_{\phi}$, $I_c$, and $I_p$ over time](graph.png)
STUDY OF LOW TORQUE CASES HAS BEGUN

- More nearly perpendicular neutral beams impart less torque.
- 110 GHz gyrotrons provide some of the input power.
- Active coil currents demanded by $\delta B_p$ feedback are similar to other cases.
- Explicit Mode Control feedback can suppress RWM and sustain rotation at $\beta_N \sim \beta_{N\text{ no-wall}}$.
- Feedback may be acting directly on mode as well as correcting field.

![Graphs showing various parameters over time](image)
SUMMARY

- Error field correction allows rotational stabilization of Resistive Wall Mode.
- Stable operation has been sustained for almost 2 s at $\beta_N$ well above $\beta_N^{\text{no-wall}}$.
- When magnetic error fields are minimized, toroidal plasma rotation can be sustained by torque from neutral beams.
  - 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.
  - Error fields can also be corrected by shot-to-shot optimization.
- Rapid toroidal rotation increases the effectiveness of the conductive wall in stabilizing Resistive Wall Modes.