Resistive Wall Mode Stabilization with Internal Feedback Coils in DIII–D

by

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in collaboration with


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Advanced tokamak scenarios (and other magnetic fusion concepts) require wall stabilization of external kink modes for operation at high beta.

A finite-conductivity wall does not completely stabilize the ideal kink mode, but converts it to a slowly-growing Resistive Wall Mode (RWM).

There are two approaches to stabilization of the resistive wall mode:

- Passive: rapid plasma rotation
- Active: feedback control

Internal coils are predicted to be effective for both passive and active control of RWMs.

DIII–D internal coils support RWM stabilization by plasma rotation:
- Feedback-controlled error field correction

DIII–D internal coils improve RWM stabilization by direct feedback control:
- Stabilization at higher beta, lower rotation than external coils.
TWO DISTINCT APPROACHES FOR RWM CONTROL HAVE BEEN PROPOSED

Passive: Plasma Rotation with Dissipation
- Required rotation for stability
  ~ a few % of Alfvén velocity

Active: Magnetic Feedback
- Required power level is modest

\[ \Omega = 0 \]

\[ G = 0, G = -5, G = -10 \]

STABLE

Ideal-Wall Limit

Increase Rotation

Higher Gain

Ideal-Wall Limit

\[ \gamma \tau_w \]

\[ \beta \rightarrow \]

No-Wall Limit

\[ \beta \rightarrow \]

Ideal-Wall Limit

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PLASMA ROTATION AND DIRECT FEEDBACK CONTROL PROVIDE STABILITY WITH A RESISTIVE WALL

- Rotation stabilizes RWM before feedback is turned on
- Feedback becomes important as rotation decreases
- Resistive wall mode grows ($\gamma^{-1} \sim 4$ ms) when feedback is turned off

**Graphical Representation:**

- $\beta_N$ axis
- $V_\phi$ at $q = 2$ (km/s)
- I-coil Currents (kA)
- $\delta B_p$ (Gauss)

**Timeline:**

- Feedback On
- 2.4 $\ell_i$ ≈ No-Wall Limit

**Time (ms):**

- 1100 to 1500
NEW INTERNAL CONTROL COILS ARE AN EFFECTIVE TOOL FOR PURSUING ACTIVE AND PASSIVE STABILIZATION OF THE RWM

- Inside vacuum vessel: Faster time response for feedback control
- Closer to plasma: more efficient coupling

- 12 “picture-frame” coils
- Single-turn, water-cooled
- 7 kA max. rated current
- Protected by graphite tiles

G.L. Jackson, G01.003
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G.L. Jackson, G01.003
I–COIL CONNECTIONS ALLOW A WIDE RANGE OF \((m,n)\) SPECTRA

- Toroidal mode number: \(0 \leq n \leq 3\)
  - Antisymmetric pairs \((n = \text{odd})\)
    used for most experiments

- Poloidal mode number: \(0 \leq m \leq 4\)
  - 240 degree upper-lower phase difference used for most experiments
ERROR FIELD COMPENSATION IS MOST EFFICIENT WHEN I–COIL FIELD MATCHES RWM STRUCTURE

- Correction field pitch scanned by varying upper/lower coil connections
- Correction field amplitude and phase determined by feedback control
- Constant phase is consistent with correcting a fixed error field

\[ \Delta \phi = \text{Upper-Lower Coil Phase Difference (deg.)} \]

\[ \Rightarrow \text{Pitch of Applied Field} \]
I–COIL FLEXIBILITY ALLOWS A GOOD MATCH TO THE HELICAL STRUCTURE OF THE $n = 1$ RWM

- Calculated and measured RWM structure agree well

Calculated Mode Structure at Plasma Surface

Measured Mode Structure at Vessel Wall

Calculated I–coil Field at Plasma Surface ($\Delta \phi = 240^\circ$ Connection)
MODELING PREDICTS THAT INTERNAL COILS IMPROVE RWM STABILIZATION BY FEEDBACK CONTROL

- Improved feedback performance is predicted for internal coils
  - Faster time response
  - Improved coupling to plasma
- Feedback stabilization up to the ideal-wall limit requires that coil-wall coupling is not too large, compared to direct coil-plasma coupling:

\[ C = \frac{M_{pw} M_{wc}}{L_w M_{pc}} \leq 1 \]

  - In cylindrical model: \( C = 1 \) for external coils;
    \[ C = \left( \frac{r_c}{r_w} \right)^{2m} \] for internal coils
- Feedback performance is improved with internal poloidal field sensors
  - Faster time response
  - Decoupled from radial field of control coils
SIMPLE ANALYTIC MODEL OF RWM FEEDBACK SHOWS BENEFITS OF INTERNAL COILS

- Slab model with decoupled poloidal field sensors
- Strong reduction in gain, even for small coil-wall spacing

![Graph showing the gain vs. \( \gamma_0 \tau_w \) (Unstabilized Growth Rate) with different coil configurations and wall distances.]

- External Coils
- Internal Coils
- DiIII-D

- Gain values for different wall distances:
  - \( d/r = 0.008 \)
  - \( d/r = 0.015 \) 
    - \( \sim \) DiIII-D
  - \( d/r = 0.03 \)
I-COIL SHOULD PROVIDE RWM STABILIZATION COMPARABLE TO AN IDEAL WALL

- Modeling with VALEN (3D electromagnetics code) using realistic geometry
  - Idealized amplifiers (optimistic)

![VALEN 3-D Graph]

- Growth Rate (s⁻¹)
- No Feedback
- Previous 6-coil set
- 12-coil set (internal)

![Diagram of DIII-D Device]

- Upper I-coils
- Lower I-coils
- Bp probe
- C-coils

DIII-D NATIONAL FUSION FACILITY SAN DIEGO
NOISE AND TIME DELAY LIMIT FEEDBACK CONTROL

- Time-dependent modeling with VALEN
- With noise, system can approach (but not reach) ideal wall limit
  - Broadband noise (1.5 Gauss) and ELMs (6 to 16 Gauss)
  - Resonant RWM response to noise increases closed loop current

- Feedback loop delay time $\tau_d$ also limits beta
  - Stabilization limited to $\gamma_{RWM} \leq 0.25 \tau_d^{-1}$

Ideal-Wall Limit

$C_\beta = \frac{\beta - \beta_{no-wall}}{\beta_{ideal-wall} - \beta_{no-wall}}$

Noise on the Sensor (Gauss)

Max Current (Amp)
DIII–D INTERNAL COILS ASSIST RWM STABILIZATION BY PLASMA ROTATION

- I–coil selectively and efficiently corrects the resonant component of the error field

- Previous experiments have confirmed theoretical predictions that RWM is stabilized by plasma rotation frequency ~few % of Alfvén frequency
  - $f_{\text{rot}} \sim 5–10$ kHz for typical DIII–D plasmas

- Minimization of magnetic field errors is crucial to rotational stabilization
  - A weakly stabilized RWM has a resonant response to an external magnetic perturbation (field error, for example)
  - Resonant enhancement of the magnetic perturbation slows the plasma rotation, leading to loss of stability

- Feedback-controlled error field correction with the I-coil maintains plasma rotation
  - Resonant response of stable RWM enhances detection of small error fields
  - Feedback system corrects the error field by minimizing the plasma response

A.M. Garofalo, QP1.031
J.T. Scoville, QP1.036
“MHD SPECTROSCOPY” PROBES RWM RESONANCE

- Frequency scan of rotating $n = 1$ field applied with I–coil
- Plasma response has resonant peak at $f_{RWM} \approx 15$ Hz
- Plasma response increases as $\beta$ rises above the no-wall limit

Resonant Field Amplification ($n = 1$) Measured with Midplane $B_r$ Loops

- Amplitude
- Phase (deg)
- Frequency of Externally Applied Field $f_{ext}$ (Hz)

$\beta$ 40% above no-wall limit
$\beta$ 20% above no-wall limit

H. Reimerdes, G01.003
I-COIL WITH FEEDBACK CONTROL CAN NULL OUT RESONANT FIELD AMPLIFICATION FROM AN EXTERNALLY APPLIED FIELD

○ n = 1 error field pulse applied with external C-coil

\[ \delta B_{n=1} \text{ (gauss)} \]

\[ n = 1 \text{ Plasma Response} \]

Positive Feedback

No Feedback

Negative Feedback

\[ I\text{-Coil with feedback control can null out resonant field amplification from an externally applied field} \]

Time (ms)

2100 2200 2300 2400 2500

I-Coil

\[ n = 1 \text{ ampl. (kA)} \]

Positive Feedback

Applied \( B_{n=1} \) Field (C-coil)

No Feedback

Negative Feedback

\[ n = 1 \text{ plasma response} \]

113157 113162 113161

\[ \text{DIII-D} \]

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12.0

0.0

-2.5

2.5

0.0

2.5

12.0

113157 113162 113161

\[ \text{DIII-D} \]

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FEEDBACK–CONTROLLED ERROR FIELD CORRECTION ALLOWS SUSTAINED OPERATION ABOVE THE NO-WALL BETA LIMIT

- Rotation and stability are lost if error correction is turned off
Stability at higher beta
— Closer to ideal-wall limit

Stability at lower rotation
— Farther below critical rotation frequency

Consistent with modeling
FEEDBACK CONTROL WITH THE I-COIL SUCCESSFULLY STABILIZES THE RESISTIVE WALL MODE

- Rotational stabilization is slowly decreasing
- RWM becomes unstable during 10 ms when feedback is off

![Graph showing the stabilization effect of the I-coil on the resistive wall mode](image-url)
FEEDBACK CONTROL WITH I–COILS STABILIZES RWM AT HIGHER BETA AND LOWER ROTATION

- Good qualitative agreement with MARS modeling of rotational stabilization
  - Feedback allows discharges to go beyond rotation-only stability limit

\[
C_\beta = \frac{\beta_n - \beta_{n \text{ no-wall}}}{\beta_{n \text{ ideal-wall}} - \beta_{n \text{ no-wall}}}
\]

MARS Prediction
q = 2

I-coil Gp/Gd
114819 40/20
114820 40/40
114821 40/0
114822 40/80
114817 No FB

NO FEEDBACK

Magnetic Braking

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FEEDBACK CONTROL WITH INTERNAL COILS STABILIZES RWM WITH LOW ROTATION

- Magnetic braking reduces rotation to zero in the outer half of the plasma
- Feedback with internal coils maintains stability for >100 ms
- Case without feedback becomes unstable at lower beta, even with rotation
FEEDBACK WITH I-COIL CAN CONTROL RWM GROWTH CLOSER TO THE IDEAL WALL LIMIT

- Observed growth rate of unstable RWM is consistent with VALEN calculation
I-COIL PROVIDES SUSTAINED WALL STABILIZATION AT HIGH BETA

- Beta exceeds estimated no-wall limit for >1 s
  - $\beta_N \sim 6 \ell_i$
  - $\beta_T \sim 6\%$

![Graph showing time series data for $\beta_N$, $\beta_T$, $P_{NB} (10 \text{ MW})$, and $q_{95}$ over time (ms).]
FUTURE WORK

● Continue to develop basic physics of RWM stabilization
  — In cooperation with JET, JT-60U, ASDEX-Upgrade, MAST, NSTX, HBT-EP, . . .
  — High priority of International Tokamak Physics Activity (ITPA)

● Validate models of feedback control – with and without rotation
  — Develop means of controlling rotation
    ★ Magnetic braking
    ★ RF heating
    ★ Counter-NBI (planned)

● Increase bandwidth of feedback system
  — Modeling indicates bandwidth increase ~factor of 3 is needed to reach the ideal-wall limit
  — Improve existing system
  — Audio amplifiers

● Routine application to stabilization of advanced tokamak plasmas in DIII–D
SUMMARY

- DIII–D’s new internal coils have improved passive and active control of resistive wall modes

- Feedback-controlled correction of resonant error field allows RWM stabilization by plasma rotation
  - Good agreement with calculated mode structure
  - Rotational stabilization sustained for >2.5 s (>500 $\tau_w$)

- Initial results confirm direct feedback contributes to stabilization of the RWM
  - Stability with plasma rotation well below the threshold for RWM stabilization
  - Better performance than external coils

- Flexible, high-bandwidth control coils have many other applications in measurement and control of MHD stability
  - MHD “spectroscopy”
  - Stochastic boundary for pedestal control

RWM orals: GO1.002–3 (Tuesday PM)
RWM posters: QP1.027–37 (Thursday AM)