Control of the Resistive Wall Mode with Internal Coils in the DIII–D Tokamak (EX/3-1Ra)

Active Measurement of Resistive Wall Mode Stability in Rotating High Beta Plasmas (EX/3-1Rb)

by

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CONTROL OF THE RESISTIVE WALL MODE WITH INTERNAL COILS IN THE DIII–D TOKAMAK


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ACTIVE MEASUREMENT OF RESISTIVE WALL MODE STABILITY IN ROTATING HIGH BETA PLASMAS

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20th IAEA Fusion Energy Conference, Vilamoura, Portugal 2004
EXTERNAL KINK CONTROL WITH RESISTIVE WALL WALL

● Steady state advanced tokamak scenarios need wall stabilization of external kink modes
  — for operation at high beta with a high fraction of bootstrap current

● Finite-conductivity wall
  — Does not completely stabilize ideal kink mode,
  — Converts it to a slowly-growing Resistive Wall Mode (RWM)

● Two approaches to RWM stabilization
  — Passive: fast plasma rotation (EX/3-1Ra)
  — Active: magnetic feedback control (EX/3-1a)

● New Internal coils installed just after the last IAEA conference:
  Very productive for RWM physics studies and active control of RWMs
  — Active MHD spectroscopy with applied rotating field:
    RWM stability physics
  — Plasma rotation sustained by feedback-controlled error field correction:
    Long duration high $\beta$ plasmas
  — Direct feedback control:
    RWM stability at higher beta below critical rotation
NEW INTERNAL CONTROL COILS ARE AN EFFECTIVE TOOL FOR PURSUING STABILIZATION OF THE RWM

- Inside vacuum vessel: Faster time response for feedback control
  Closer to plasma, flexible magnetic field pattern: more efficient coupling

- 12 "picture-frame" coils
- Single-turn, water-cooled
- 7 kA max. rated current
- Protected by graphite tiles
- 10 gauss/kA on plasma surface
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FEEDBACK WITH I-COILS INCREASES STABLE PLASMA PRESSURE TO NEAR IDEAL-WALL LIMIT

- VALEN code prediction

Normalized Growth Rate $\gamma \tau_w$

Resistive Wall Mode: Open loop growth rate

$$c_\beta = \frac{\beta - \beta_{\text{no.wall}}}{\beta_{\text{ideal.wall}} - \beta_{\text{no.wall}}}$$

$\beta_{\text{no.wall}}$ is the vacuum vessel flux diffusion time (5 ms is used in VALEN code)

- VALEN code:
  - DCON MHD stability
  - 3D geometry of vacuum vessel and coil geometry

DIII-D

VALEN code:

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FEEDBACK WITH I-COILS INCREASES STABLE PLASMA PRESSURE TO NEAR IDEAL-WALL LIMIT

- **C-coil stabilizes slowly growing RWMs**

- **VALEN code:**
  - DCON MHD stability
  - 3D geometry of vacuum vessel and coil geometry

- **τₘ is the vacuum vessel flux diffusion time constant**
  (5 ms is used in VALEN code)

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

\[
\gamma = \frac{G}{\tau_w}
\]
FEEDBACK WITH I-COILS INCREASES STABLE PLASMA PRESSURE TO NEAR IDEAL-WALL LIMIT

- I-coil stabilizes RWMs with growth rate 10 times faster than C-coils

VALEN code:
- DCON MHD stability
- 3D geometry of vacuum vessel and coil geometry

\( \tau_w \) is the vacuum vessel flux diffusion time (5 ms is used in VALEN code)

\[
C_\beta = \frac{\beta_{\text{ideal.wall}} - \beta_{\text{no.wall}}}{\beta_{\text{no.wall}}}
\]
OBSERVED OPEN LOOP GROWTH RATES AGREE WITH VALEN PREDICTION

VALEN prediction
No Feedback

γτ_w

No-wall limit

Ideal-wall limit

C_β

0.0

1.0

0

10

20

30

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TWO DISTINCT STABILIZATION APPROACHES HAVE BEEN PROPOSED

Plasma Rotation
- **Required**: A few % of Alfvén velocity

Magnetic Feedback
- **Required**: Practical power level
- **System stability limits gain**

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**Exp/3-1Rb**

- **No-Wall Limit**
- **Ideal-Wall Limit**

- **$\Omega = 0$**
- **Increase Rotation**

- **STABLE**

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**Exp/3-1Ra**

- **No-Wall Limit**
- **Ideal-Wall Limit**

- **$\Omega = 0$**
- **Gain = 0**
- **Higher Gain**

- **STABLE**
WALL STABILIZATION WITH ROTATION ALLOWS HIGH BETA OPERATION

- Stable at $\beta_N \approx 6 \ell_i$ and $\beta_T$ reaching to 6%
- Beta exceeds estimated no-wall limit for $>1s$ ($> 200 \tau_w$)

- Broad current profiles can greatly benefit from wall stabilization

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HOW MUCH PLASMA ROTATION IS REQUIRED TO STABILIZE THE n=1 RWM?

Insufficient error field correction causes slow-down

Onset of RWM marks critical rotation $\Omega_{\text{crit}}$

Measured rotation threshold

$\Omega_{\text{crit}}$ / $\Omega_A$ (%) (q = 2)

$\beta_N$

$\Omega_{\text{rot}}/(2\pi)$ at $\rho=0.6$ (kHz)

$\Omega_{\text{crit}}/(2\pi)$

$B_{\text{ESL}}$ n=1 amplitude (Gauss)

Time (ms)

$\Omega_{\text{crit}}/\Omega_0$ (kHz)

$\rho=0.6$ (kHz)

$\Omega_{\text{rot}}/(2\pi)$

$\beta_N$

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$B_{\text{ESL}}$ n=1 amplitude (Gauss)

Time (ms)
HOW MUCH PLASMA ROTATION IS REQUIRED TO STABILIZE THE n=1 RWM?

Onset of RWM marks critical rotation $\Omega_{\text{crit}}$.

Soundwave damping overestimates the critical rotation.

Kinetic damping underestimates the critical rotation.

MARS includes rotation and viscous dissipation.
MHD SPECTROSCOPY PROBES THE RWM STABILITY WHILE THE PLASMA REMAINS STABLE

\[ \beta_N \]

Upper I coil (\( \phi=30\text{Deg} \)) (kA) (10 Hz)

Midplane \( B_r \) (\( \phi=139\text{Deg} \)) (Gauss) (10 Hz)

Magnitude of \( n=1 \) plasma response (Gauss/kA)

Tor. phase of \( n=1 \) plasma response (Deg.)

\[ \beta \approx 0.5 \]

\[ \beta \approx 0.4 \]

Experiment / fit

Amplitude

Phase shift (Deg.)

Frequency of applied field (Hz)

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SPECTRUM REVEALS GROWTH RATE AND MODE ROTATION FREQUENCY OF THE STABLE RWM

- **Spectrum Analysis with a Single Mode Model**
  \[ \gamma_0 = \gamma_{RWM} + i \omega_{RWM} \]

- **Amplification Factor**
  \[ M \left( 1 + \gamma_0 \tau_w \right) \frac{1}{(i\omega_{ext} \tau_w - \gamma_0 \tau_w)} \]
  - Coupling between external field and RWM

**Experiment**

**Amplitude**
- \( C_{\beta} \approx 0.5 \)
- \( C_{\beta} \approx 0.4 \)

**Phase shift**
- Experiment / fit
  - \( t=1500 \text{ms} \)
  - \( t=1800 \text{ms} \)

**Frequency of applied field (Hz)**

**Growth rate**
- \( \gamma_{RWM} \tau_w \)

**Mode rotation frequency**
- \( \omega_{RWM} \tau_w \)

**Experiment / fit**
- \( \gamma_{RWM} \approx 0.5 \)
- \( \gamma_{RWM} \approx 0.4 \)
SPECTRUM REVEALS GROWTH RATE AND MODE ROTATION FREQUENCY OF THE STABLE RWM

- **Spectrum Analysis with a Single Mode Model**
  \[ \gamma_0 = \gamma_{RWM} + i \omega_{RWM} \]

- **Amplification Factor**
  \[ M \left( 1 + \frac{\gamma_0 \tau_w}{(i \omega_{ext} \tau_w - \gamma_0 \tau_w)} \right) \]
  Coupling between external field and RWM

- **MARS Comparison**
  - Growth rate
    - sound wave / kinetic overestimates stabilizing effect
  - Mode rotation frequency
    - kinetic: agreement
    - sound wave damping underestimate coupling
TWO DISTINCT STABILIZATION APPROACHES HAVE BEEN PROPOSED

Plasma Rotation
- Required: A few % of Alfven velocity

Magnetic Feedback
- Required: Practical power level
- System stability limits gain

● Rational surface damping mechanism \( \rightarrow \Omega \) at \( q=2 \) as a measure of rotations
DIRECT MAGNETIC FEEDBACK SUSTAINS BETA ABOVE NO-WALL LIMIT EVEN WHEN $\Omega_{\text{rot}} < \Omega_{\text{crit}}$

$\beta_N$

$\Omega_{\text{rot}} / \Omega_A$

(at $q=2$)

Feedback Current (kA)

$\delta B_p n=1$

Amplitude (gauss)

$2.4 \ell_i$

Estimated no-wall limit

Feedback on

Feedback off

1%

Stable

Growth time $\approx 4$ ms

Time (ms)
FEEDBACK SUSTAINS A DISCHARGE WITH NEAR-ZERO ROTATION AT ALL n=1 RATIONAL SURFACES

- Comparison case without feedback is unstable even with lower beta and faster rotation

The graph shows the evolution of rotation frequency, time, and magnetic field perturbation with and without feedback. The feedback stabilized with low rotation maintains stability, while the comparison case without feedback is unstable even with lower beta and faster rotation.
FEEDBACK WITH I-COILS HAS ACHIEVED HIGH $\beta_N$ AT ROTATION BELOW CRITICAL PREDICTED BY MARS

\[ C_\beta = \frac{\beta - \beta_{\text{no.wall}}}{\beta_{\text{ideal.wall}} - \beta_{\text{no.wall}}} \]
With near zero rotation, $C_\beta$ is near the maximum set by control system characteristics.

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

MARS /VALEN prediction for zero rotation, with measured feedback system time response.
FEEDBACK WITH I-COILS HAS ACHIEVED HIGH $\beta_N$ AT ROTATION BELOW CRITICAL PREDICTED BY MARS

- With near zero rotation, $C_\beta$ is near the maximum set by control system characteristics
- Feedback with I-coils attained $C_\beta$ higher than with C-coils

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

MARS /VALEN prediction for zero rotation, with measured feedback system time response
RWM FEEDBACK ASSISTS IN EXTENDING $\beta_N \approx 4$ ADVANCED TOKAMAK DISCHARGE MORE THAN 1 SECOND

The rotation is similar for both cases
MARS ANALYSIS PREDICTS THAT STABLE FEEDBACK GAIN RANGE IS NARROW

- With experimental profiles and present hardware
- Stable mode becomes unstable with higher gain due to finite feedback time response

\[ \gamma \tau_w \]

RWM growth rate

\[ \tau_w \text{ is } 2.5 \text{ ms in MARS-F} \]
High-bandwidth audio amplifiers are being installed to increase the range of stable operation.

MARS ANALYSIS PREDICTS THAT STABLE FEEDBACK GAIN RANGE IS NARROW

\(\tau_w\) is 2.5 ms in MARS-F
OVERALL SUMMARY

- Active MHD Spectroscopy has been developed to investigate RWM stability (EX/3-1Rb)
  - Detailed comparison of experiments with damping models are now possible
  - Sound wave and kinetic damping model results are comparable to experimental values
  - Further improvements of models are needed for a quantitative comparison

- Direct magnetic feedback with I-coils has been demonstrated as an essential tool for achieving high $\beta$ plasmas (EX/3-1Ra)
  - Internal Coils are more effective and efficient than External Coils
  - High $\beta_n$ close to ideal-wall limit has been achieved with $\Omega_{\text{rot}} < \Omega_{\text{crit}}$
  - Feedback has assisted in sustaining advanced tokamak discharges with $\beta_n \approx 4$ over 1 second
  - High-bandwidth audio-amplifiers are being installed to increase the range of stable operation