RWM Feedback of AT plasmas with Audio Amplifiers on the DIII-D Device
- Issues of Robustness of Feedback Performance -

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Synergetic Advantage of Combined RWM Stabilization with Rotation and Feedback Substantially Reduces Both Required Plasma Rotation and Feedback Gain

Marginal stability condition ($\gamma \tau_w = 0$) with Rotational stabilization

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

Unstable

Rotation-alone stabilizing

AT Reactor

Target

FY05 Exp. condition

FY06 Balanced NBI

ideal wall limit

no wall limit

$0.0$

$1.0$

$\Omega/$ $\Omega_{\text{crit\_max}}$

$\gamma \tau_w = 0$

$\Omega_{\text{crit\_max}}$

$1.0$
Synergetic Advantage of Combined RWM Stabilization with Rotation and Feedback Substantially Reduces Both Required Plasma Rotation and Feedback Gain

Marginal stability condition ($\gamma\tau_w = 0$) with Rotational stabilization + Feedback

Combined stabilization Feedback gain

$$G = \frac{\delta \Psi_{FB, coil}}{\delta \Psi_{mode, sensor}}$$

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

AT Reactor Target

FY06 Balanced NBI

FY05 Exp. condition

Feedback G = 0.1

Rotation-alone stabilizing

Rotation + FB stabilizing

DIII-D National Fusion Facility
Synergetic Advantage of Combined RWM Stabilization with Rotation and Feedback
Substantially Reduces Both Required Plasma Rotation and Feedback Gain

Marginal stability condition ($\gamma \tau_w = 0$) with Rotational stabilization + Feedback

Combined stabilization Feedback gain

$$G = \left| \frac{\delta \Psi_{\text{FB coil}}}{\delta \Psi_{\text{mode sensor}}} \right|$$

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

Feedback

$$G = 0.3$$

FY06 Balanced NBI

Rotation alone stabilizing

Target

Rotation + FB stabilizing

Marginal stability condition ($\gamma \tau_w = 0$) with Rotational stabilization + Feedback

FY05 Exp. condition

No wall limit 0.0

Ideal wall limit 1.0

DIII-D

National Fusion Facility
Synergetic Advantage of Combined RWM Stabilization with Rotation and Feedback Substantially Reduces Both Required Plasma Rotation and Feedback Gain

Combined stabilization

Feedback gain

\[ G = \frac{\delta \Psi_{FB, coil}}{\delta \Psi_{mode, sensor}} \]

\[ C_\beta = \frac{\beta - \beta_{no\_wall}}{\beta_{ideal\_wall} - \beta_{no\_wall}} \]

Marginal stability condition \((\gamma \tau_W = 0)\) with Rotational stabilization + Feedback

\(\gamma \tau_W = 0\)

\(\gamma\) - \(\tau_W\) limit

\(\tau_W\) - \(\gamma\) limit

\(0.0\)

\(1.0\)

Feedback \(G = 0.5\)

Rotation-alone stabilizing

FY05 Exp. condition

FY06 Balanced NBI

AT Reactor Target

Rotation + FB stabilizing

\(\beta\) - \(C_\beta\)

\(C_\beta\)

\(\beta_{ideal\_wall}\)

\(\beta_{no\_wall}\)

\(\beta\)

\(\delta \Psi\)

\(\delta \Psi_{FB, coil}\)

\(\delta \Psi_{mode, sensor}\)

\(\delta \Psi\)

\(\gamma\)

\(\tau_W\)

\(\beta_{no\_wall}\)
Two independent power supply system for non-axisymmetric magnetic field is effective and efficient

- Existing Slow Switching Power Amplifiers (SPA) → Dynamic Error Field Correction
- New Audio Amplifiers (AA): DC- 40 kHz → Direct RWM feedback

With better error field correction, RWM behaves as predicted by theory (without feedback)

- Together with commonality of RWM in other devices (JET/NSTX)
  -> added the confidence on RWM physics understanding

RWM feedback assisted the performance in q>2 AT plasmas

Without feedback abrupt events (like ELMs) cause bursting RWMs

- Large ELM event can lead to a major collapse by exciting RWM

With Feedback feedback reduces the n=1 RWM bursting activity

- A possible hidden parameter for robust feedback operation can be "ELM event"
Two Independent Power Supply Combination is Effective and Efficient for Improving the $n=1$ RWM Stabilization

- Rotational Stabilization
- I-coils
- External C-coils
- Internal coils
- RWM Feedback
- Sensor $\delta \Psi$
- High-speed audio amp
- Low-speed SPA
- Dynamic Error Field Correction
- Pre-Programmed correction
- Unknown Error field
- Unknown Error field
- Fast (small current)
- Slow (large current)
Observed Relation: Real Frequency $\omega \tau_w >$ Growth Rate $\gamma \tau_w$
are Consistent with RWM Theory (Without Feedback)

$\gamma^{-1} = 3 \text{ ms}$

$\gamma = 1.6$

$\omega/(2\pi) = 90 \text{ Hz}$

$\omega \tau_w = 2.8$

$\beta n/(4li)$

Four sensor signals

$\delta B_p$ (gauss)

Phase (radian)

$\Omega / \Omega_{\text{crit}}$

MARS Results

Rotationally stabilized

$\gamma = 0$ marginal condition

RWM must rotate with $\omega > \gamma$

Unstable
Audio Amplifiers have been installed to improve the time response. Audio Amplifiers expand the stable operation.

Audio Amplifiers
- 200A 100V
  (6 units in FY05)
- Parallel connection capability
- DC-40 kHz

Audio Amplifiers have been installed to improve the time response.

G. Jackson CP1.0001 9 Monday afternoon
RWM Stabilization Has Opened Path to New High Performance Regimes

- Simultaneous dynamic error field correction and RWM feedback control assists AT operation

\( (\beta_N \sim 4 \text{ with } q_{\text{min}} > 2) \)

- Normalized beta (\( \beta_n \)) graph showing improvement with feedback and error field correction
- C-coil and I-coil x5 graphs indicating coil currents
- \( q_{\text{min}} \) graph showing minimum safety factor
- Pressure graph (in units of \( 10^5 \) Pa)
- Current density graph (in A/cm\(^2\))

-> A. Garofalo  U12.03 Friday Morning
Feedback with Audio Amplifiers Reduces the Bursting $n=1$ Activity

- $\delta B_{\text{max}} \approx 5$ gauss RWM is repetitively excited
Feedback Also Reduces the n=1 RWM Activity at ELM Aftermath

• Sometimes, n=1 RWM amplitude remains finite at the following ELM event
Possible Excitation of Unstable RWM by ELMs (without feedback)

- Hypothesis: Near marginal stability for the RWM ...
  - Sometimes, ELM excites a weakly damped RWM at a large amplitude ($\approx 10$ Gauss)
  - Magnetic braking by the RWM causes plasma rotation to decrease
  - If sufficient braking occurs during the damping time, the RWM becomes unstable

\[
\frac{dB}{dt} (T/s) \quad ELM \quad \Delta B_p (G) \quad \Delta B_p = 50G, \tau_g \approx 1.5 ms
\]

\[
\frac{\delta B_p}{\delta B_p} = 20 G, \quad \tau_g \approx 150 \mu s
\]

\[
\text{Initial ELM instability } \quad \Delta B_p = 50G, \quad \text{Initial } \tau_g \approx 750 ms
\]

\[
\text{Saturated RWM } \quad \Delta B_p = 50G, \quad \tau_g \approx 1.5 ms
\]

\[
\text{Rotation decreasing } \quad \rho \approx 0.6
\]

\[
D_{C\alpha} \quad 2 \text{ ms}
\]
Feedback Suppressed Large Amplitude RWM Buildup and Allows the Plasma to Survive Transient Intervals of Low Rotation

RWM was stabilized while preserving a single mode

ELM events

Rotation $\approx$ zero

Frequency $\approx$ 200 - 300 Hz

Four sensor signals separated by 30 deg.

Three I-coil currents separated by 60 deg.
SUMMARY

• Two independent power supply system is effective and efficient for RWM control,
  - SPA: slow, high current with External Coils --> Dynamic Error field correction
  - New AA: fast, small current with Internal Coils --> RWM feedback
  --> G. Jackson CP1.19 Monday afternoon

• RWM (no feedback) is excited as predicted by RWM theory
  - Universality of RWM in other devices - added confidence on RWM physics understanding
  --> H. Reimerdes GI1.05 Tuesday afternoon (Invited paper)

• RWM feedback assisted the performance in $q_{\text{min}} > 2$ AT plasmas
  --> A.Garofalo U12.03 Friday Morning (Invited paper)

• Without feedback, bursting n=1 RWMs are excited during high beta
  - Possibility of fatal RWM: ELM induces large amplitude RWM leading to rotation collapse
  --> T. Strait : CP1.22 Monday afternoon

• Feedback reduced these n=1 bursting activities
  - Feedback can avoid the beta collapse even though rapid rotational collapse takes place
  - Need of precise mode identification near ELM event
  --> Y. In: CP1.00021 Monday afternoon

• A possible hidden parameter of robustness for RWM control is "ELM events"
  - will be studied in FY06 with AA currents up to 1200A in balanced NBI low rotation plasmas
  --> G. Jackson CP1.19 Monday afternoon