Magnetic Feedback Strategy Near No-wall Stability Limit

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Magnetic feedback control would be the indispensable tool to bridge physics and engineering in high-\(\beta\) plasmas

- The RWM stabilization is essential to sustain high performance plasmas in ITER or reactor-grade devices

- Although passive RWM stabilization is ideal, both the uncertainty of pressure-driven RWM stability boundary and pending experimental evidence challenge the robustness of the concept

- Even if RWM is passively stabilized, a coupling of marginally stable RWM with other MHD activities readily destabilizes the plasmas, requiring another safeguard (e.g. magnetic feedback control)\(^1,2\)

\(^1\)M. Okabayashi et al, NF(2009); \(^2\)Y. In et al, PPCF (2010);
Several challenges need to be addressed for successful magnetic feedback control near no-wall stability limit.

### Physics-oriented
- Resonant Field Amplification
- Uncertainty of RWM stability boundary
- Preciseness of feedback
- Multimode identification

### Engineering-oriented
- Error Field Correction
- Robustness of RWM stabilization
- Effectiveness of feedback
- Multimode control

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**Potential Problems**

**Enabling Solutions**
The requirements of direct feedback (DF) stabilization on RWM have been specified.*

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Potential Problems

*Y. In et al., MHD workshop (2009); Y. In et al, PPCF (2010)*
The EFC strategy also needs to be developed in consideration of RWM stability*

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* Y. In et al., IAEA FEC, Daejon, Korea (2010);
Outline

• Introduction
  – Distinction between EFC and DF stabilization on RWM
  – Magnetic feedback control system in DIII-D

• Magnetic feedback in low-$\beta$ plasmas
  – Subtlety of EFC in stable, marginal, and unstable RWM regimes

• Magnetic feedback in high-$\beta$ plasmas
  – Broadband magnetic feedback

• Conclusions
The EFC is to minimize the lack of axisymmetry of external fields that vary slower than wall characteristic time $\tau_w$.

- The roles of error-field-correction (EFC) and direct feedback (DF) stabilization on RWM are distinctive in magnetic feedback control.

“The EFC is to minimize the lack of axisymmetry of external fields, while the DF stabilization on RWM is to nullify the magnetic perturbation originating from unstable RWM” \(^1\)

- Unstable RWM is extremely sensitive to any small but uncorrected resonant EF.

\(^1\)Y. In et al, NF (2010)
Magnetic feedback control system is primarily required to reduce the resonant component in plasmas

**Strategy against the resonant $\delta B_{n=1}$** ($=\delta B_{EF}+\delta B_{RWM}+? $)

- **Pre-programmed EFC**
  
  $[\text{bandwidth} << \tau_w^{-1}]$
  
  - Duplicate the “optimized” feedback coil currents (usually requires a few iterations of DEFC)
  
  - Empirical formula of error fields with respect to $I_p$ and $B_t$ (popular but insufficient in high-$\beta$)

- **Dynamic EFC (DEFC)**
  
  $[\text{bandwidth} < \tau_w^{-1}]$
  
  - Feedback-controlled EFC
  
  [See also Garofalo, La Haye, Scoville, NF (2002)]

- **Direct Feedback**
  
  $[\text{bandwidth} > \gamma_0 (\sim \tau_w^{-1})]$

where $\tau_w^{-1}$: resistive wall characteristic frequency
DIII-D is uniquely equipped with internal coils for fast time response and external feedback coils for slower time response.

• **Tools**
  - Internal coils ("I-coils"):
    - Direct Feedback + Dynamic/Pre-programmed EFC
  - External coils ("C-coils"):
    - Dynamic/Pre-programmed EFC

• **Magnetic feedback control**

\[ V_{FB}^{n=1}(\tau_{w},\tau_{L/R}, \delta I_{FB}^{n=1}) \]

\[ \text{Plant (DIII-D/RWM)} \]

\[ \text{Controller} \]

\[ K(s) = \frac{1}{1+Ts} \left( G_p + \frac{G_d s}{1+s\tau_d} \right) \]

- \( G_{p,d} \) : Gain
- \( \tau_{p,d} \) : time constant
- \( p \) - proportional, and
- \( d \) - derivative

\[ ? : \text{Unknown n=1 error field} \]
Reproducible current-driven RWMs during low-$\beta$ ohmic discharges provide a simple system for feedback tests$^{1,2}$

- Error field (EF) closely tied with RWM stability
- A part of EF topology, similar to that of RWM
- So, RWM control system can also be used for EFC

- Current-driven RWM (in low-$\beta$) vs pressure-driven RWM (high-$\beta$)
  - Similar external mode structure, as well as $\tau_g = \gamma_0^{-1} \sim \tau_w$
  - BUT, little or no passive sources of stabilization (e.g. rotational stabilization$^3$, kinetic effects$^4$)

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1 Y. In et al, PPCF (2010) 2Y.Q. Liu et al, PoP (2010);
Active feedback control is required to stabilize RWM

- Pre-programmed currents that duplicate the feedback output do not provide stabilization\(^1\)

\(^1\)Y. In et al, NF (2010)
The RWM feedback action should be taken faster than the mode growth time, as predicted\(^1\), \(^2\)

\[ \tau_p \text{ scans with a fixed gain} \]

\[ \delta B^{n=1}[G] \]

\begin{align*}
10 \text{ ms} & \quad 5 \text{ ms} & \quad 1 \text{ ms} & \quad 0.05 \text{ ms} \\
0 & \quad 5 & \quad 10 & \quad 15 & \quad 20
\end{align*}

\[ \tau_g : 3 - 4 \text{ ms} \]

- When \( \tau_p < \tau_g \) : effective, while \( \tau_p > \tau_g \) : ineffective
- \( \tau_p \) : feedback response time

\( ^1\) E.J. Strait et al, NF (2003) \(^2\) Y. In et al, PPCF (2010)
The EFC strategy needs to be developed in consideration of the RWM stability conditions.

- Experimental results (stable and marginal RWMs) are consistent with an analytic cylindrical model.

- Feedback-controlled EFC always underestimates the EF in stable RWM regime, while being predicted to overestimate it in unstable RWM regime.

- In both stable and unstable RWM regimes, high gain helps the feedback coil current converge to the desired EF correction level.

1 M. Okabayashi et al, NF (1998)
Broadband magnetic feedback aiming at active RWM stabilization adds more benefits to high-$\beta$ plasmas

Unlike low-$\beta$ plasmas, high-$\beta$ plasmas requires further understanding about:

- **Stronger plasma response:** non-ideal MHD effect
  - **Resonant field amplification (RFA)**

- **Passive sources of RWM stabilization**
  - **Rotational stabilization** (shielding or braking)

- **Kinetic effects**
  - e.g. **resonance (mode-particle)** with trapped energetic particles ($n_{EP}$) moving in the relevant frequencies of precession-drift and/or bounce

- **Resilience against other MHD events** (e.g. edge-localized modes (ELMs), Fishbones etc): coupling or destabilization
Broadband magnetic feedback appears contributing to improved \( \tau_E \), density and \( \beta_N \)

- The broadband feedback may remove resonant \( \delta B \) (from various bursty MHD events or uncorrected residual error field) quickly, before RFA or coupling with RWM is involved.
BUT magnetic feedback does not remove fishbone-driven kink-like mode nor fishbone-driven tearing mode directly.

(Feedback: $G_p = 40$, $\tau_p = 0.5$ msec)

Before and after a fishbone-driven kink-like mode, followed by tearing.

Fishbone-driven tearing mode.
A systematic comparison in high-$\beta$ plasmas shows the importance of EFC and broadband feedback. Given the plasma conditions (with $\beta_N > 3$), a comparison of no feedback (black) vs DEFC (red) allow for $|\text{RFA}| \sim 7 \text{ G/kA}$. Loss of EFC (no EFC) and DEFC with broadband feedback result in an elevated baseline of $\sim 10 \text{G}$ error field and a required EFC coil current of $\sim 1.5 \text{kA}$.
The feedback did not remove the fishbones, though there were some changes in terms of mode spectra.

Based on a B-dot probe

- The penetration and life times of resonant $\delta B$ could be important.
The resonant $\delta B$ is substantially reduced as expected, as the bandwidth is broadened.

Based on RWM sensor (i.e. integrated signal of B-dot probe)

- Unlike conventional DEFC ($\omega < \tau_w^{-1}$), broadband feedback has reduced resonant $\delta B$
Broadband magnetic feedback in high-\(\beta\) plasmas enhances the decay rates of bursty MHD events

- Broadband magnetic feedback would be an effective tool in enhancing the decay rates of the resonant \(\delta B\) driven by bursty MHD events, as well as in providing the necessary EFC and DF on RWM. [See also Reimerdes et al, PPCF (2007)]
Magnetic feedback-controlled EFC and active RWM stabilization is essential in high-$\beta$ plasmas

- The EFC strategy should be developed in consideration of the RWM stability status (stable, marginal and unstable)

- Broadband magnetic feedback (beyond $\tau_w^{-1}$) appears contributing to improved $\tau_E$, density and $\beta_N$
  - Removes resonant $\delta B$ (from various bursty MHD events or uncorrected residual error field) quickly, before RFA or coupling with RWM is involved

$\rightarrow$ helps to create and sustain high-performance plasmas