ERROR FIELD CORRECTION IN UNSTABLE RESISTIVE WALL MODE (RWM) REGIME

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Feedback-controlled Dynamic Error Field Correction in the unstable RWM regime is highly beneficial in high–β plasma

- **Steady-state, high-β tokamak may require active feedback stabilization of the resistive wall mode (RWM)**
  - uncertain about passive stabilization on RWM by rotation or kinetic effects in burning plasmas
- **High-β operation also requires precise error field correction**
  - Weakly stable RWM can have a strong resonant response to small error fields
- **Feedback-controlled Dynamic Error Field Correction (DEFC) has been successful in high-β plasmas that are stable to the RWM**
  - resonant response to the error field provides input to the feedback system
- **Important differences arise in DEFC when the RWM is unstable (and feedback-stabilized)**
  - requires a different approach to DEFC feedback optimization

Key Points

- The **EFC strategy should be developed in consideration of the RWM stability** status
- **Simultaneous operation of EFC and DF on RWM** could be the only practical method in unstable RWM regime
- A **"fast-track" EFC**, far fewer iterations than the conventional EFC method, has been identified
- **Broadband magnetic feedback** (beyond τ_w^{-1}) helps to create and sustain high-performance plasmas
- **Active feedback stabilization would safeguard steady-state, high-β tokamak against the uncertainty** about passive stabilization on RWM

The EFC is to minimize the lack of axisymmetry of external fields that vary slower than wall characteristic time τ_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]

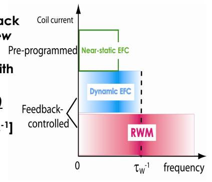
- **Unstable RWM is extremely sensitive to any small but uncorrected resonant EF**

[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 $\delta B^{n=1}$ (=$\delta B_{EF}+\delta B_{RWM}+$?)

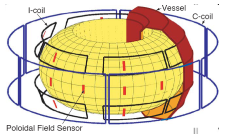
- **Pre-programmed EFC** [bandwidth << τ_w^{-1}]
  - Duplicate the "optimized" feedback coil currents *(usually requires a few iterations of DEFC)*
  - Empirical formula of error fields with respect to I_p and B_t *(popular but insufficient in high-β)*
- **Dynamic EFC** [bandwidth < τ_w^{-1}]
- **RWM** [bandwidth > γ_0 (~ τ_w^{-1})]



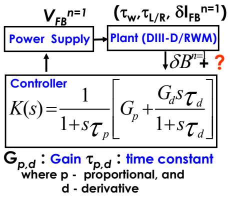
where τ_w^{-1} : resistive wall characteristic frequency

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**



$V_{FB}^{n=1}$ → Power Supply → Plant (DIII-D/RWM) ($\tau_w, \tau_{L/R}, \delta I_{FB}^{n=1}$) → $\delta B^{n=1}$ + ?

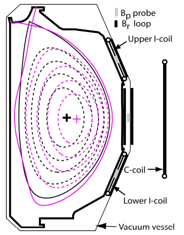
Controller

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

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

? : ***Unknown n=1 error field***

Reproducible current-driven RWMs during low-β ohmic discharges provide a simple system for feedback tests [1, 2]



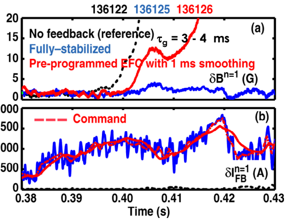
- **Error field (EF) closely tied with RWM stability**
- **A part of EF topology, similar to that of RWM**

➔ **So, RWM control system can also be used for EFC**

- **Current-driven RWM (in low-β) *vs* pressure-driven RWM (high-β)**
  - **Similar external mode structure, as well as τ_g ~ τ_w**
  - **BUT, little or no passive sources of stabilization (e.g. rotational stabilization[3], kinetic effects[4])**

[1] Y. In *et al*, PPCF (2010) [2]Y.Q. Liu *et al*, PoP (2010);
[3] Bondeson and Ward, PRL (1994) [4] Hu and Betti, PRL (2004)

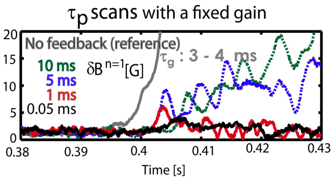
Active feedback control is required to stabilize RWM



- ***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]



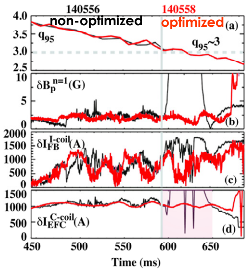
- **When τ_p < τ_g : effective , while τ_p > τ_g :ineffective**

where τ_p is feedback response time that limits the bandwidth

- **So far, the requirements for DF stabilization on RWM were clearly specified (See an example[2])**

[1]E.J. Strait *et al*, NF (2003) [2]Y. In *et al*, PPCF (2010)

Simultaneous operation of DEFC and DF helps us to determine the necessary EFC using the feedback-stabilized RWM

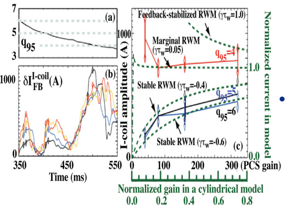


- **Simultaneous operation of DEFC (*C-coil, slow feedback*) and DF (*I-coil, fast feedback*) stabilization on RWM**
  - **Stabilize the unstable RWM**
  - **Based on the feedback-stabilized RWM, the EFC waveform is determined**

➔ **The only practical method (if not the only way) in unstable RWM regime**

- **When the EFC is not sufficient, the DF, which originally aims at stabilizing an unstable RWM, is reacting to the need to correct the uncorrected residual EF**

High gain helps the feedback coil current converge to the desired EF correction level

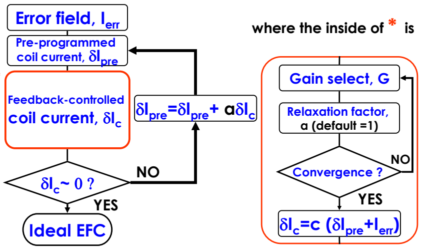


- **Experimental results (*stable* and *marginal* RWMs) are consistent with an analytic cylindrical model**[1]
- **Feedback-controlled EFC always underestimates the EF in stable RWM regime, while being predicted to overestimate it in unstable RWM regime**

[1] M. Okabayashi, N. Pomphrey, R.E. Hatcher, NF (1998)

Iterative approach reduces the feedback error

- **Use feedback output to determine a programmed "offset" current for the next discharge**



Error field, I_{err}

Pre-programmed coil current, δI_{pre}

* Feedback-controlled coil current, δI_c

δI_c ~ 0 ? NO → $\delta I_{pre}=\delta I_{pre}+a\delta I_c$; YES → Ideal EFC

where the inside of * is

Gain select, G

Relaxation factor, a (default =1)

Convergence ? NO → Gain select, G; YES → $\delta I_c=c\,(\delta I_{pre}+I_{err})$

A relaxation factor is introduced to improve the numerical convergence to the desired EFC level

At (i+1)-th iterative step,

$$\delta I_{pre}^{(i+1)}=\delta I_{pre}^{(i)}+a\left[\delta I_{TARGET}^{(i)}-\delta I_{pre}^{(i)}\right]=\delta I_{pre}^{(i)}+a\delta I_c^{(i)}$$

where *a* is the relaxation factor[1]

At the *n*-th step, the pre-programmed current $\delta I_{pre}^{(n)}$ and feedback coil current $\delta I_c^{(n)}$ are

$$\delta I_{pre}^{(n)}=-I_{err}\left[1-(1+ac)^n\right] \qquad \delta I_c^{(n)}=c\,I_{err}(1+ac)^n$$

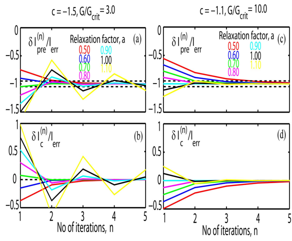
only if |1+ac| < 1 : convergence criterion,

leading to G > G$_{crit}$ [2/(2-a)]

where G$_{crit}$ is defined as the gain necessary to stabilize the unstable RWM

[1] See an example; PRESS, W.H., *et al.*, *Numerical Recipes* (1992)

"Fast Track" EFC strategy can be established using a relaxation factor with high gain

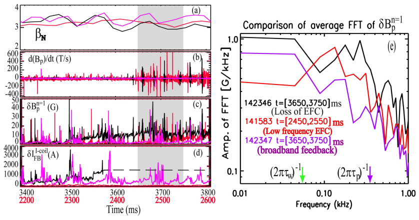


- **Conventional EFC (a=1, black)**
  Low G/G$_{crit}$: 5 times
  High G/G$_{crit}$: 2 times
- **Under-relaxation EFC (a=0.9, cyan) with G/G$_{crit}$ = 10**
  ONLY 1 iteration

In principle, no more need to repeat the same discharges just for EFC

Here, 0 < a < 1(under-relaxation), while 1 < a < 2 (over-relaxation)

Broadband magnetic feedback in high-β 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 components driven by bursty MHD events, as well as in providing the necessary EFC and DF on RWM.**

The methodology to determine the optimized EFC waveform in various RWM regimes is applicable to ITER and beyond

- The **EFC strategy should be developed in consideration of the RWM stability** status (*stable, marginal and unstable*)
- **Simultaneous operation of EFC and DF on RWM** could be the only practical method in unstable RWM regime
  - Demonstrated with little or no passive RWM stabilization sources involved
- A choice of **'under-relaxation' factor with high feedback gain could achieve a "fast-track" EFC**, far fewer iterations than the conventional EFC method
- **Broadband magnetic feedback** (beyond τ_w^{-1}) enhances the decay rates of resonant magnetic perturbations induced by bursty MHD events, helping to create and sustain high-performance plasmas