RESISTIVE WALL MODE CONTROL ON THE DIII-D DEVICE

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SUCCESSFUL RESISTIVE WALL MODE (RWM) CONTROL IS
A PREREQUISITE FOR SUSTAINING IGNITION IN REACTOR ORIENTED DEVICES
- HIGH $b_n$ PROVIDES HIGH BOOTSTRAP CURRENT CONFIGURATION

(Example: Fusion Ignition Research Experiment device)

External kink $b_n$ limit

$\frac{b_n}{ Ip/aB_t}$

Advanced Tokamak Regime with Reversed $q(y)$

Ideal-Wall

No-Wall $b_n$ Limit

Performance

$\frac{bt}{(1+q^2)/2}$

AT Reversed $q(y)$
35 sec burning
(8.5T, 5.3MA)
fbs = 65 - 75%

Conventional $q(y)$
18 sec burning
(10T, 6.5MA)
fbs = 15 - 20%

$\begin{align*}
q = 2 \\
n = 4 \\
q = 3 \\
n = 3 \\
q = 4 \\
n = 2
\end{align*}$
OUTLINE

- Introduction
  - RWM characteristics
  - Two RWM control approaches
    Plasma rotation and magnetic feedback
- Recent RWM control experiments
  - Magnetic feedback compensates residual error field, increasing rotation and plasma pressure
- Achievement
  - Normalized Beta $\beta_n$ reached twice the no-wall limit, $\beta_n^{\text{no-wall}}$
  - $\beta_n$ is near the ideal-wall $\beta_n^{\text{ideal-wall}}$
- Improvement of RWM physics
  - Discovery of error field amplification (EFA)
- Modeling
- Future plan
- Summary
RESISTIVE WALL MODE
- AN EXTERNAL KINK BRANCH WITH RESISTIVE WALL

\[ \frac{dW_p}{dw} + \frac{(dW_p + dW_v)}{(dw + 1)} + (dw + iN) = 0 \]

Stable with Ideal-Wall

Unstable with Resistive-wall

Dissipation Stabilizing

Ideal Kink Shell Branch (ideal-wall)

Unstable Window

Stable Window
RWM CHARACTERISTICS PREDICTED BY THEORY

Mode structure:
- Retains mostly ideal MHD global mode structure

Growth time:
- Wall skin time

Toroidally quasi-stationary

No magnetic islands

-> "Slowly evolving quasi-helical equilibrium"
EXPERIMENT SHOWS THAT THE RW MODE STRUCTURE EXTENDS FROM PLASMA CORE TO OUTSIDE THE VACUUM VESSEL

SXR at two toroidal locations separated by 150°
TWO DISTINCT APPROACHES FOR RWM CONTROL HAVE BEEN PROPOSED

Use of Dissipation (Plasma Rotation: by Bondeson)

Critical rotation velocity for stability a few % of Alfven velocity

Magnetic Feedback

Required power level is modest

Plasma dissipation parameter

No Rotation

Higher Rotation

Stable

\[ G = 0 \]

\[ G = -5 \]

\[ G = -10 \]

No Feedback

Higher Gain

\[ (1 + \frac{n_{\text{ideal-wall}}}{n_{\text{no-wall}}} - \frac{n_{\text{ideal-wall}}}{n_{\text{no-wall}}}) \]

\[ (1 + \frac{n_{\text{ideal-wall}}}{n_{\text{no-wall}}} - \frac{n_{\text{ideal-wall}}}{n_{\text{no-wall}}}) \]
PLASMA ROTATION DELAYS RWM ONSET

A decrease in rotation with $n > n_{\text{no-wall}}$, leading to rapid RWM growth
Small amplitude RWM near threshold may cause rotational drag

Estimated ideal MHD limit

$n=1$ $B_r$ at wall

Plasma Toroidal Rotation $\sim 0.6$
### RWM MAGNETIC CONTROL HARDWARE ON DIII-D

#### Diagram:
- Vacuum Vessel
- Internal $\text{Br}$ Saddle Loops (12 pairs)
- Internal $\text{Bp}$ Probes (4 locations)
- External $\text{Br}$ Saddle Loops (6 pairs)
- Active Coil

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<td><strong>Mode-only flux</strong></td>
<td>$\text{Bp}$ Probe</td>
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**Error Field Correction and Feedback**

**6 coils (3 pairs) + 3 Power Supplies**
INTERNAL LOOPS ARE MORE EFFECTIVE THAN EXTERNAL LOOPS

- Comparison of $^{3}$Br loops with smart shell logic
  - Experiment agrees with theoretical predictions
  - $I_p$ ramp is used to maintain no-wall $B_n$ limit roughly constant in time

![Graph showing comparison between internal and external $B_n$ limits with no feedback and smart shell logic.](image)

- Internal $B_n$ limit
- Estimated no-wall $B_n$ limit
- $\frac{B}{2B}$ vs. Time (ms)
- $I_p$ (MA) vs. Time (ms)

$q_{95} = 4.5$ for external $B_n$ loops
$q_{95} = 4.0$ for internal $B_n$ loops

Comparison of $d$Br loops with smart shell logic
Experiment agrees with theoretical predictions
Internal loops are more effective than external loops.
Bp "MODE CONTROL" IS FAR SUPERIOR TO Br "SMART SHELL LOGIC"

- Plasma rotation was well maintained over a longer duration in spite of lowering edge-q
HIGH $n$ DURATION WAS EXTENDED BY > 500 ms

$n$ reached twice the $n_{no-wall}$, close to $n_{ideal-wall}$ (GATO-code)

MHD at collapse is ideal kink like behavior

(With $B_p$ sensor and modest Ip ramp operation)

$\sim 300$ s

Rotation Period $\sim 1$ ms

Ideal MHD Like Behavior
- Preprogramming coil currents without feedback, matched to currents with feedback, produce similar $b_n$ and rotation.

**FEEDBACK COMPENSATES RESIDUAL ERROR FIELD**

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**Estimated no-wall $b_n$ limit**

- Optimized Preprogram only
- With Feedback

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**Coil Amplitude**

- With Feedback

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**Coil Tor. Phase**

- Optimized Preprogram only
ERROR FIELD AMPLIFICATION (EFA) INCREASED AT $n > n_{\text{no-wall}}$

- Helical resonance to non axi-symmetric magnetic field

- First predicted by A. Boozer
TWO PROCESSES: ROTATIONAL STABILIZATION AND MAGNETIC FEEDBACK HAVE BEEN UNIFIED IN A SYNERGISTIC MANNER, OPENING A PATH TO IDEAL-WALL $n$ LIMIT

Maintain Plasma Rotation  
Reducing Residual Error Field

Magnetic Feedback

RWM / EFA

Sensor

$G=-5$  
no FB  
no Rotation

$G=0$  
Stable

$G=-10$  
Increasing Gain

(1 + \frac{\sqrt{n}_{\text{ideal-wall}} - \sqrt{n}_{\text{no-wall}}}{\sqrt{n}_{\text{ideal-wall}} - \sqrt{n}_{\text{no-wall}}})
LUMPED PARAMETER FORMULATION
- Explicit Presentation of Boundary Condition

\[ j = M_{jk} I_k \]

Dissipation
\[ \frac{\partial}{\partial t}(W + iW) + W_p \]

Plasma

Resistive Wall
\[ \frac{\partial W}{\partial t} + \frac{W_v W}{(W + 1)} = 0 \]

Lumped formulation

Ideal MHD
\[ \left\{ \frac{(a - 2/f)}{m} + a(a \frac{d}{dr}) ) \right\} \right|_{r=a} \]

\[ f = m - nq \]

Plasma surface

Wall surface

Slow time limit:
\[ L_{\text{eff}} I_p + M_{pw} I_w + M_{pc} I_c = 0 \]

\[ L_{\text{eff}} = \frac{(a - 1 + iW + W^2)}{(a + 1 + iW + W^2)} \]

EFA Amplitude \[ 1/L_{\text{eff}} \]

\[ L_{\text{eff}} : \text{equivalent to "magnetic decay index" of vertical instability (I_p <-> Zp)} \]
EFA RESPONSE TO PULSED FIELD IS QUALITATIVELY CONSISTENT WITH MODEL ESTIMATE
EXPERIMENTS SUPPORT "RIGID DISPLACEMENT" MODE STRUCTURE

- Simplify model development of RWM like Lumped parameter formulation and VALEN code

Three Toroidal Arrays of Saddle Loops
Provide Poloidal Mode Structure

Mode Structure Relative to Midplane

\[ \text{Without Feedback (103353)} \]
\[ \text{With Feedback (103355)} \]

\[ \text{Relative Toroidal Angle} \]

\[ \text{Time (ms)} \]

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PROPOSED IMPROVEMENT OF RWM FEEDBACK ON DIII-D

Additional six upper- and six lower- coils and internal Bp sensors increase achievable \( B_n \) very close to ideal-wall \( B_n \) limit (VALEN CODE / no rotation)

\[
\frac{B_n}{B_n} - \text{ideal-wall} - \text{no-wall} \quad \frac{B_n}{B_n} - \text{no-wall}
\]

\( \text{no wall limit} \quad \text{ideal wall limit} \)

No Feedback (no FB)

Present coil and External Br

Present coil and Internal Br

Present coil and internal Bp

New coils and internal Bp

New feedback coil

Present Coil

New feedback coil

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PRINCETON PLASMA PHYSICS LABORATORY
RWM control

- Two schemes, rotational stabilization and magnetic feedback, previously considered distinct, now function as a unified process in a synergistic manner
- Feedback process tracks and compensates the residual error field, maintains the rotation, and achieves high $B_n$
- A key to this success is the use of Bp sensors inside the vessel and mode control logic
- High $B_n$ condition is also achievable with optimized error field correction without feedback

High $B_n$ achievement

- Achievement of twice the no-wall $B_n$ limit close to ideal-wall $B_n$ limit consistent with experimental MHD observation

Understanding of RWM physics

- Greatly improved by the discovery of Error Field Amplification

Future plans

- New coils will be installed for achieving high $B_n$ over wide parameter ranges