RWM Control in FIRE and ITER

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OUTLINE

• REVIEW OF VALEN MODEL

• BENCHMARKING MARS & VALEN/DCON
  + MAPPING OF ‘S’ TO $b_N$: IDEAL WALL BETA LIMIT
  + TRANSITION TO IDEAL BRANCH IN DISPERSION RELATION

• CRITICAL ISSUES IN RWM CONTROL DESIGN
  + ITER PASSIVE STABILIZER PERFORMANCE: IMPORTANT ROLE OF THE BLANKET MODULES
  + CONTROL COIL-PLASMA-STABILIZER COUPLING OPTIMIZATION IN FIRE AND ITER
  + POWER REQUIREMENTS: INITIAL VALUE SIMULATIONS AND EFFECTS OF NOISE
VALEN combines 3 capabilities

- Unstable Plasma Model (PoP Boozer 98)
- General 3D finite element electromagnetic code
- Arbitrary sensors, arbitrary control coils, and most common feedback logic (smart shell and mode control)
VALEN Model

• All conducting structure, control coils and sensors, are represented by a finite element integral formulation, we have a matrix circuit equation: i.e.,

\[
[L]\{\dot{I}\} + [R]\{I\} = \{V(t)\}
\]

• Unstable Plasma mode is modeled as a special circuit equation. We start with a plasma equilibrium, use DCON without any conducting walls, to obtain \(\delta W\), and the magnetic perturbation represents the plasma instability.

• The instability is represented via a normalized mode strength

\[
s = \frac{-\delta W}{(LI^2 / 2)}, \quad \text{the equations are now}
\]

\[
[L'(s)]\{\dot{I}\} + [R']\{I\} = \{V'(t)\}
\]

\(L\)
VALEN predicts growth rate for plasma instability as function of the instability strength parameter 's'

- 's' is a normalized mode energy

\[ s = \frac{-\delta W}{(LI^2 / 2)} \]

- computed dispersion relation of growth rate vs. 's' is an eigenvalue calculation

![Graph showing ideal and resistive branches](image)
The ITER vacuum vessel is modeled as a double wall configuration with time constants for low order modes in range 0.15 s to about 0.3 s.
DCON Calculation of ITER RWM: B-normal vs Poloidal Angle

Use B-normal to Compute Equivalent Plasma Surface Current
RWM Induces Stabilizing Image Currents Largely on the Inner Vessel Wall

- Vacuum Vessel Modeled with and without wall penetrations.
ITER Double Vacuum Vessel Passive RWM Dispersion Relation

- Shows usual transition from RWM to Ideal Branch at $s \sim 0.1$
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DCON Benchmark with Series of Conformal Wall ITER Equilibria

EQDSK_512x512_a(series)

- Use series of ITER conformal wall equilibria as input into VALEN
Benchmark Calibration of VALEN with DCON

- DCON ideal $\beta_N$ limit found for series of conformal wall ITER plasmas.
- VALEN ideal $s$ limit found for same conformal wall series.

Use to calibrate $\beta_N$ vs $s$
Use DCON Computation of $\delta W$ to Calibrate $s$ to $b_N$

- Error found in DCON ‘$\delta W$’ to VALEN ‘$s$’ conversion!
- This NEW calibration used to replot passive response.
Note absence of Ideal Kink Branch Transition when $C_b \sim 1$

In Liu, et al., $\frac{\Delta}{\text{wall}} \sim 0.188$ s so at $C_b \sim 1$ is between 53 to 120 s$^{-1}$

In VALEN modeling, $\frac{\Delta}{\text{at}} C_b \sim 1$ is between 1000 to $10^4$ s$^{-1}$

Growth rate disparity consistent with $\frac{\Delta}{\text{wall}}$ in Liu, et al. too small for claimed values of $C_b$
VALEN vs MARS RWM Benchmarking

New MARS results and benchmarked VALEN results agree!
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Include ITER Ports & Blanket Modules in Passive RWM Stabilization Model

- Modeled as set of isolated plates above the inner vessel wall.
- Each blanket module adjusted to have 9 ms radial field penetration time constant.
ITER Ports Cause Small Reduction in Ideal Limit

- No wall $\mathcal{N}$ limit is 2.4; Ideal Wall Limit Drops to $\mathcal{N} \sim 3.3$
VALEN Model of ITER Double Wall Vessel and Blanket Modules
ITER Blanket Opens Up Large AT Regime

- No wall $\frac{2}{3}$ limit is 2.4; Ideal Wall Limit With Blanket is 4.9!
Basic Feedback Control Loop with Voltage Amplifiers and Sensors Uncoupled to Control Coils

Amplifier: Gp and Gd

Control Coils

B-radial

Plasma Response RWM

no-coupling

Feedback Volts/Weber

Bp Sensors
The ITER vacuum vessel is modeled as a double wall configuration using design data provided by Gribov, with feedback control provided by 3 $n=1$ pairs of external control coils on the mid-plane.
VALEN Model of ITER Vessel and Control Coils: Base Case Feedback Control System

- Vacuum Vessel Modeled with and without wall penetrations.
• Feedback Saturates at $\beta_n \sim 2.97$ for $G_p=10^8$ V/W & $G_d=10^9$ V/V
• $G_p=10^8$ V/W is Liu’s $K_i=0.32$ and $G_d=10^9$ V/V is Liu’s $K_p=15.6$
ITER Basic Coils: Use Liu & Bondeson Gain Parameters

- Liu uses $V_f = -L_f b_s / bo s[K_i/s+K_p ]; b_o=28x10^{-7}T/A; L_f=0.04H; b_s=F_s/A_s$
- VALEN uses $V_f = - L_f / b_o A_s [K_i+K_p d/dt ] [ ] s = -1.4x10^8[K_i+K_p d/dt ] [ ] s$
- $G_p= 6x10^8 V/W$ is Liu’s $K_i=4.318$ and $G_d= 2x10^8 V/V$ is Liu’s $K_p=1.5$
- These values reduce $\Delta N \sim 2.78!$ Only 15% towards ideal limit!!
RWM Dispersion Relation with Mode Control Feedback*

* A. Boozer, Phys. Plasmas 5, 3350 (1998)

Apply Voltage to Control Coil, \( V_f(t) = -\frac{L_f}{M_{fp}} \left[ \boxtimes \ G_p + G_d \frac{d}{dt} \right] \ boxtimes \)

\( G_p = \) Proportional Gain \( \quad G_d = \) Derivative Gain

\( \boxtimes = \frac{R_{wall}}{L_{wall}} \quad \boxtimes_\tau = \frac{R_{control \ coil}}{L_{control \ coil}} \quad \boxtimes_\tau = \) feedback delay

\[ a_3 \boxtimes^3 + a_2 \boxtimes^2 + a_1 \boxtimes + a_0 = 0 \]

\[ a_0/\boxtimes = -\boxtimes + \boxtimes_\tau \ G_p \]

\[ a_1 = \boxtimes \ \text{D}(s) + \boxtimes_\tau \left[ G_d + c_f \ G_p - s \right]/s \]

\[ a_2 = \text{D}(s) + c_f \ G_d/s \quad a_3 = \boxtimes \ \text{D}(s) \]

For Stability all four Coefficients must be Positive!

\( \text{D}(s) = c[\left(1+s\right)/s - 1] \ \text{ where } c = \frac{M_{pw}M_{wp}}{L_{mode}L_{wall}} \)

At Ideal Wall \( \boxtimes_\tau \) Limit: \( \text{D}(s_{\text{crit}}) = 0 \)

Feedback Coupling Constant, \( c_f = 1 - \frac{M_{pw}M_{fw}}{L_{wall}M_{fp}} \)

For Feedback to Stabilize up to Ideal Wall \( \boxtimes_\tau \) Limit \( c_f \) must be \( \geq 0 \)

Want small \( M_{fw} \) and large \( M_{fp} \) to insure \( c_f > 0 \)

If Control Coils Outside Stabilizer then:

\( M_{wf} > M_{fp} \) and \( c_f < 0 \)
Why is Basic ITER Control Coil Set a Poor Feedback System?

\[ D(s) = c \frac{(1+s)/s}{s} - 1 \quad \text{where} \quad c = \frac{[M_{pw} M_{wp}]}{[L_{mode} L_{wall}]} \]

At Ideal Wall \[\square\] Limit: \[D(s_{\text{crit}}) = 0\]

ITER Basic System has \(s_{\text{crit}} = 0.35\) [or \(\square N \sim 4.9\)]

**Therefore** \(c = 0.26\) for ITER

Feedback Coupling: \(c_f = 1 - \frac{[M_{pw} M_{fw}]}{[L_{wall} M_{fp}]}\)

Boozer shows that feedback fails when \[D(s) + c_f = 0\]

Using VALEN model results shows ITER Feedback Saturates at \(s = 0.063\) therefore:

ITER Basic System: \(c_f = -3.39\)

Physically:

\[c_f = 1 - \frac{[V_{\text{plasma from } I_w}]}{[V_{\text{plasma from } I_f}]}\]

Says Plasma Mode is more than 4 times better coupled to wall eddy currents than external Basic ITER Control Coils.
VALEN Model Geometry: Resistive Wall & Control Coil

Simple 1-turn Control Coil: Examine Control Fields with Wall Behind & in Front of Coil

plate 130.e-08 ohm m
2 x 2 x 0.0254 thick

coil
R=0.5 m

sensor #5
0.01 x 0.01
z=0.5

sensor #8
0.01 x 0.01
z=-0.5

z=-0.1
z=0
**Frequency Dependence of Control Field**

**Magnitude of Control Field vs Frequency**

Data from "FRdemo2a"

\[ t = 0.0254 \quad \rho = 130. \times 10^{-8} \, \text{ohm m} \]

- **sensor #5** (0.5 m right of coil)
- **sensor #8** (0.5 m left of coil)
- Plate between coil & sensor

**Phase of Control Field vs Frequency**

Data from "FRdemo2a"

\[ t = 0.0254 \, \text{m} \quad \rho = 130. \times 10^{-8} \, \text{ohm m} \]

- **current in coil**
- **current in plate**
- **sensor #5** right of coil
- **sensor #8** left of coil
At High Frequency: Destabilizing Wall Image Currents

**Phase of Control Field vs Frequency**

Data from "FRdemo2a"

\[ t = 0.0254 \text{ m} \quad \rho = 130 \times 10^{-8} \text{ ohm m} \]

- BB ph - driver
- BB ph max plate
- BB #5 phase
- BB #8 phase

**Magnitude of Currents vs Frequency**

Data from "FRdemo2a"

\[ t = 0.0254 \quad \rho = 130 \times 10^{-8} \text{ ohm m} \]

- BB I - driver
- BB max plate
- BB #5 phase
- BB #8 phase

Currents in coil and plate are represented graphically, with phase relative to driving voltage (degrees) on the y-axis and driving frequency (Hz) on the x-axis. The graphs show how phase and magnitude of currents change with frequency.
Optimizing Resistive Wall Mode Control: FIRE Approach

Allows Ideal Beta Limit to be Achieved thru $C_f > 0$ Improved Plasma/Coil Coupling

- Copper Stabilizing Shell (backing for PFCs)
- 1st Vacuum Shell
- 2nd Vacuum Shell
- Horizontal port (1.3 m x 0.65 m)
- Port shield plug (generic)
- Resistive wall mode stabilization coil (embedded in shield plug)
Try FIRE RWM Control Scheme in ITER

- Add Control Coils in Vacuum Vessel Ports: Good Coupling to Plasma
- Use Poloidal Sensors on Midplane Behind Blanket Armor
ITER Internal Coils in Port Plugs Easily Reach Ideal Limit

- Ideal Beta Limit Reached with only Proportional Gain $G_p=10^8$ V/W
- Control Coils use only three $n=1$ pairs in 6 port plugs!
At **Moderate Beta** \((s=0.1)\) we observe simple damped suppression in 20 to 30 ms

- Peak Current in Control Coils reaches peak of 3.5 kA
- Peak voltage on single turn control coils is only 5 volts
- Reactive power requirements only ~5 kW in each coil pair
At **Ideal Beta Limit** \((s=0.35)\) highly damped suppression in \(~6\) ms

- Peak Current in Control Coils reaches peak of only \(1.5\) kA
- Peak voltage on single turn control coils is only 5 volts
- Reactive power requirements only \(~7\) kW in each coil pair
• Beta chosen to be near predicted limit of $\beta_N \sim 2.9$ which is only 20% between no-wall limit (2.4) and ideal limit (4.9).

• Voltage limited to 40 V/turn times 28 turns = 1120 Volts
• Peak Current in Control Coils reaches peak of 28 kA-Turns
• Reactive power requirements exceed 1 MW per coil pair!
SUMMARY OF RESULTS

• Basic ITER External Control Coils with Double-wall Vacuum Vessel in ITER Reduces Effectiveness of Feedback System: Stable only up to ~ 20% above No-wall Beta Limit. Voltage requirements at coil operating limits (1.1 kV) degrade feedback performance and multi-MW reactive power required.

• Inclusion of Blanket Modules Significantly Increases Ideal Wall Beta Limit from about $\beta_N$ of ~3.4 to ~4.9

• Use of Single Turn Modular Coils in 6 of the 18 ITER Midplane Ports allows the feedback system to reach the Ideal Wall Beta Limit for the double wall ITER vacuum vessel plus blanket modules. Time dependent modeling shows only 5 Volts at 1.5 kA of current or 7.5 kW of reactive power needed.
Next Steps for ITER Modeling

• Continue Benchmark with MARS on Feedback Limits…
• Add Noise to Estimate Power Requirements and Performance Limits.
• Extend VALEN to Include Rotation Effects:
  + Mode Rotation Relative to Wall: torque balance ($\omega_{\text{mode}} < 1/\omega_{\text{wall}}$): small stabilizing effect
  + Use MARS and/or DCON+ to find $s(\omega_p)$
Simulated RWM Noise on DIII-D with ELMs

To the low level noise ELMs (Edge Localized Modes) were added as small group of Gaussian random numbers from 6 to 16 Gauss approximately every 0.01 sec with different signs +/- chosen with 50% probability.
DIII-D I-Coil Feedback model for the Control Coils $L=60 \text{ mH}$ and $R=30 \text{ mOhm}$ with Proportional Gain $G_p = 7.2 \text{ Volts/Gauss}$

Control coil current
Maximum control coil current and voltage with noise in DIII-D as function of $\beta_N$
Effects of Noise on Feedback Dynamics for L=60 μH and R=30 mOhm DIII-D I-Coil Feedback model with Proportional Gain $G_p=7.2\text{Volts/Gauss}$

![Graph showing sensor flux over time with and without feedback and with noise. The graph indicates the flux response for different conditions: FB on with Noise, No FB with Noise, FB on w/o Noise, No Fb w/o Noise. The turn on FB at $t=1.65\text{ ms}$ is highlighted.](image-url)