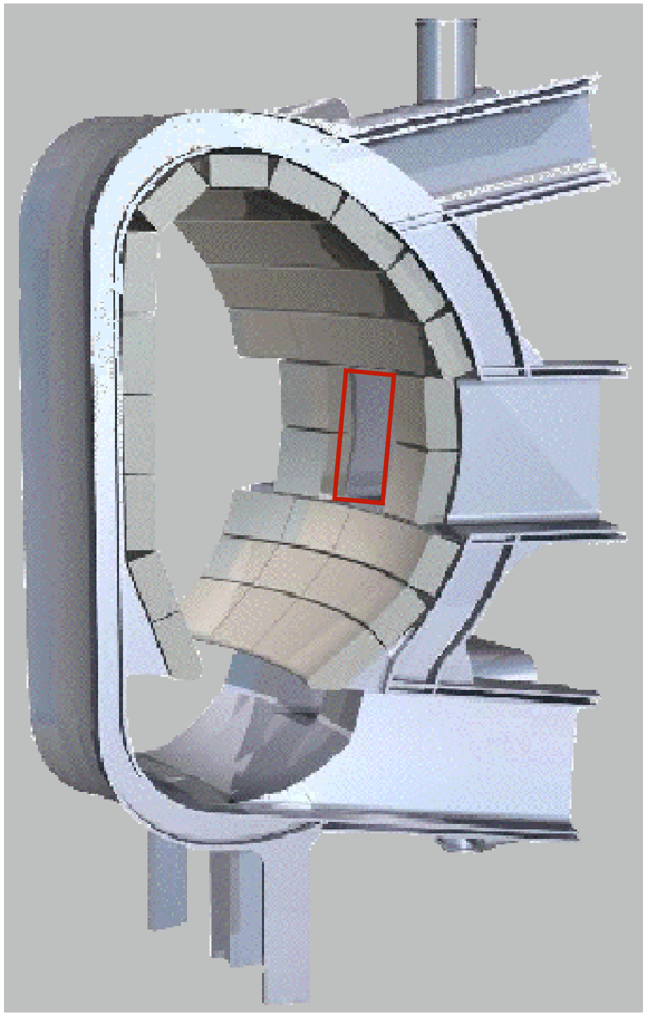
RWM Control in FIRE and ITER



Gerald A. Navratil
with
Jim Bialek, Allen Boozer
& Oksana Katsuro-Hopkins

Columbia University

MHD Mode Control Workshop
University of Texas-Austin
3-5 November, 2003

OUTLINE

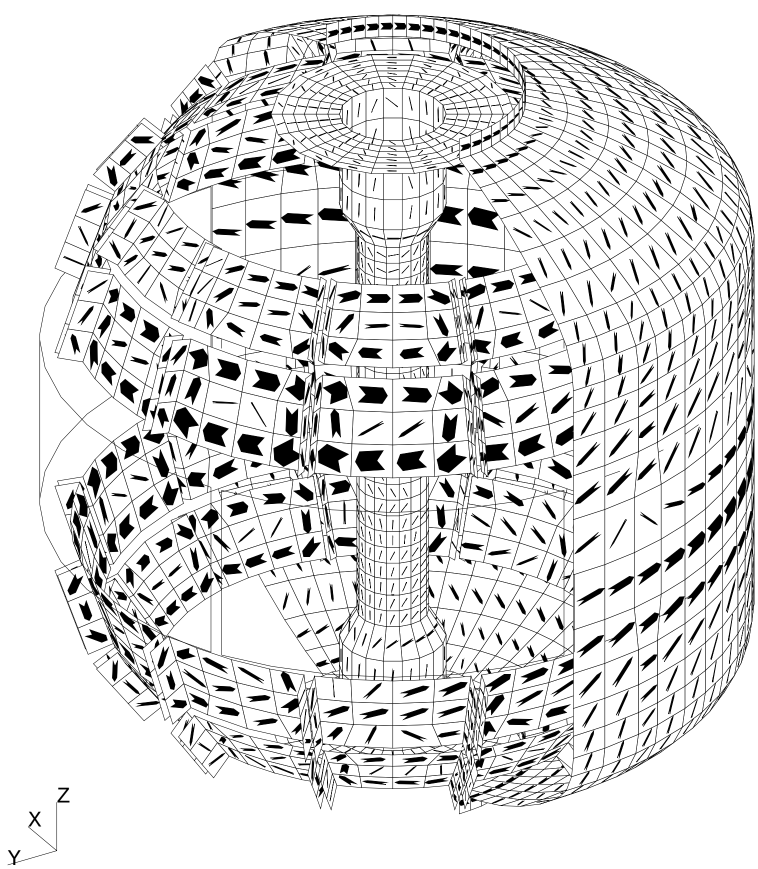
- REVIEW OF VALEN MODEL
- BENCHMARKING MARS & VALEN/DCON
  + **MAPPING OF 'S' TO β_N: IDEAL WALL BETA LIMIT**
  + **TRANSITION TO IDEAL BRANCH IN DISPERSION RELATION**
- CRITICAL ISSUES IN RWM CONTROL DESIGN
  + **ITER PASSIVE STABILIZER PERFORMANCE: IMPORTANT ROLE OF THE BLANKET MODULES**
  + **CONTROL COIL-PLASMA-STABILIZER COUPLING OPTIMIZATION IN FIRE AND ITER**
  + **POWER REQUIREMENTS: INITIAL VALUE SIMULATIONS AND EFFECTS OF NOISE**

Columbia University

VALEN combines 3 capabilities

see PoP **8 (5)**, 2170 (2001) – Bialek J., et al.

- 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.,

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

- Unstable Plasma mode is modeled as a special circuit equation. We start with a plasma equilibrium, use DCON without any conducting walls, to obtain δW, and the magnetic perturbation represents the plasma instability.

- The instability is represented via a normalized mode strength

$$s=\frac{-\delta W}{\left(\mathrm{LI}^2/2\right)}$$, the equations are now

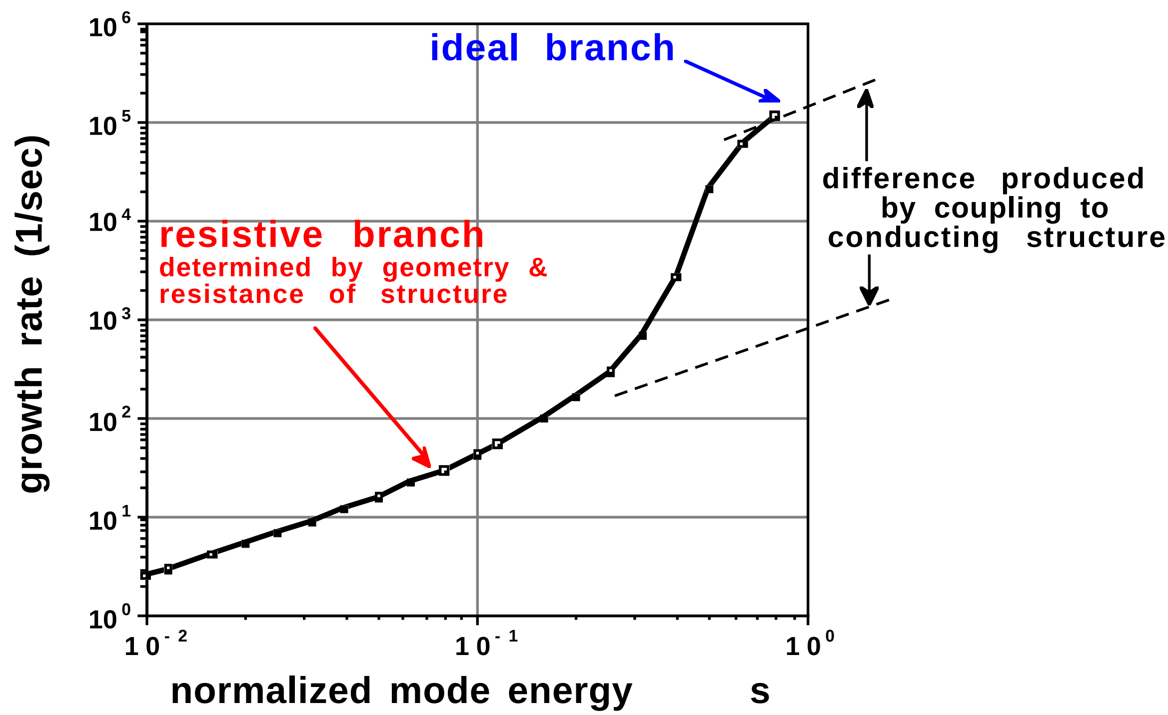
$$[L'(s)]\{\dot{\mathrm{I}}'\}+[R']\{\mathrm{I}'\}=\{V'(t)\}$$

VALEN predicts growth rate for plasma instability as function of the instability strength parameter 's'

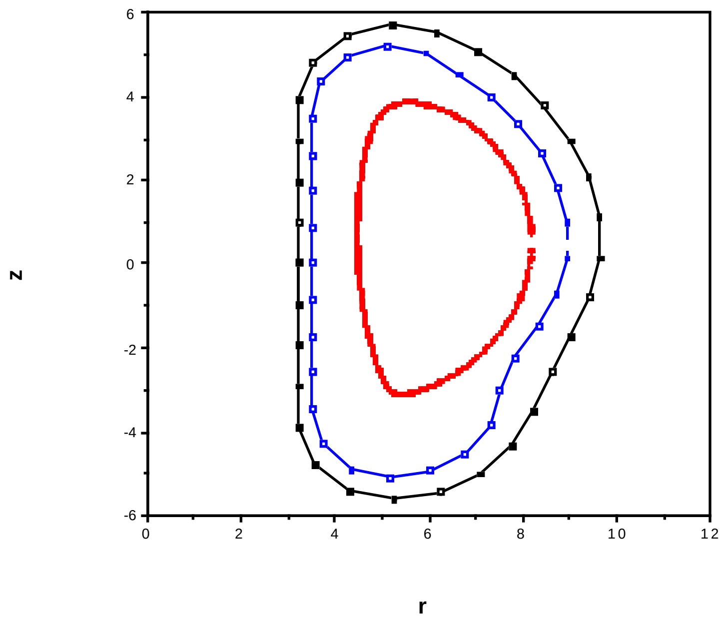
- 's' is a normalized mode energy

$$s = \frac{-\delta W}{\left(LI^2 / 2\right)}$$

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

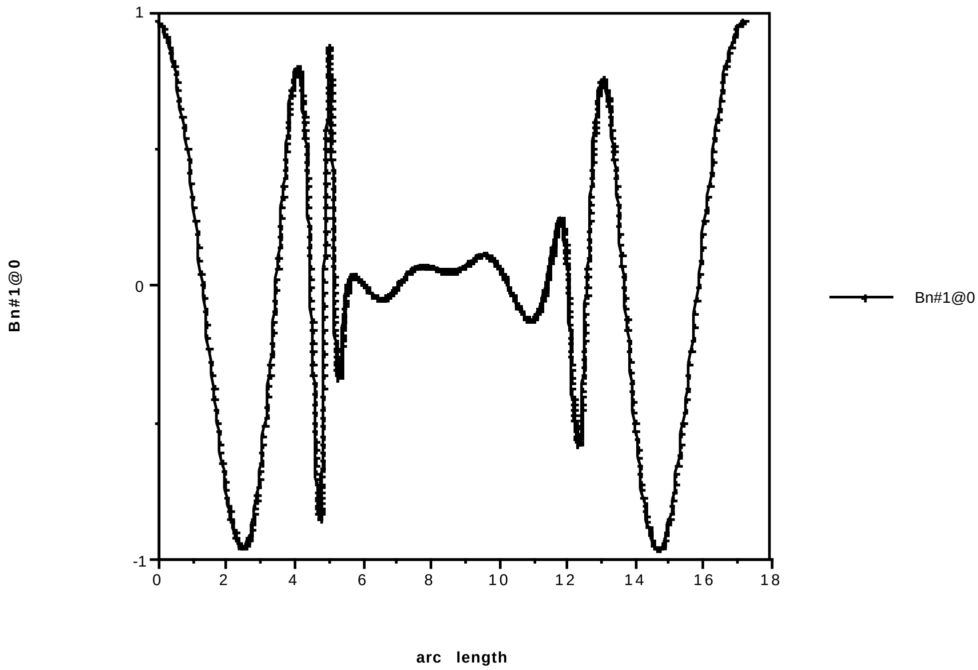


ITER Double Wall Vacuum Vessel Configuration

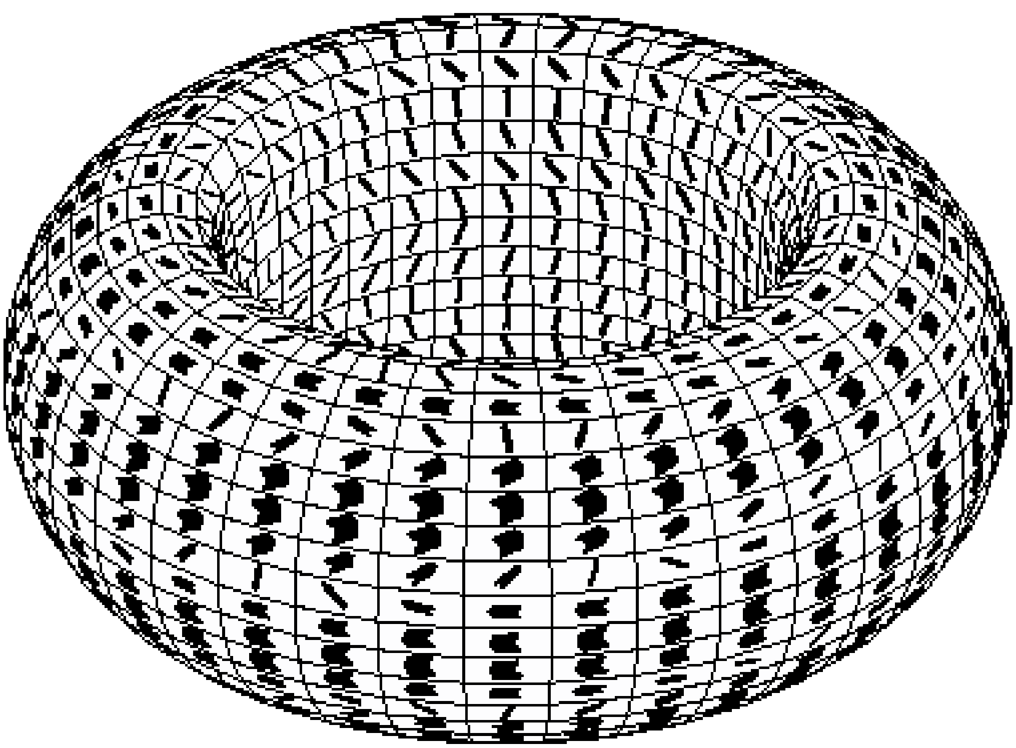


- The ITER vacuum vessel is modeled as a double wall configuration with time constants for low order modes in range 0.15 s to about 0.3 s

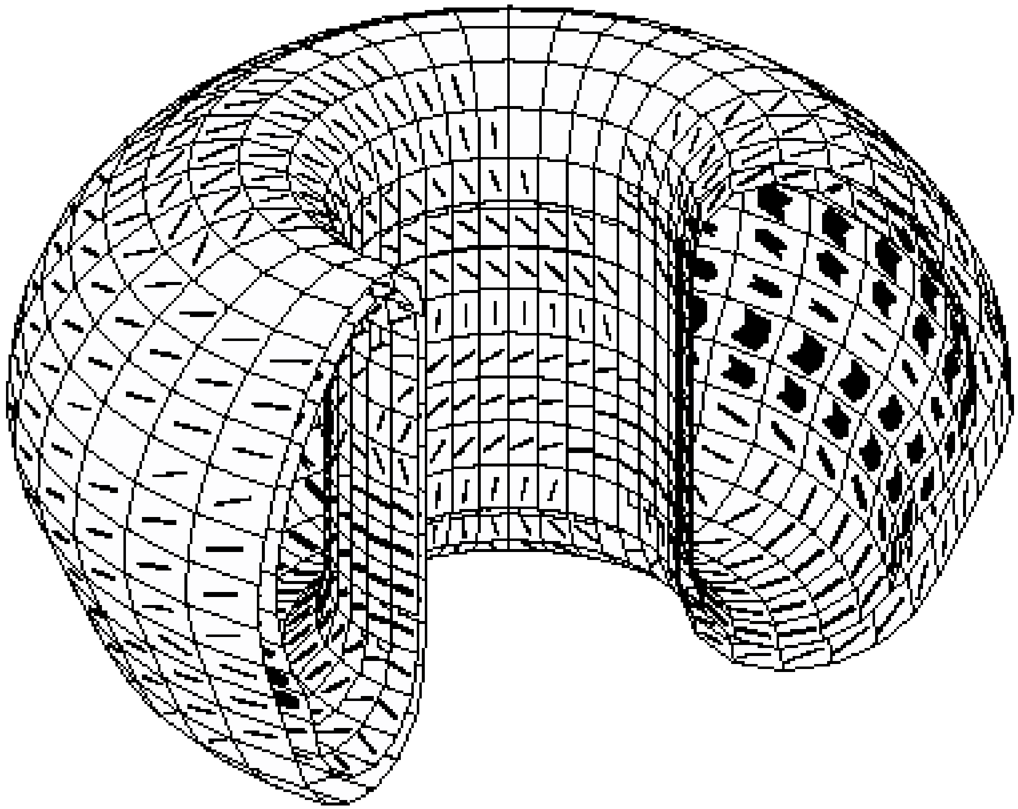
DCON Calculation of ITER RWM: B-normal vs Poloidal Angle



Use B-normal to Compute Equivalent Plasma Surface Current

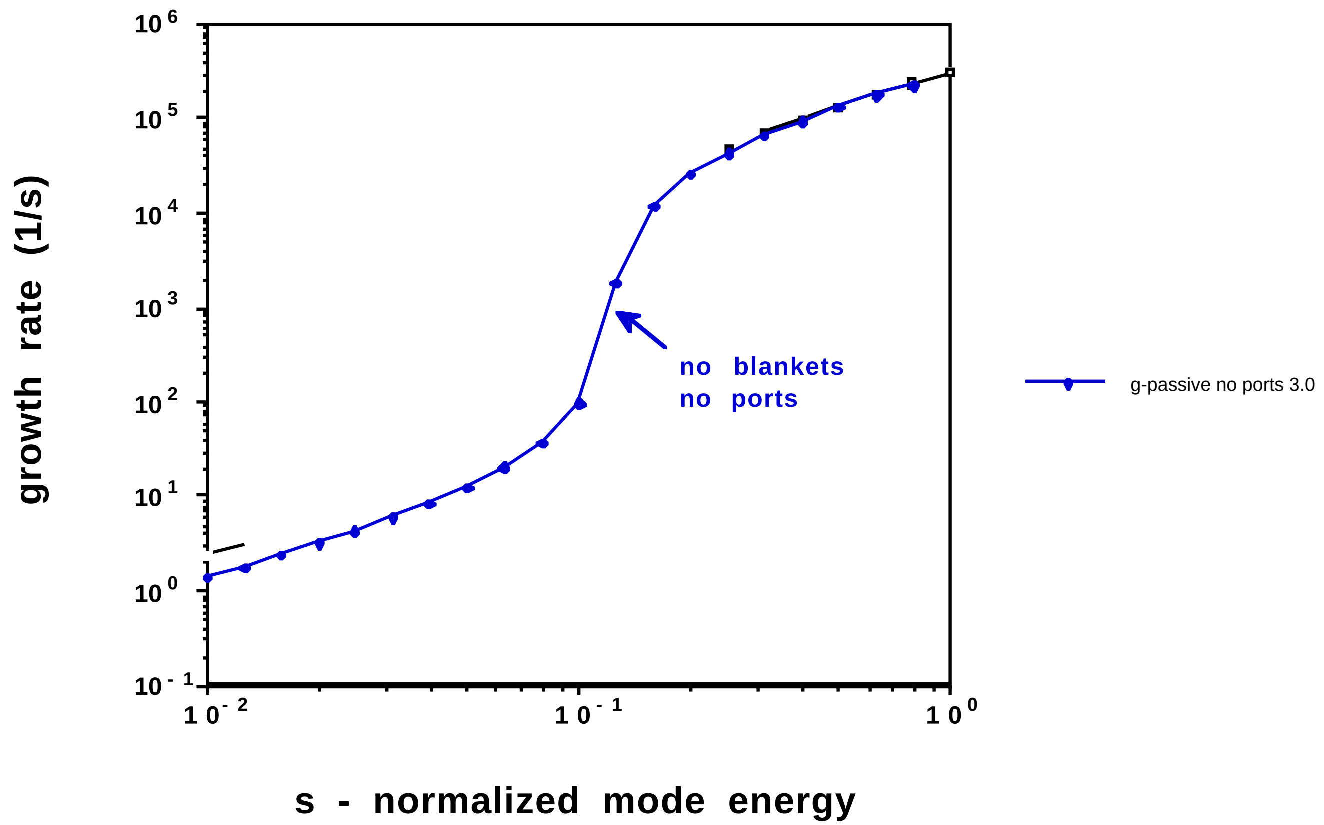


RWM Induces Stabilizing Image Currents Largely on the Inner Vessel Wall



- Vacuum Vessel Modeled with and without wall penetrations.

ITER Double Vacuum Vessel Passive RWM Dispersion Relation



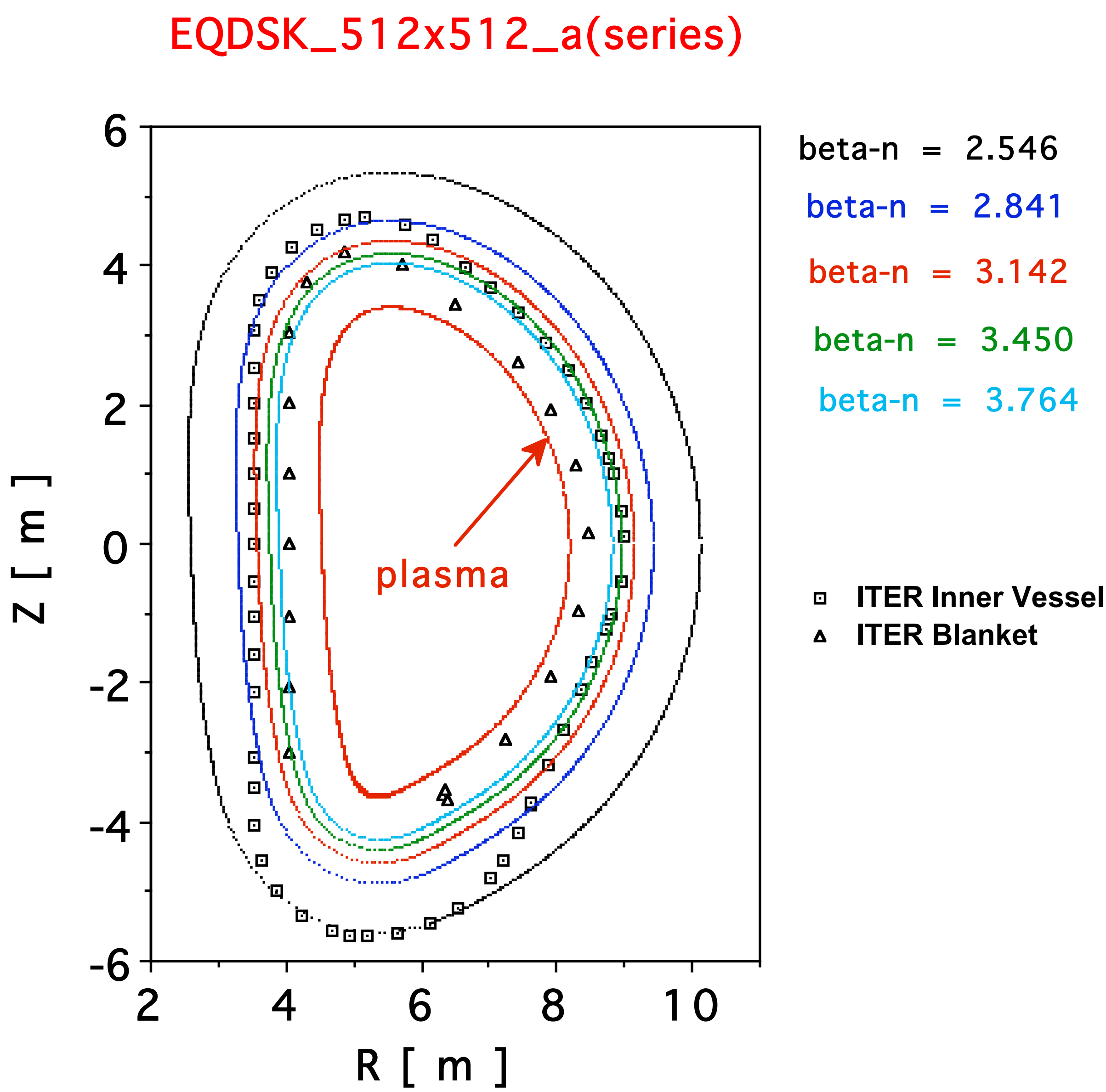
- **Shows usual transition from RWM to Ideal Branch at s~0.1**

Outline

- Review of VALEN Model
- Benchmarking MARS & VALEN/DCON
  - **Mapping of 's' to β_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**

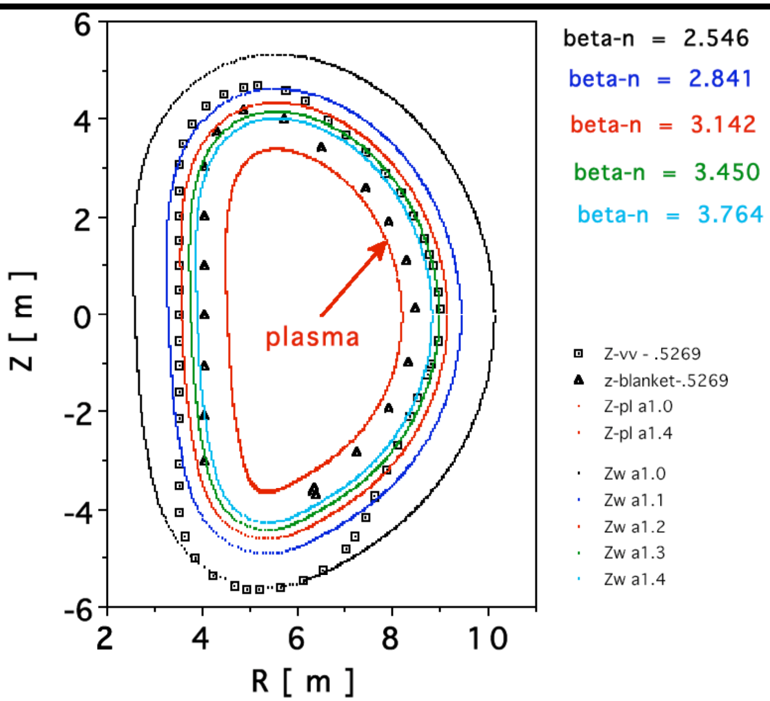
Columbia University

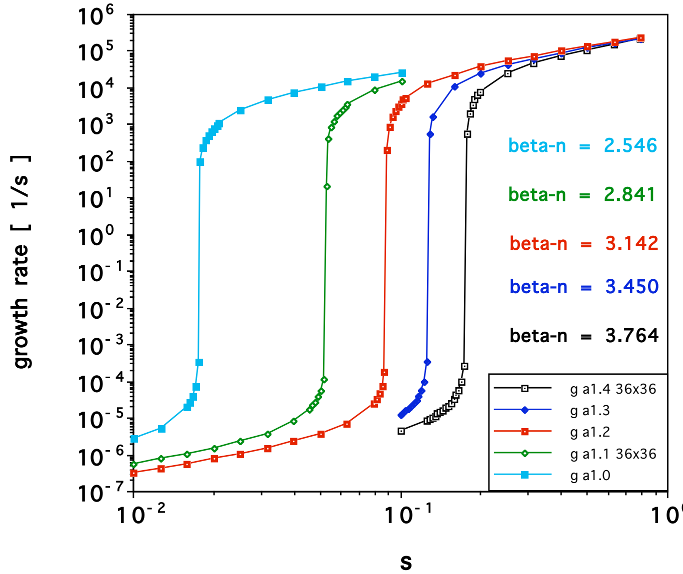
DCON Benchmark with Series of Conformal Wall ITER Equilibria



- Use series of ITER conformal wall equilibria as input into VALEN

Benchmark Calibration of VALEN with DCON

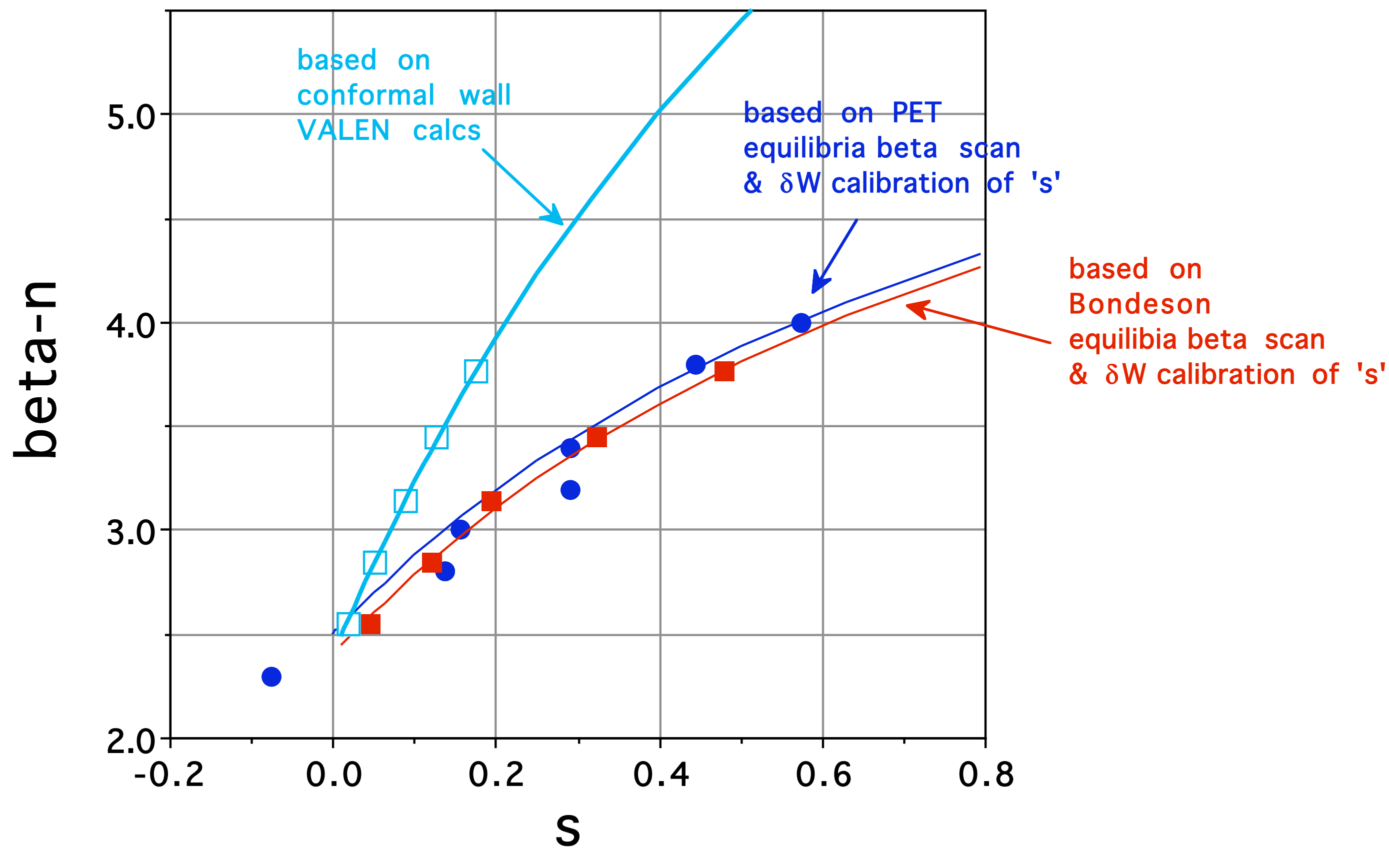




- DCON ideal β_N limit found for series of conformal wall ITER plasmas.
- VALEN ideal s limit found for same conformal wall series.

Use to calibrate β_N vs s

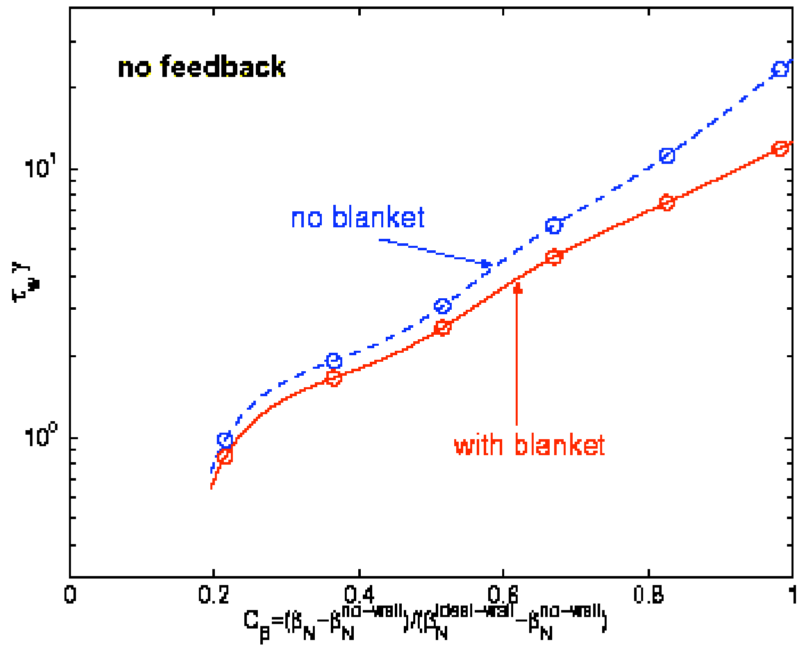
Use DCON Computation of δW to Calibrate s to β_N

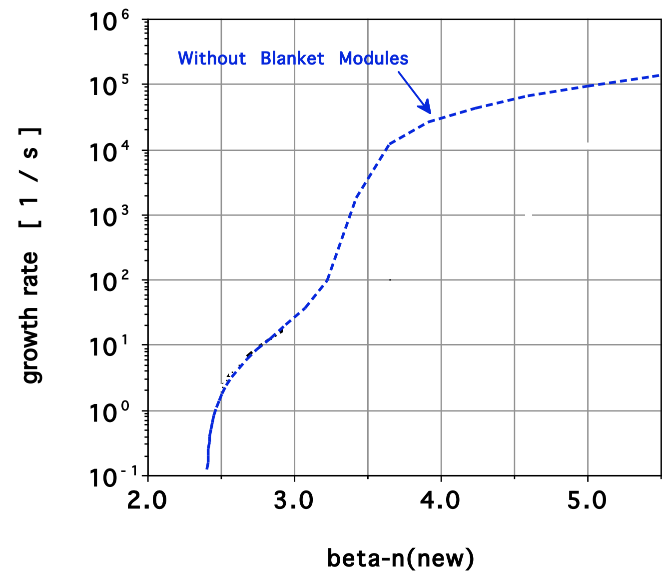


- **Error found in DCON 'δW' to VALEN 's' conversion!**
- This **NEW** calibration used to replot passive response.

[From ITPA Meeting July 2003]

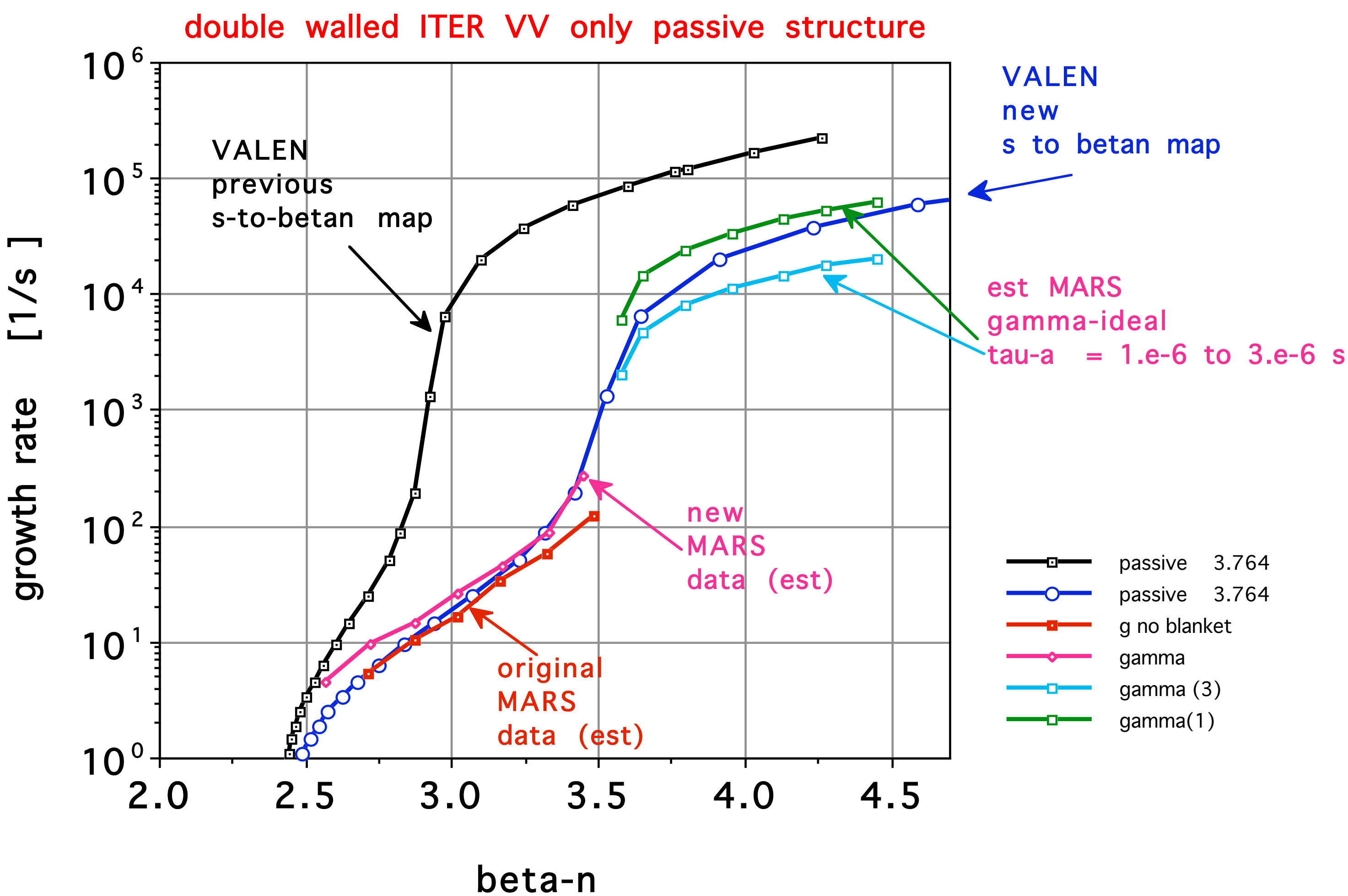
Physics of Ideal Kink Transition Seems Absent in Liu, et al.





- Note absence of Ideal Kink Branch Transition when $C_\beta \sim 1$
- In Liu, et al. $\tau_{wall} \sim 0.188$ s so γ at $C_\beta \sim 1$ is between 53 to 120 s^{-1}
- In VALEN modeling γ at $C_\beta \sim 1$ is between 1000 to 10^4 s^{-1}
- Growth rate disparity consistent with $\gamma\tau_{wall}$ in Liu, et al. too small for claimed values of C_β

VALEN vs MARS RWM Benchmarking

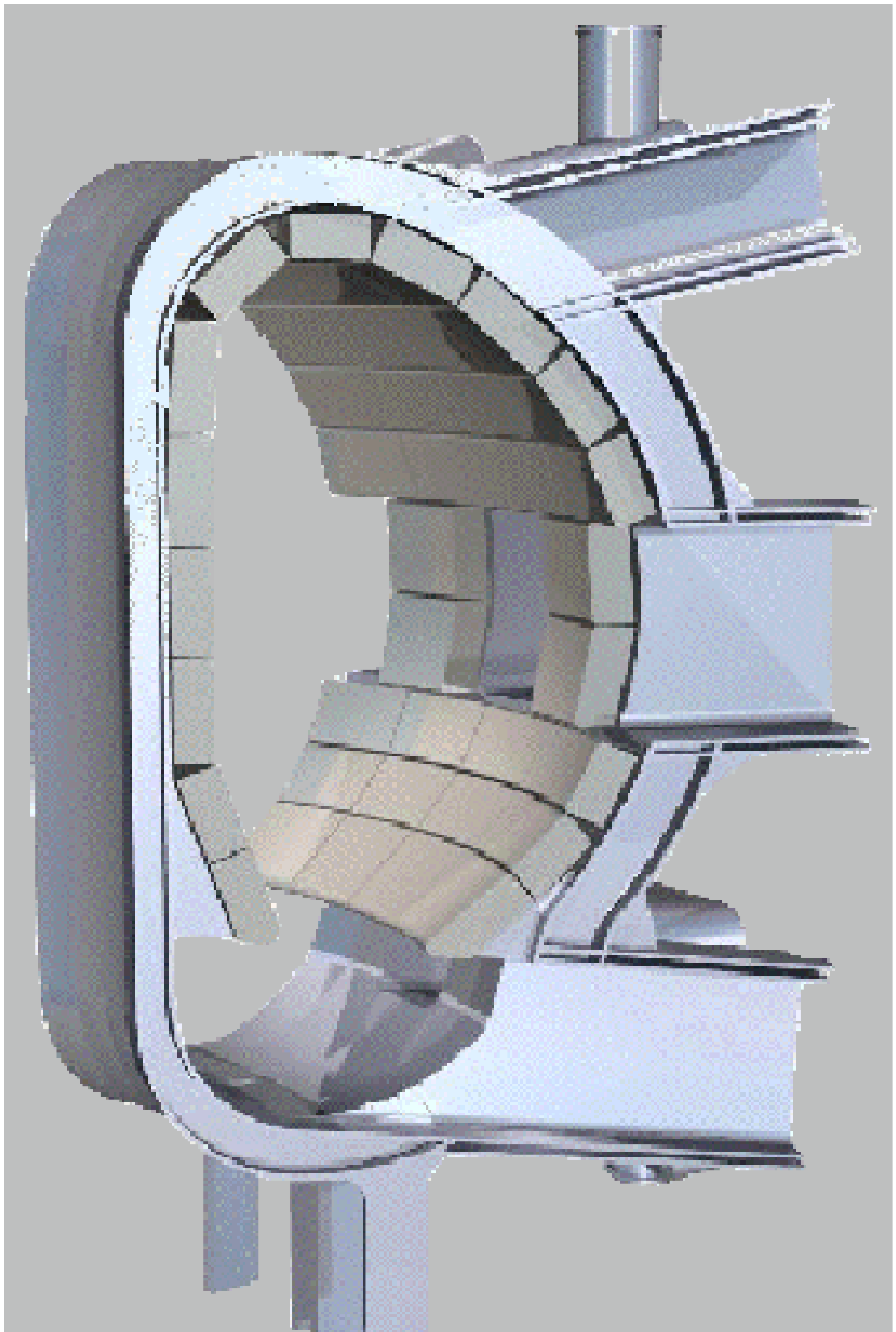


New MARS results and benchmarked VALEN results agree!

OUTLINE

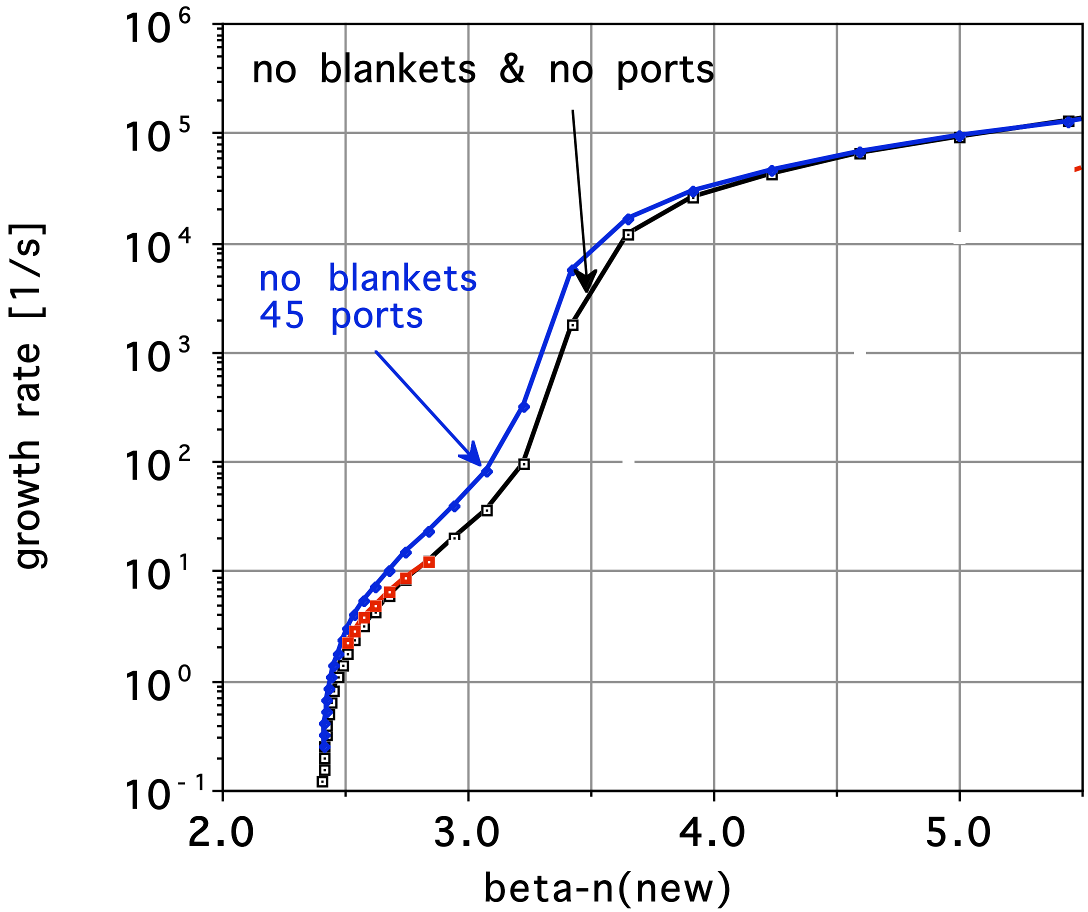
- REVIEW OF VALEN MODEL
- BENCHMARKING MARS & VALEN/DCON
  - MAPPING OF 'S' TO β_N: IDEAL WALL BETA LIMIT
  - TRANSITION TO IDEAL BRANCH IN DISPERSION RELATION
- CRITICAL ISSUES IN RWM CONTROL DESIGN
  - **ITER PASSIVE STABILIZER PERFORMANCE: IMPORTANT ROLE OF THE BLANKET MODULES**
  - **CONTROL COIL-PLASMA-STABILIZER COUPLING OPTIMIZATION IN FIRE AND ITER**
  - **POWER REQUIREMENTS: INITIAL VALUE SIMULATIONS AND EFFECTS OF NOISE**

Include ITER Ports & Blanket Modules in Passive RWM Stabilization Model



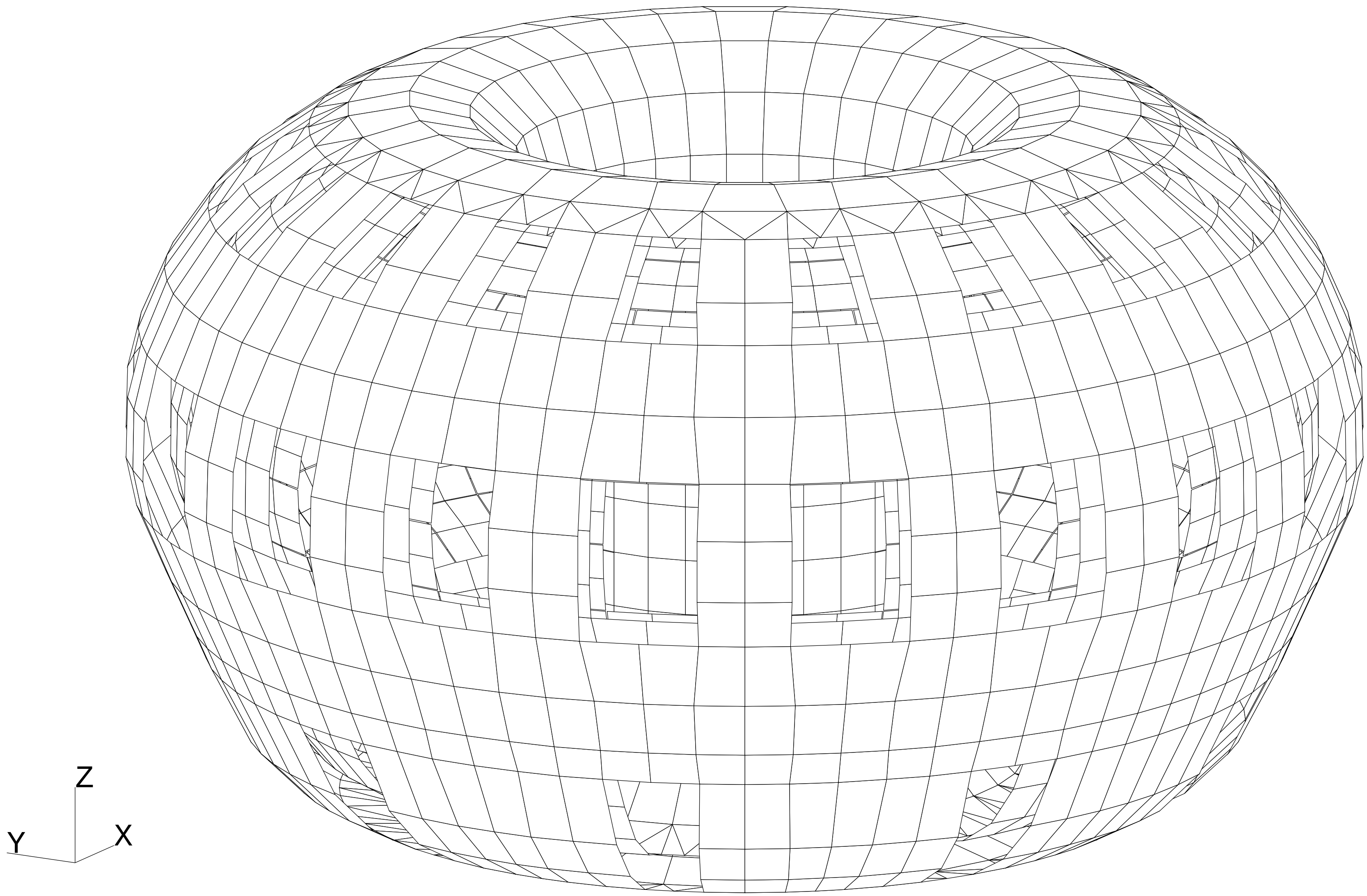
- Modeled as set of isolated plates above the inner vessel wall.
- Each blanket module adjusted to have 9 ms radial field penetration time constant.

ITER Ports Cause Small Reduction in Ideal Limit

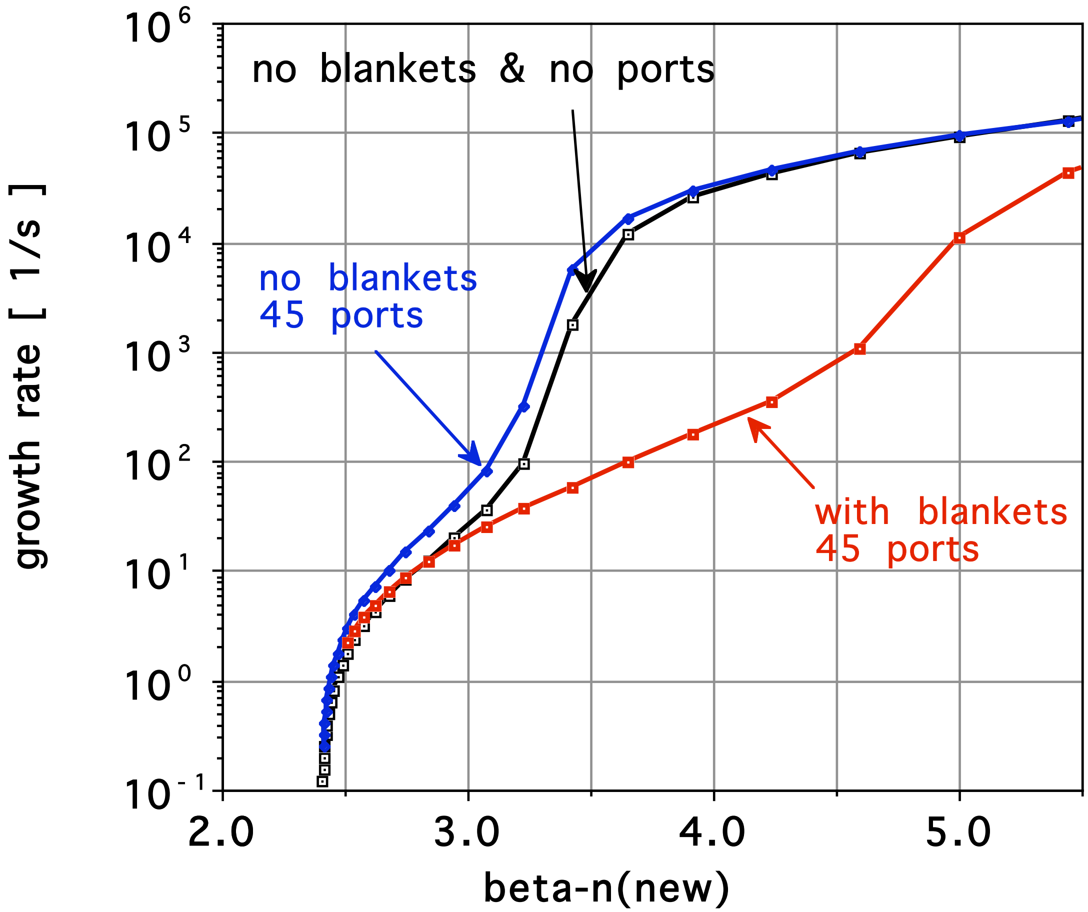


- No wall β_N limit is 2.4; Ideal Wall Limit Drops to β_N ~ 3.3

VALEN Model of ITER Double Wall Vessel and Blanket Modules

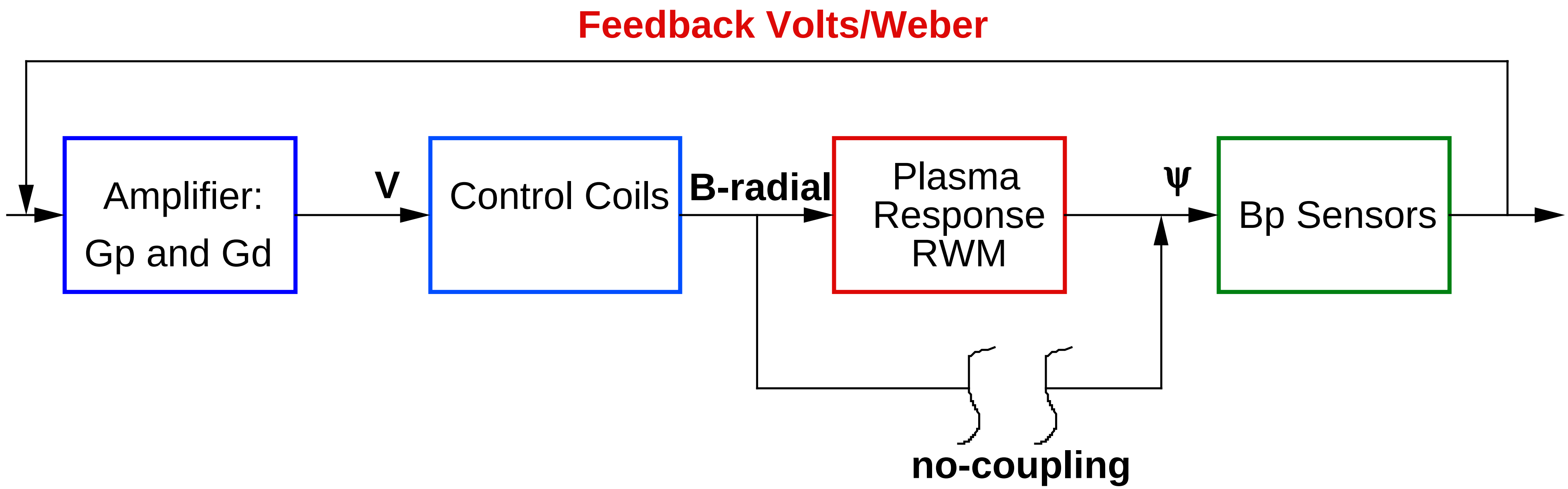


ITER Blanket Opens Up Large AT Regime

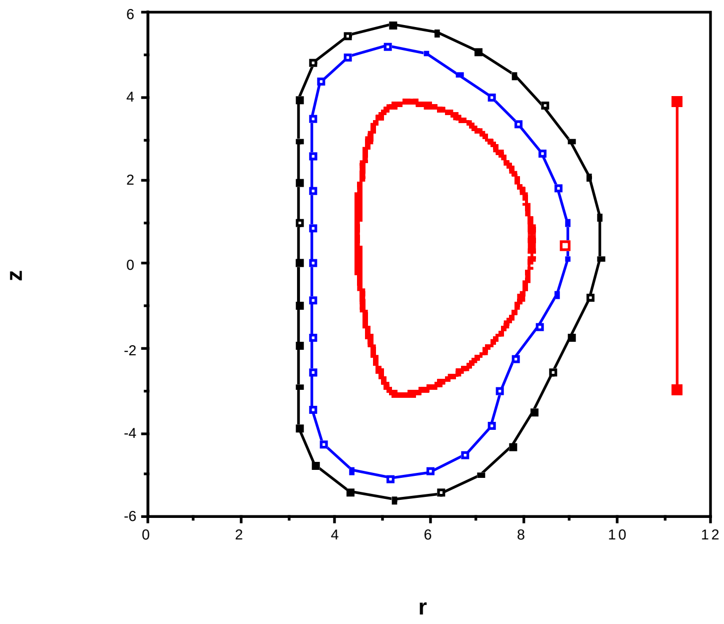


- No wall β_N limit is 2.4; **Ideal Wall Limit With Blanket is 4.9!**

Basic Feedback Control Loop with Voltage Amplifiers and Sensors Uncoupled to Control Coils

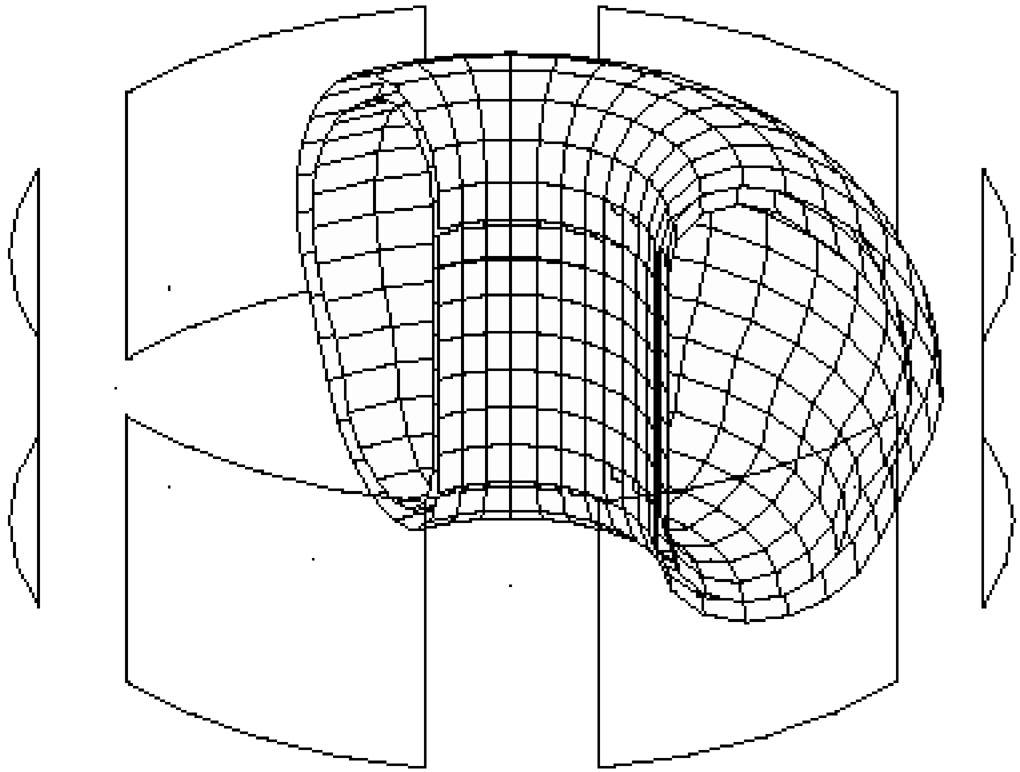


ITER Base Case Feedback Control System Geometry



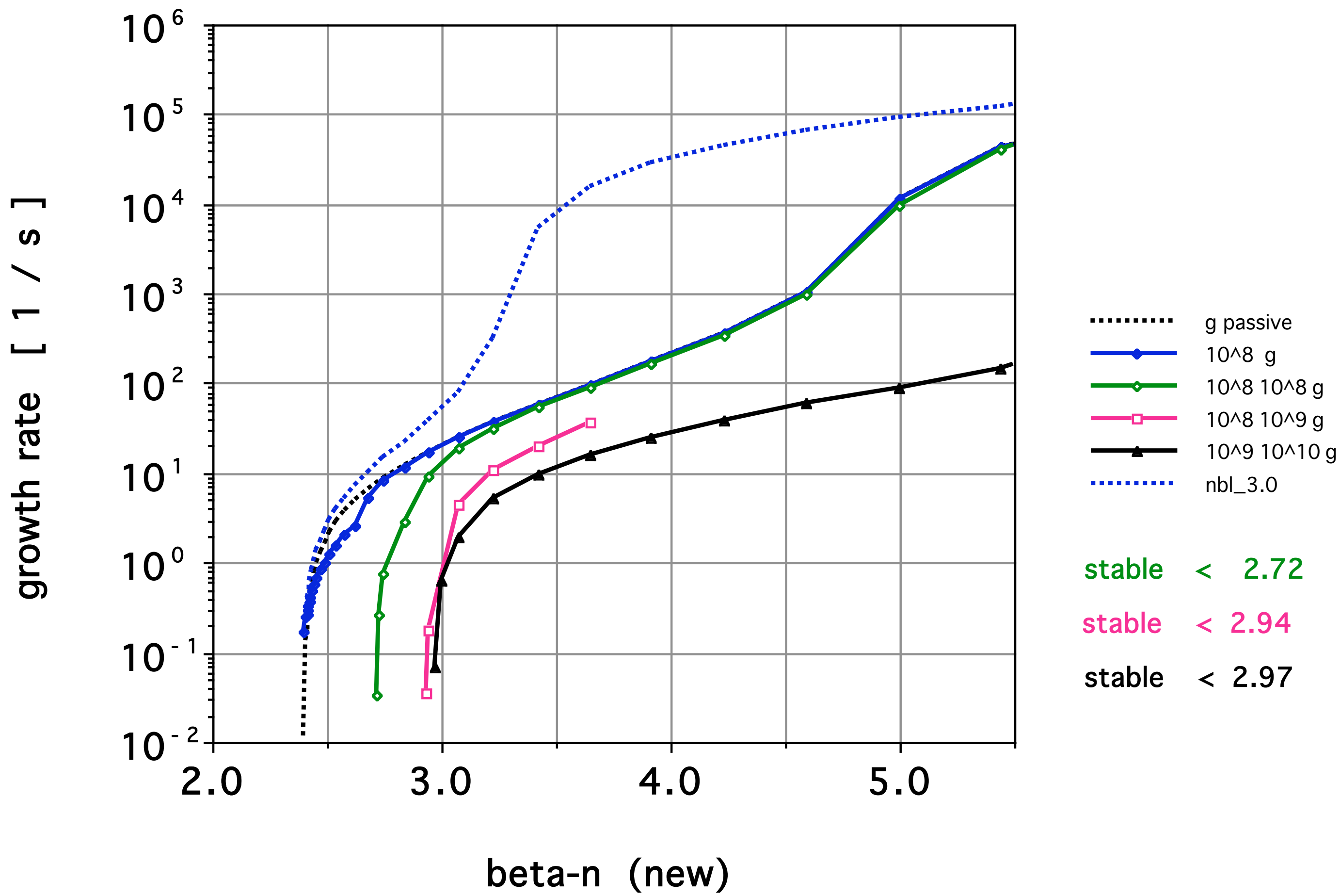
- The ITER vacuum vessel is modeled as a double wall configuration using design data provided by Gribov, with feedback control provided by 3 n=1 pairs of external control coils on the mid-plane.

VALEN Model of ITER Vessel and Control Coils: Base Case Feedback Control System



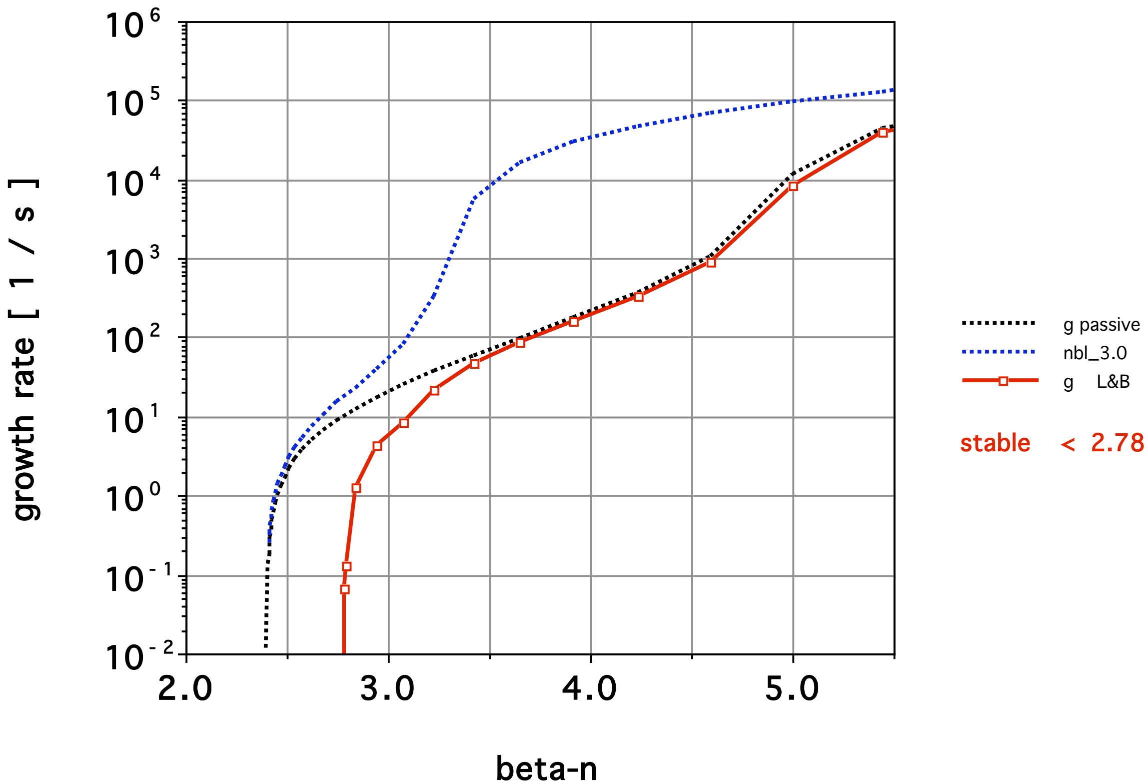
- Vacuum Vessel Modeled with and without wall penetrations.

ITER Basic Coils: Scan of Proportional & Derivative Gain



- Feedback Saturates at β_N ~ 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 $V_f = - L_f\, b_s/b_o s[K_i/s+K_p]$; $b_o=28\text{x}10^{-7}$T/A; $L_f=0.04$H; $b_s=□_s/A_s$
- VALEN uses $V_f = - L_f/\, b_o A_s\, [K_i+K_p d/dt\,]\, □_s = -1.4\text{x}10^8[K_i+K_p d/dt\,]□_s$
- $G_p= 6\text{x}10^8$ V/W is Liu's $K_i=4.318$ and $G_d= 2\text{x}10^8$ V/V is Liu's $K_p=1.5$
- These values **reduce $□_N$ ~ 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, $V_f(t) = -\frac{L_f}{M_{fp}}\,[\Box_w\, G_p + G_d \frac{d}{dt}\,]\,\Box_{sensor}$

G_p = Proportional Gain G_d = Derivative Gain

$\Box_w = R_{wall}/L_{wall}$ $\Box_f = R_{control\ coil}/L_{control\ coil}$ $\Box$ = feedback delay

$$a_3\Box^3 + a_2\Box^2 + a_1\Box + a_0 = 0$$

$$a_0/\Box_w = -\Box_f + \Box_w G_p$$

$$a_1 = \Box_f D(s) + \Box_w [G_d + c_f G_p - s]/s$$

$$a_2 = D(s) + c_f G_d/s \qquad a_3 = \Box D(s)$$

For Stability all four Coefficients must be Positive!

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

At Ideal Wall $\Box$ Limit: $D(s_{crit}) = 0$

Feedback Coupling Constant, $c_f = 1 - [M_{pw}M_{fw}]/[L_{wall}M_{fp}]$

For Feedback to Stabilize up to Ideal Wall $\Box$ Limit c_f **must be ≥ 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?

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

At Ideal Wall β Limit: $D(s_{crit}) = 0$

ITER Basic System has $s_{crit} = 0.35$ [or $\beta_N \sim 4.9$]

Therefore $c = 0.26$ for ITER

Feedback Coupling: $c_f = 1 - [M_{pw}M_{fw}]/[L_{wall}M_{fp}]$

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: $c_f = -3.39$

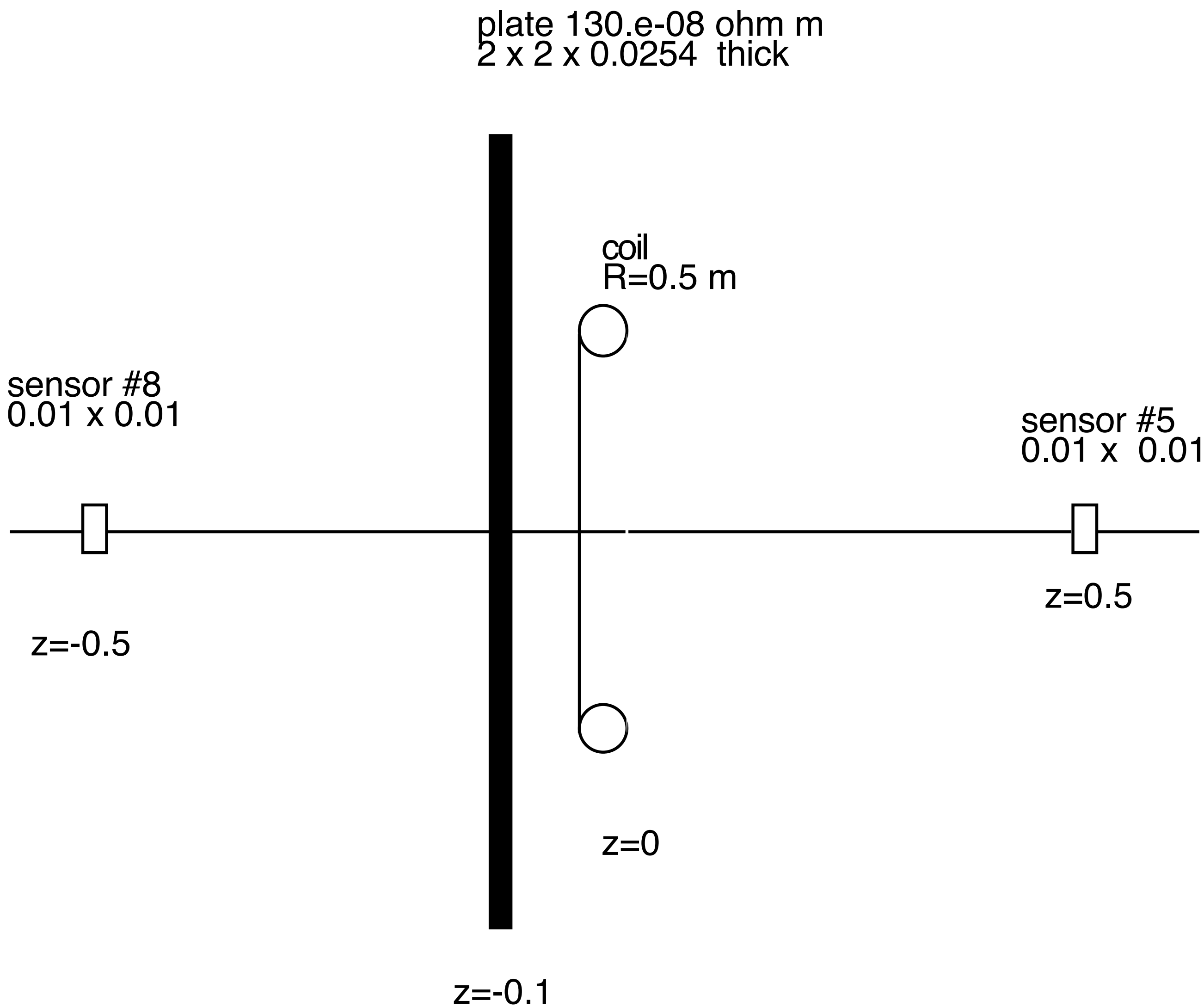
Physically:

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

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

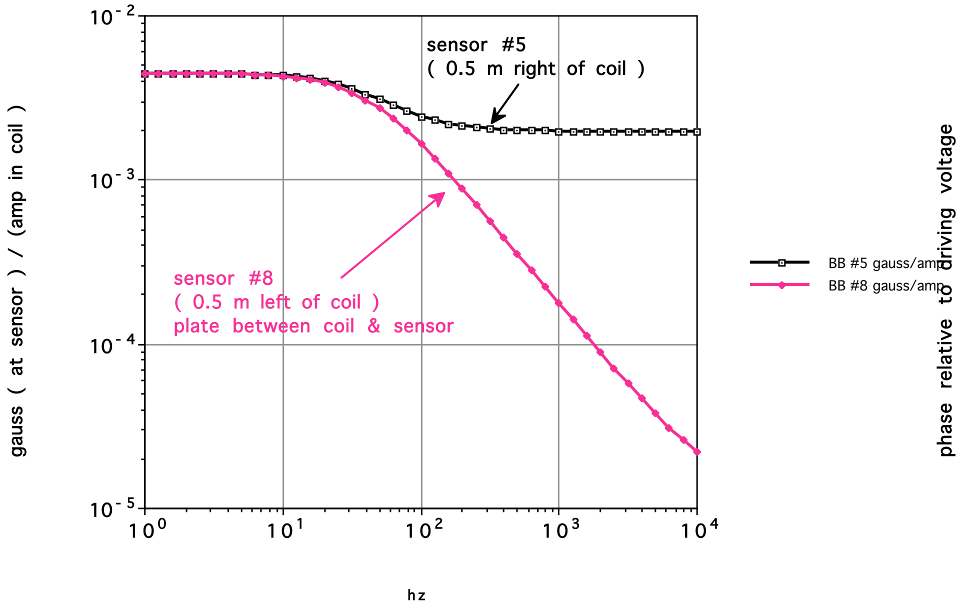
Simple 1-turn Control Coil: Examine Control Fields with Wall Behind & in Front of Coil



Frequency Dependence of Control Field

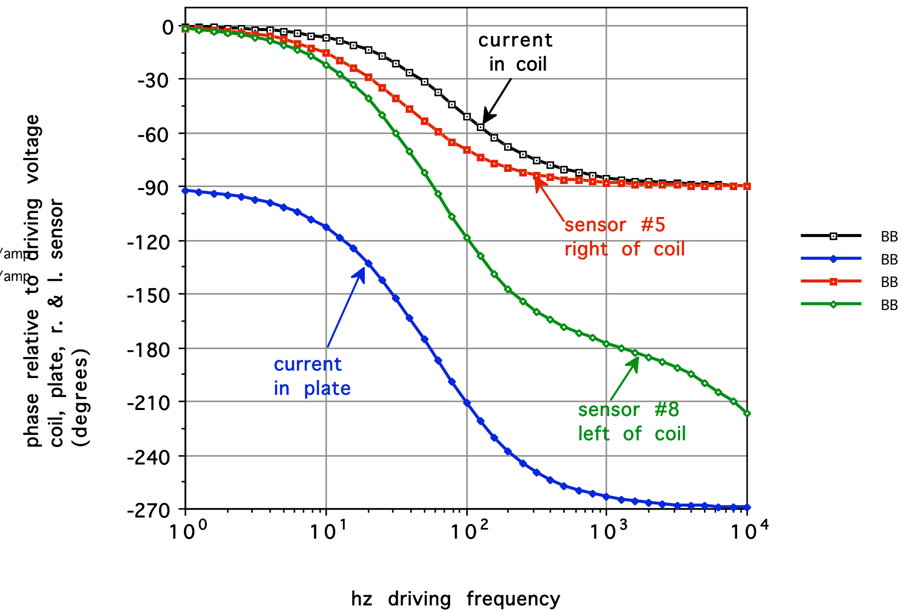
Magnitude of Control Field vs Frequency

Data from "FRdemo2a"
t = 0.0254 rho = 130.e-08 ohm m



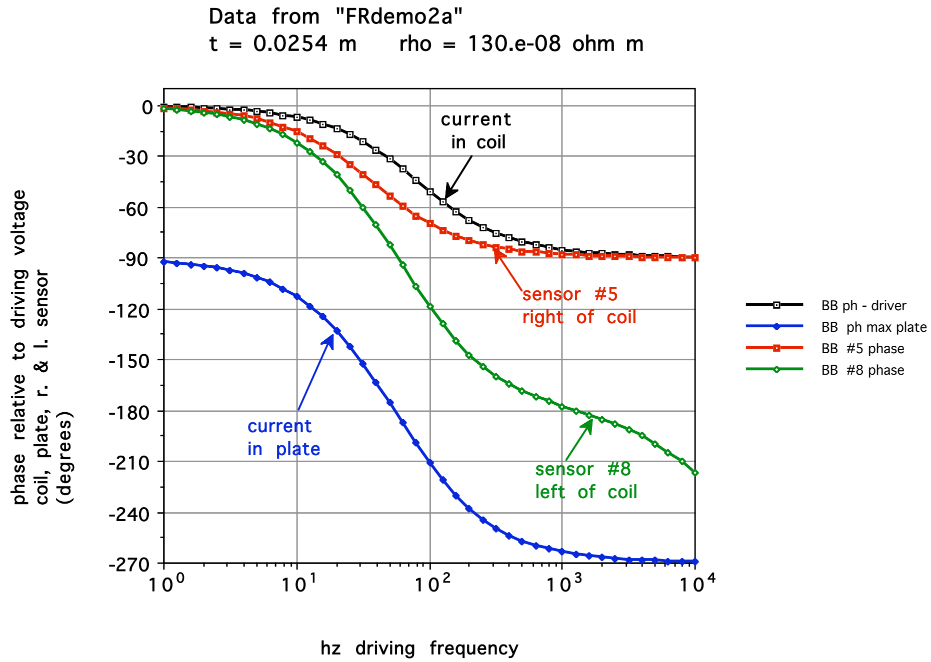
Phase of Control Field vs Frequency

Data from "FRdemo2a"
t = 0.0254 m rho = 130.e-08 ohm m

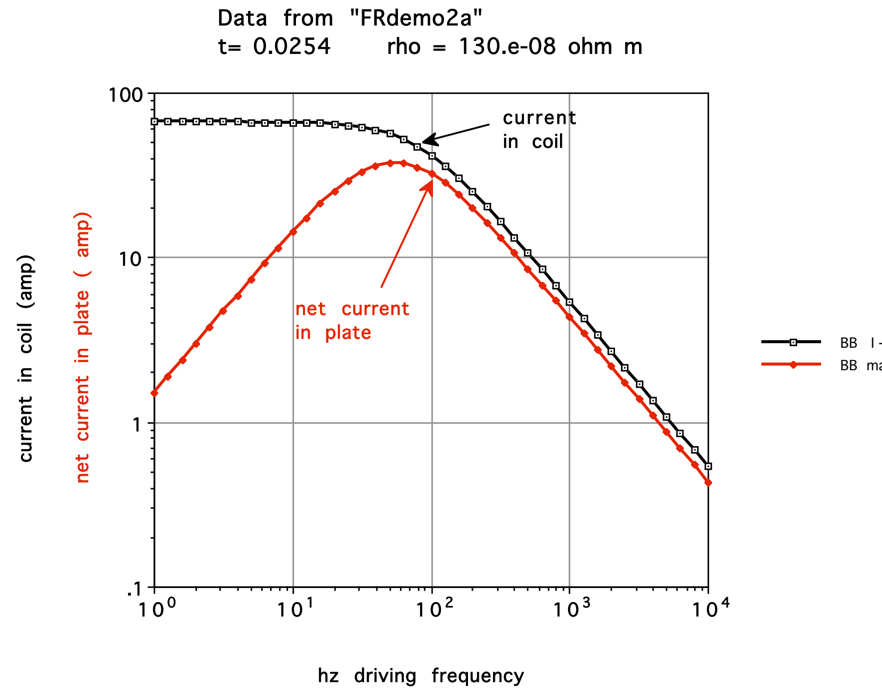


At High Frequency: Destabilizing Wall Image Currents

Phase of Control Field vs Frequency

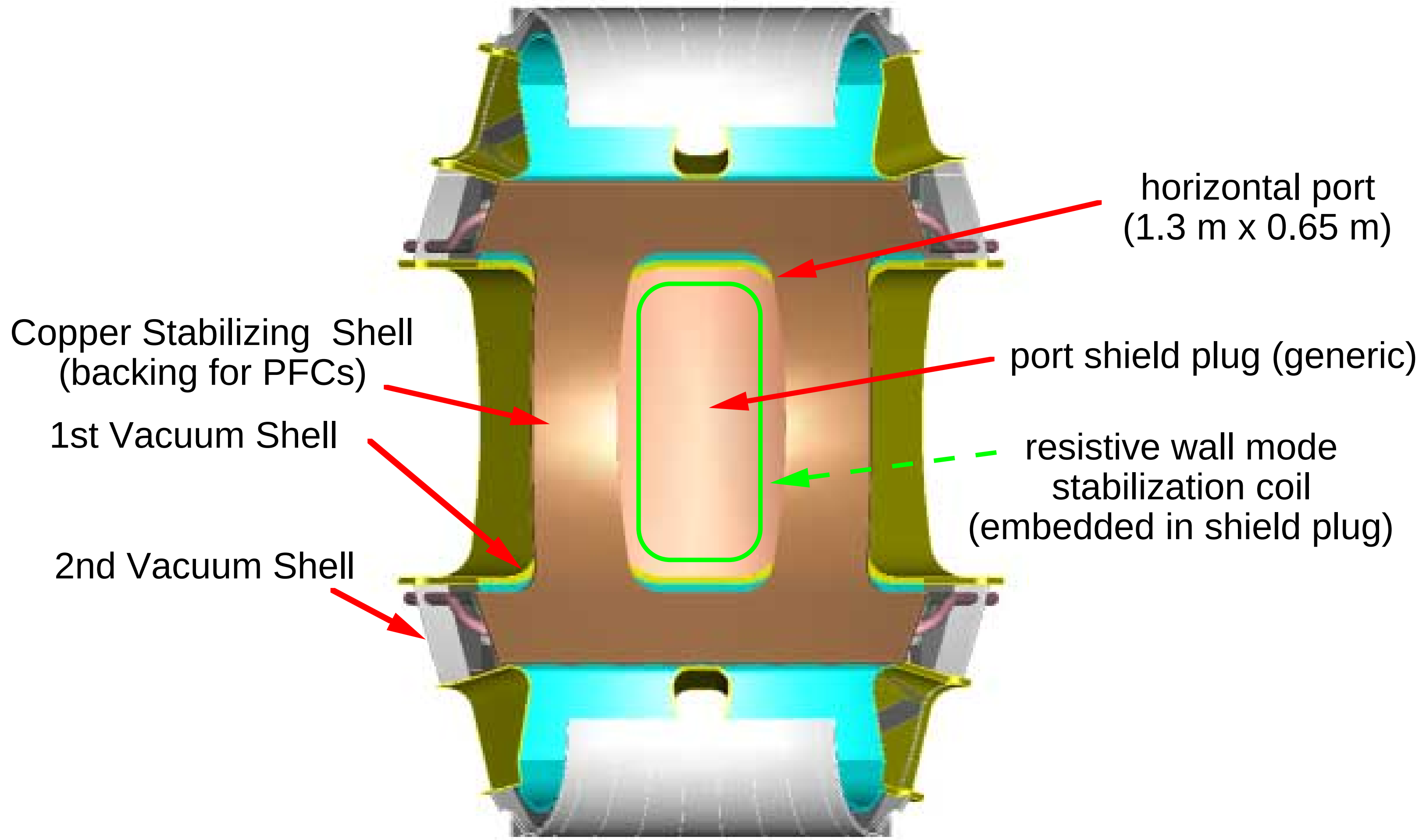


Magnitude of Currents vs Frequency

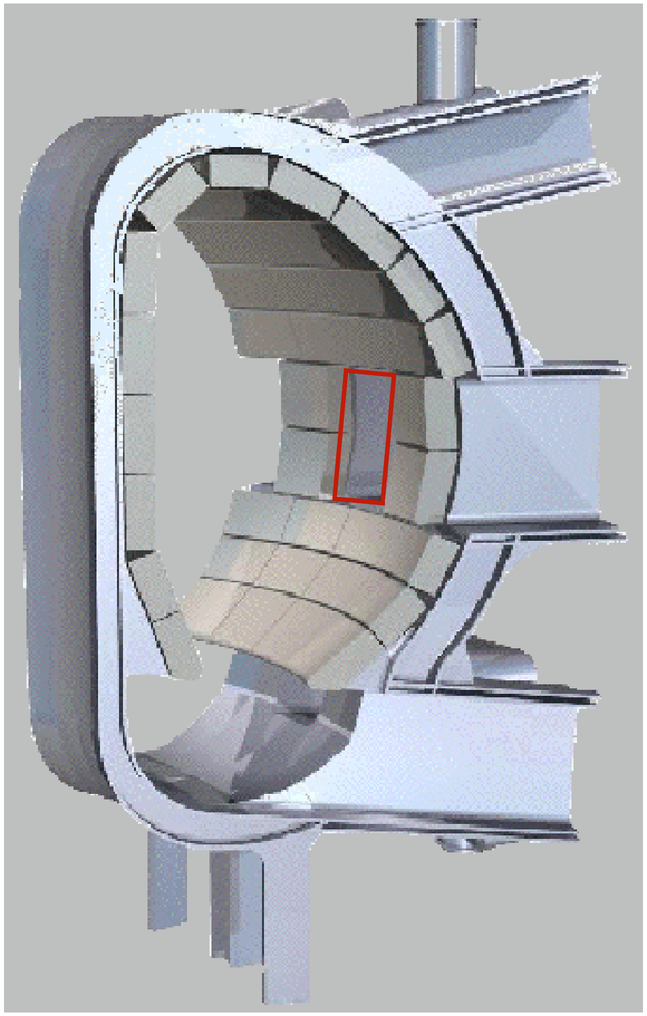


Optimizing Resistive Wall Mode Control: FIRE Approach

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

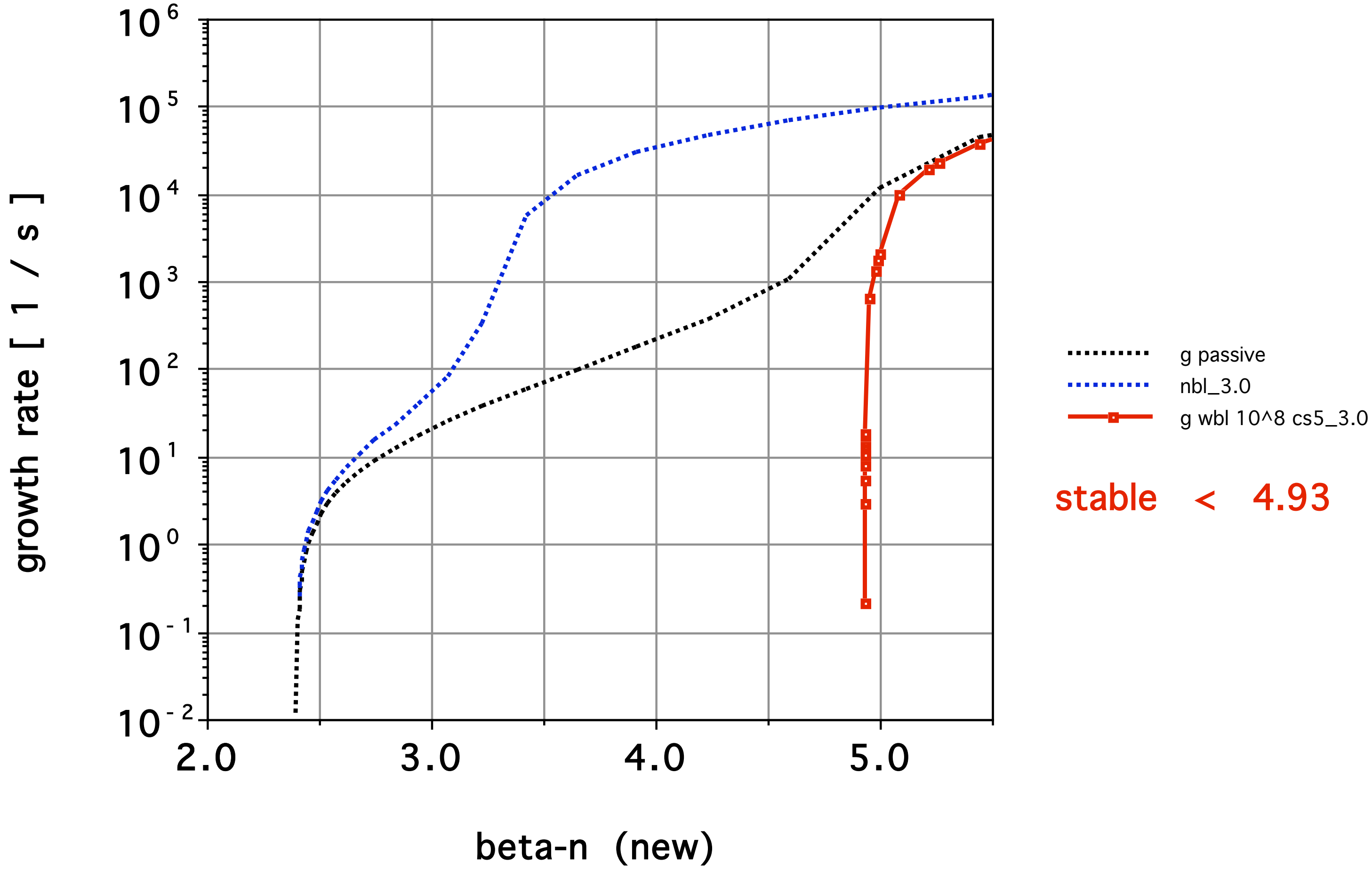


Try FIRE RWM Control Scheme in ITER



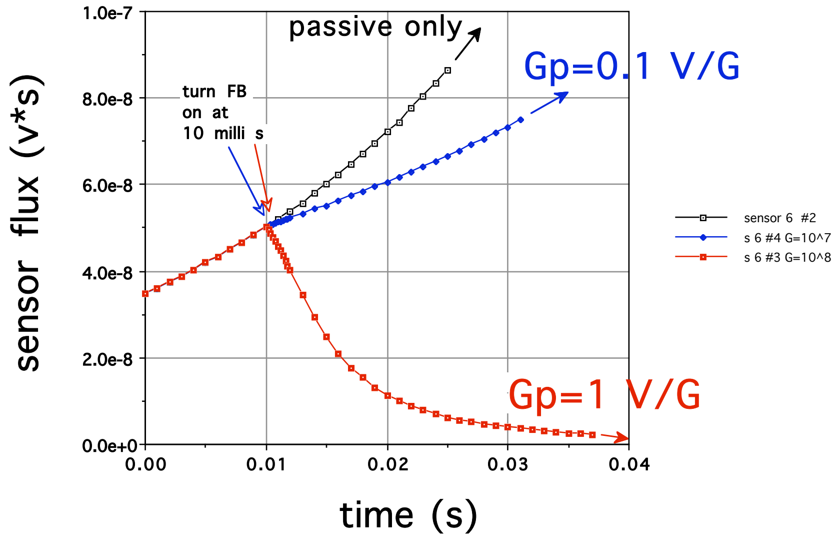
- Add Control Coils in Vacuum Vessel Ports: Good Coupling to Plasma
- Use Poloidal Sensors on Midplane Behind Blanket Armor

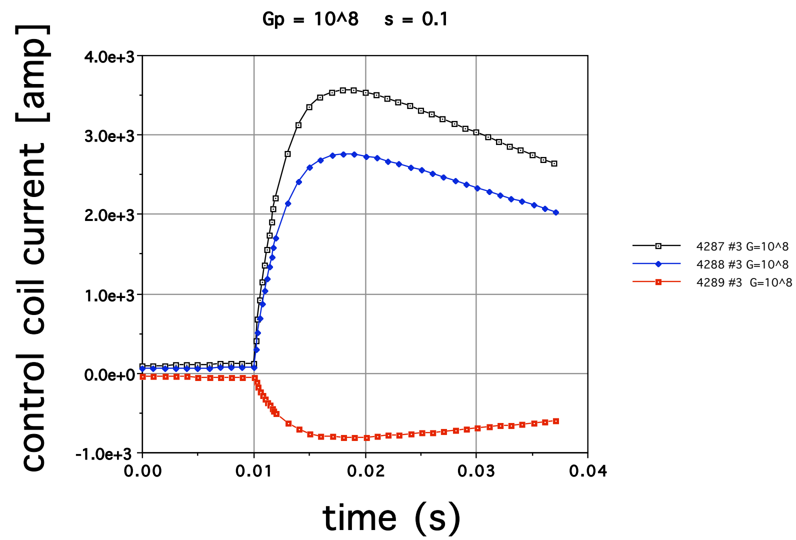
ITER Internal Coils in Port Plugs Easily Reach Ideal Limit



- 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!

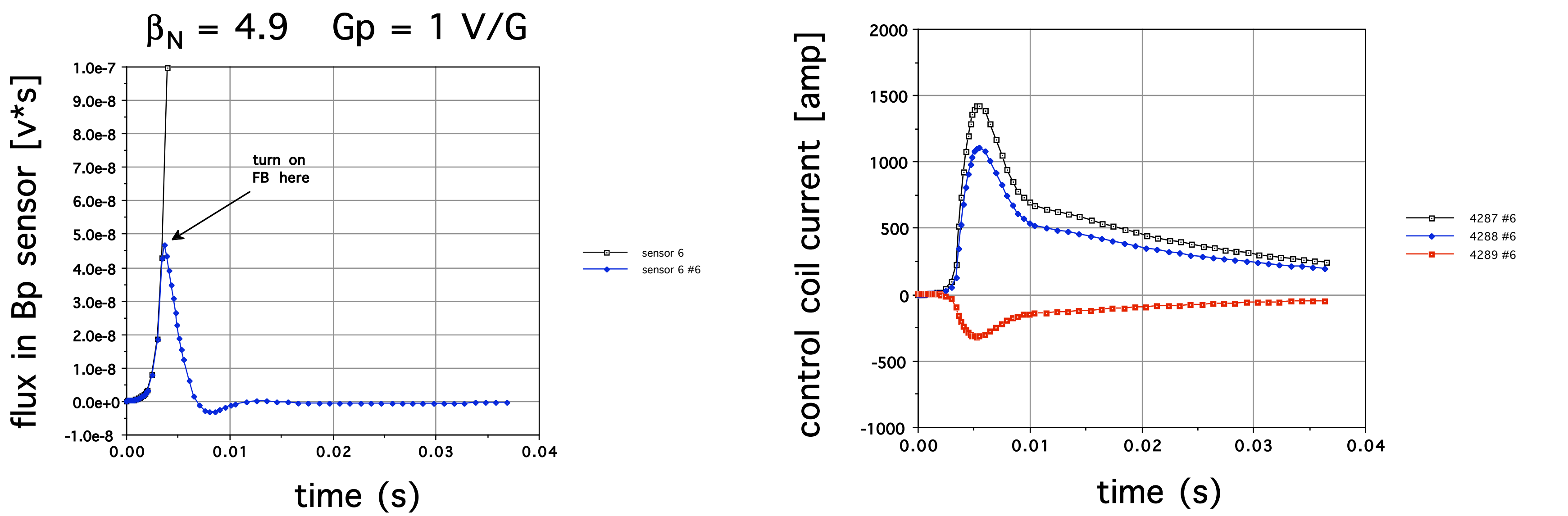
Time Dependent Feedback Model of ITER Internal Coils





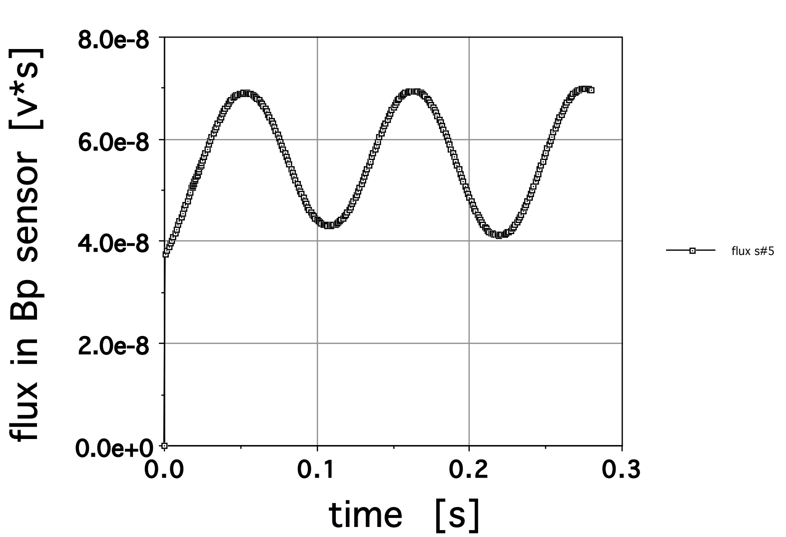
- At **Moderate Beta** (s=0.1) we observe simple damped suppression in 20 to 30 ms
- Peak Current in Control Coils reaches peak of 3.5 kA
- Peak voltage on single turn control coils is only 5 volts
- Reactive power requirements only ~5 kW in each coil pair

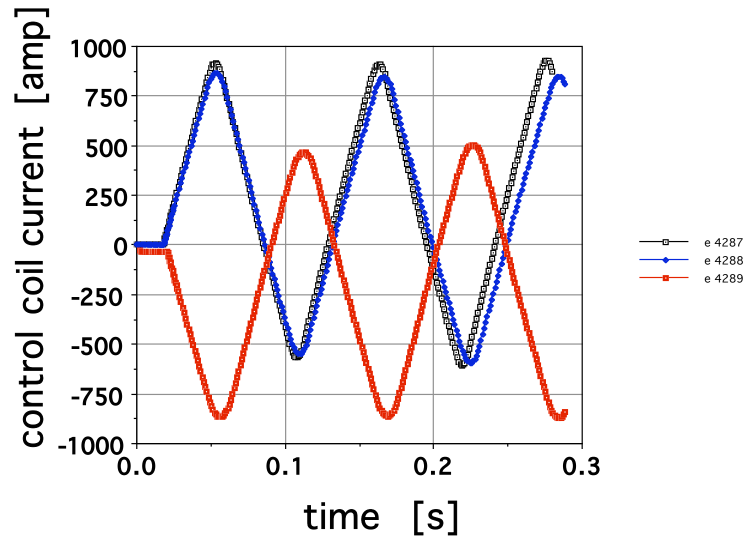
Time Dependent Feedback Model of ITER Internal Coils



- 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

Time Dependent Feedback Model of Basic ITER Coils





- Beta chosen to be near predicted limit of β_N ~ 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!

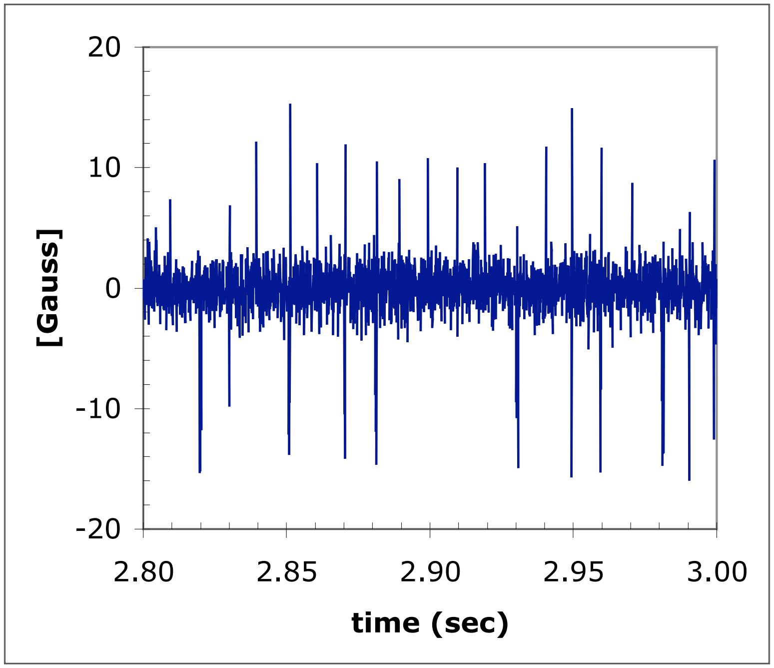
SUMMARY OF RESULTS

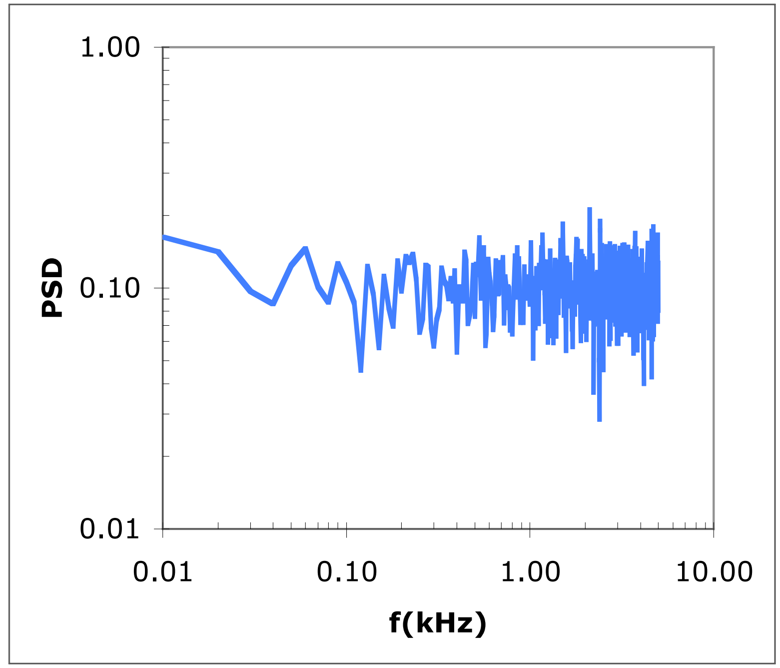
- **Basic ITER External Control Coils with Double-wall Vacuum Vessel in ITER Reduces Effectiveness of Feedback System: Stable only up to ~ 20% above No-wall Beta Limit. Voltage requirements at coil operating limits (1.1 kV) degrade feedback performance and multi-MW reactive power required.**
- **Inclusion of Blanket Modules Significantly Increases Ideal Wall Beta Limit from about β_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 ($\square_{mode} < 1/\square_{wall}$): small stabilizing effect
  - Use MARS and/or DCON+ to find $s(\square_{p})$

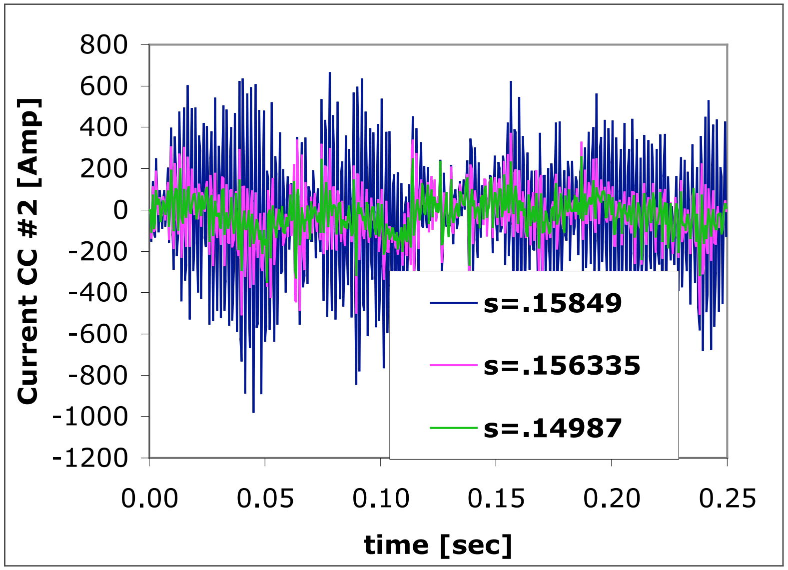
Simulated RWM Noise on DIII-D with ELMs

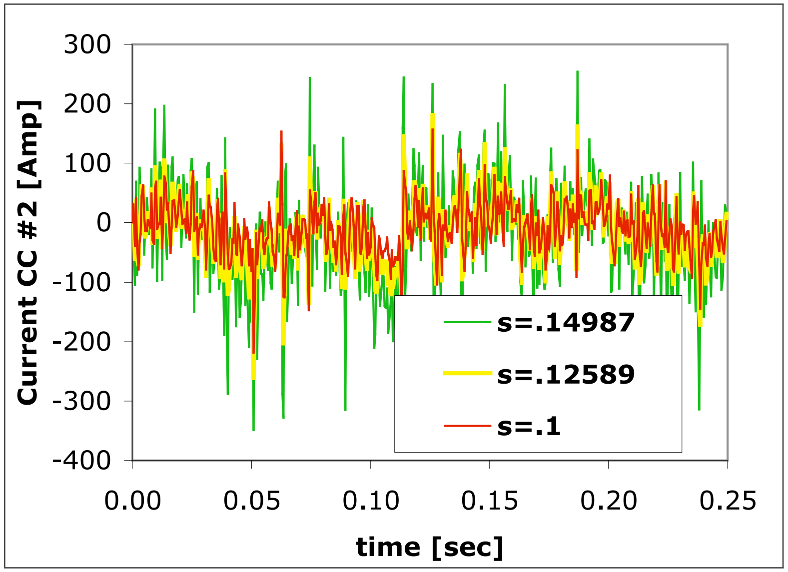




To the low level noise ELMs (Edge Localized Modes) were added as small group of Gaussian random numbers from 6 to 16 Gauss approximately every 0.01 sec with different signs +/- chosen with 50% probability

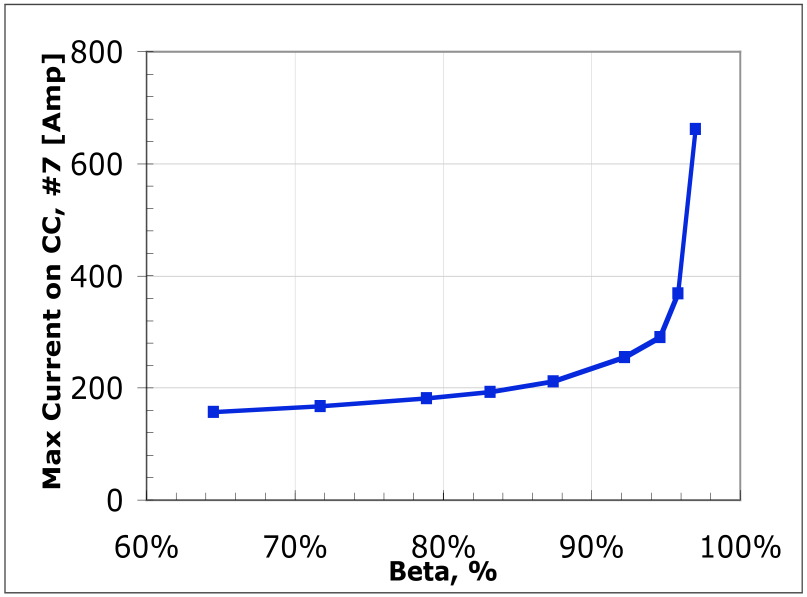
DIII-D I-Coil Feedback model for the Control Coils L=60 H and R=30 mOhm with Proportional Gain G_p=7.2Volts/Gauss

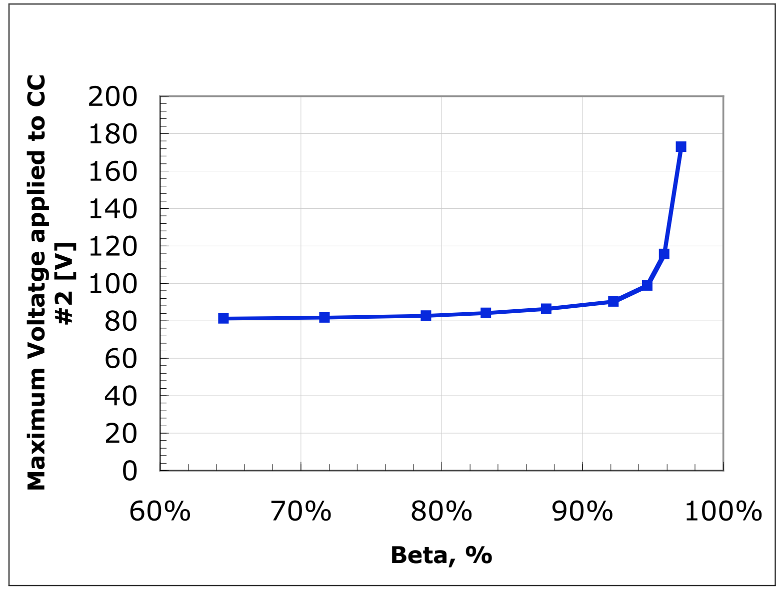




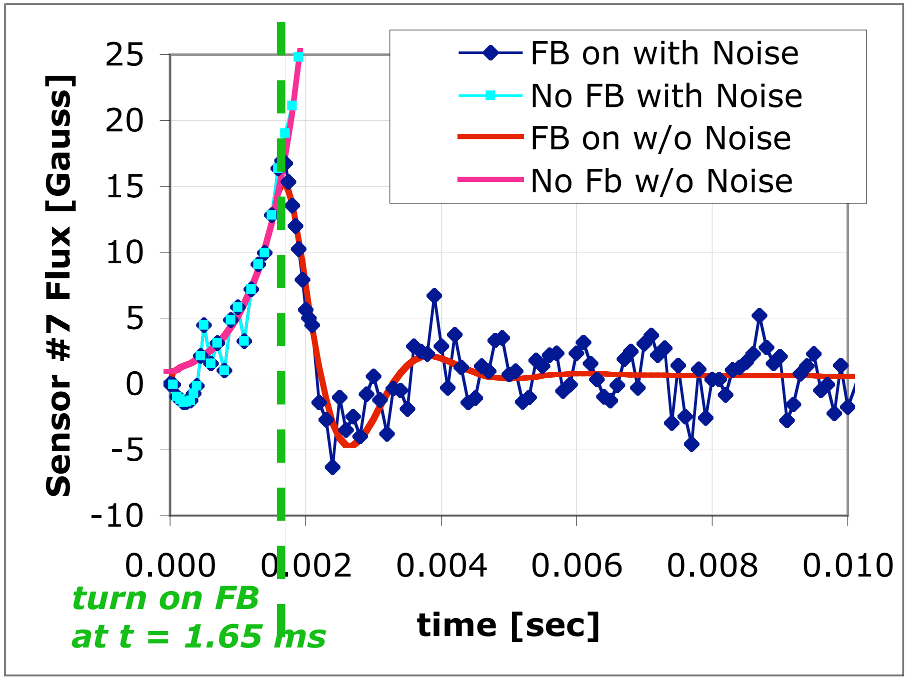
Control coil current

Maximum control coil current and voltage with noise in DIII-D as function of β_N





Effects of Noise on Feedback Dynamics for L=60 H and R=30 mOhm DIII-D I-Coil Feedback model with Proportional Gain G_p=7.2Volts/Gauss



Sensor Flux