RWM Control in BP Experiments:
Control Coil Location, Passive Stabilizer Geometry; Feedback Loop Dynamics

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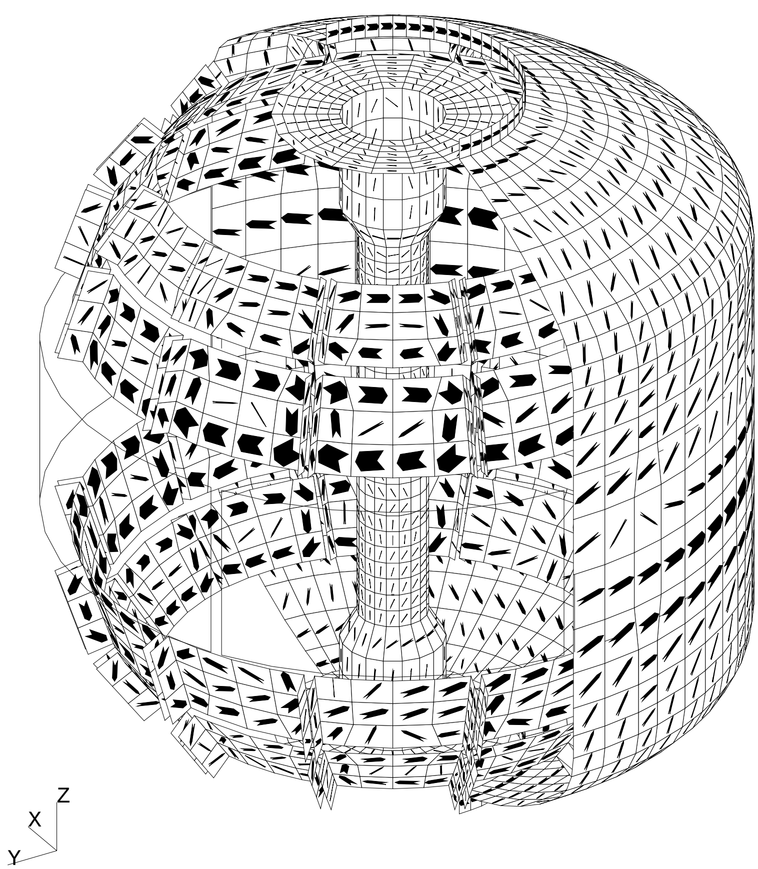
Outline

- Review of RWM Feedback
- Critical Issues in Control Design
  - **Passive Stabilizer Performance**
  - **Control Coil-Plasma-Stabilizer Coupling**
  - **Reactive vs Resistive Control Coil**
- Differences with Liu & Bondeson
  - **Transition to Ideal Branch in Dispersion Relation**
  - **Mapping of β_N to dispersion relation limits**
  - **Effectiveness of ITER Error Field Correction Coils for RWM Control**
- Resolving Differences: Benchmarks

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.

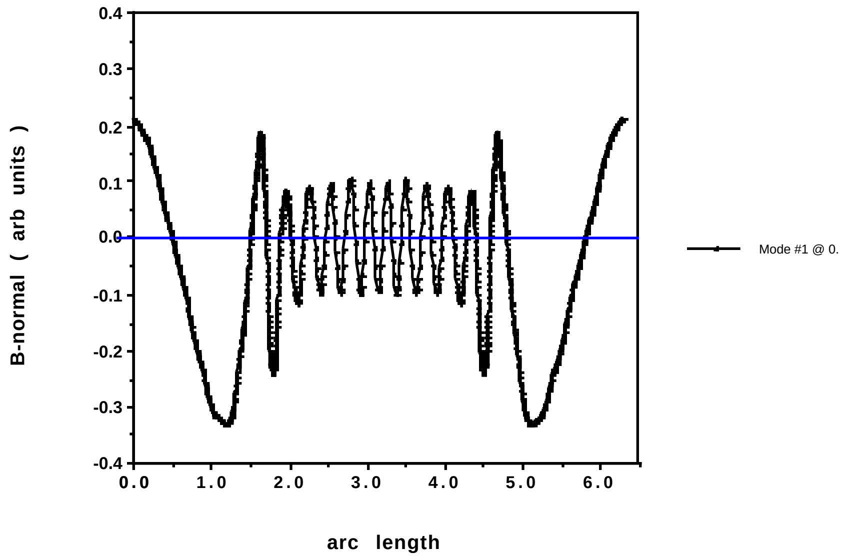
- The instability is represented via a normalized mode strength

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

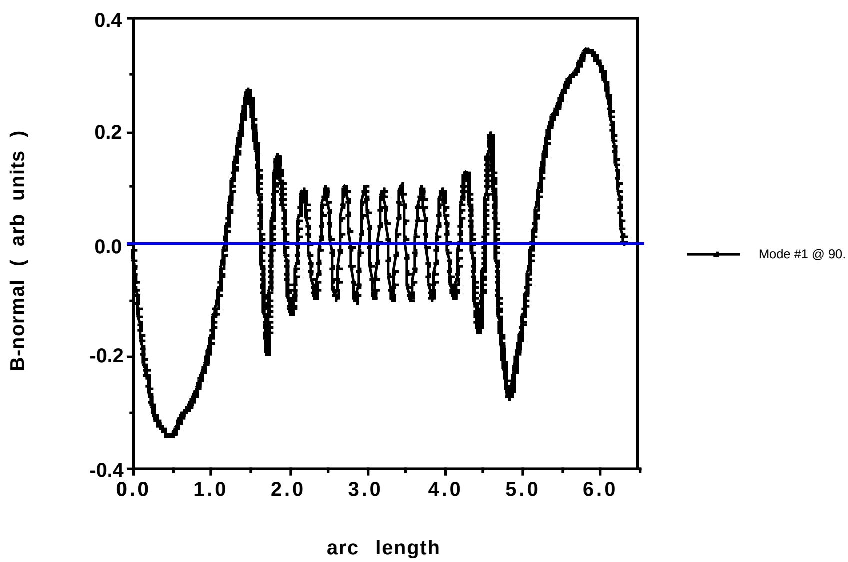
$$[L'(s)]\{\dot{\mathrm{I}}'\}+[R']\{\mathrm{I}'\}=\{V'(t)\}$$

DCON computation of mode structure NSTX - derived from EFIT reconstruction of #106165 β_n = 6.154, Fp = 2.2, n = 1

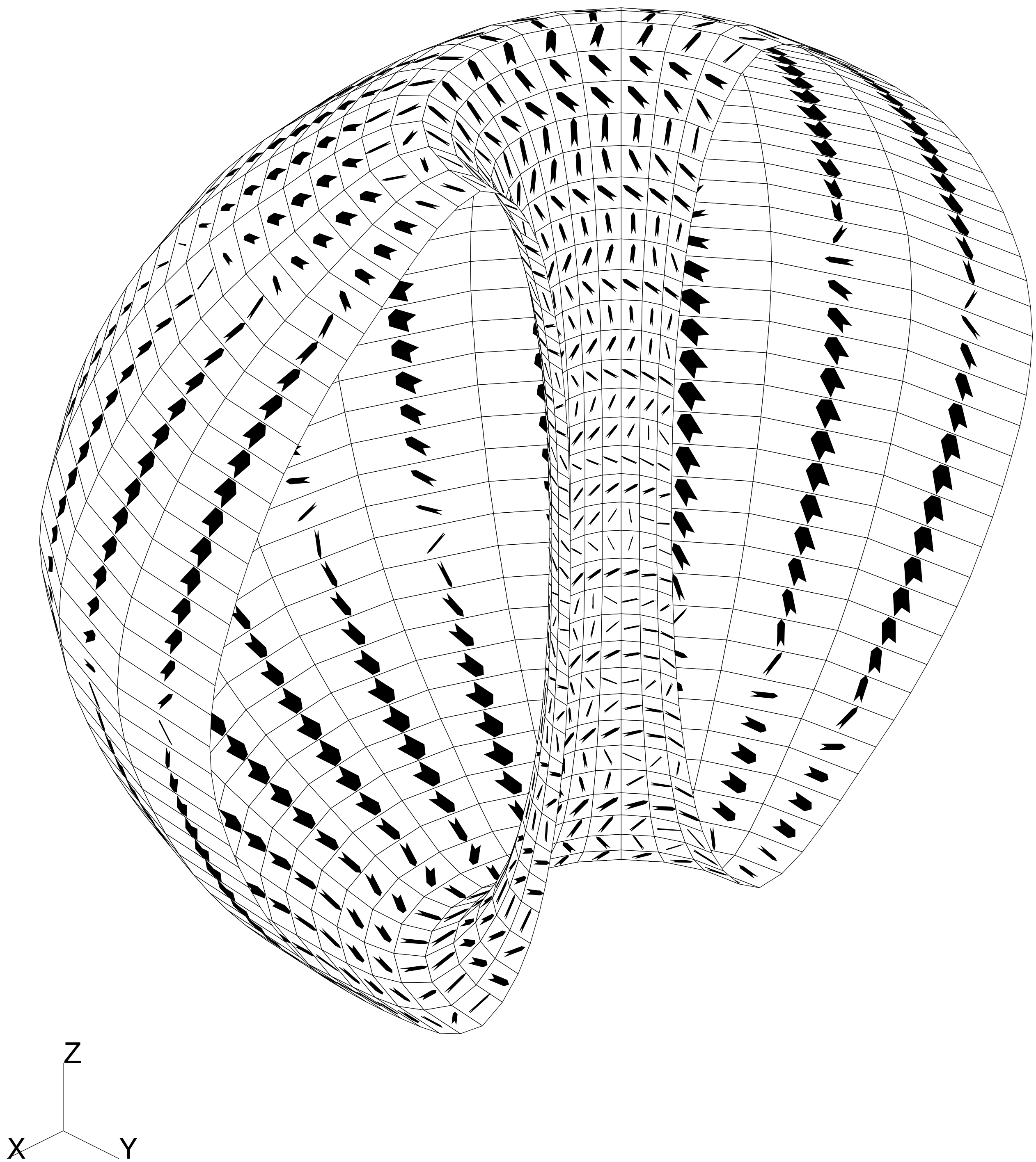
DCON mode for beta n = 6.154
mode at 0.0 deg (even)



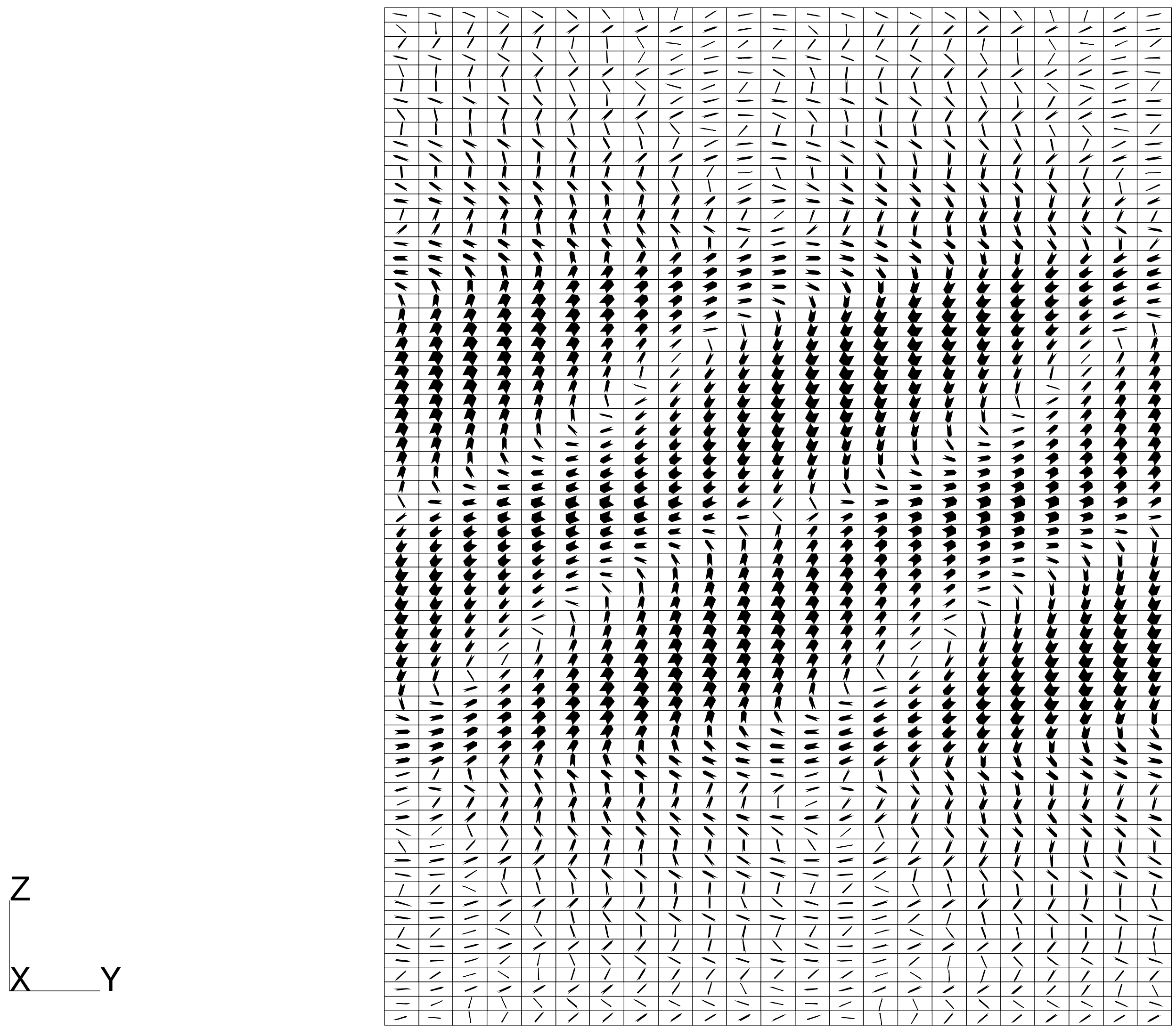
DCON mode for beta n = 6.154
mode at 90.0 deg (odd)



Equivalent Surface Current which produces mode field
from dcon_surf_Fp2.2_bn6.154 24 by 72
Input to VALEN for NSTX 's'= 2.0590e-1



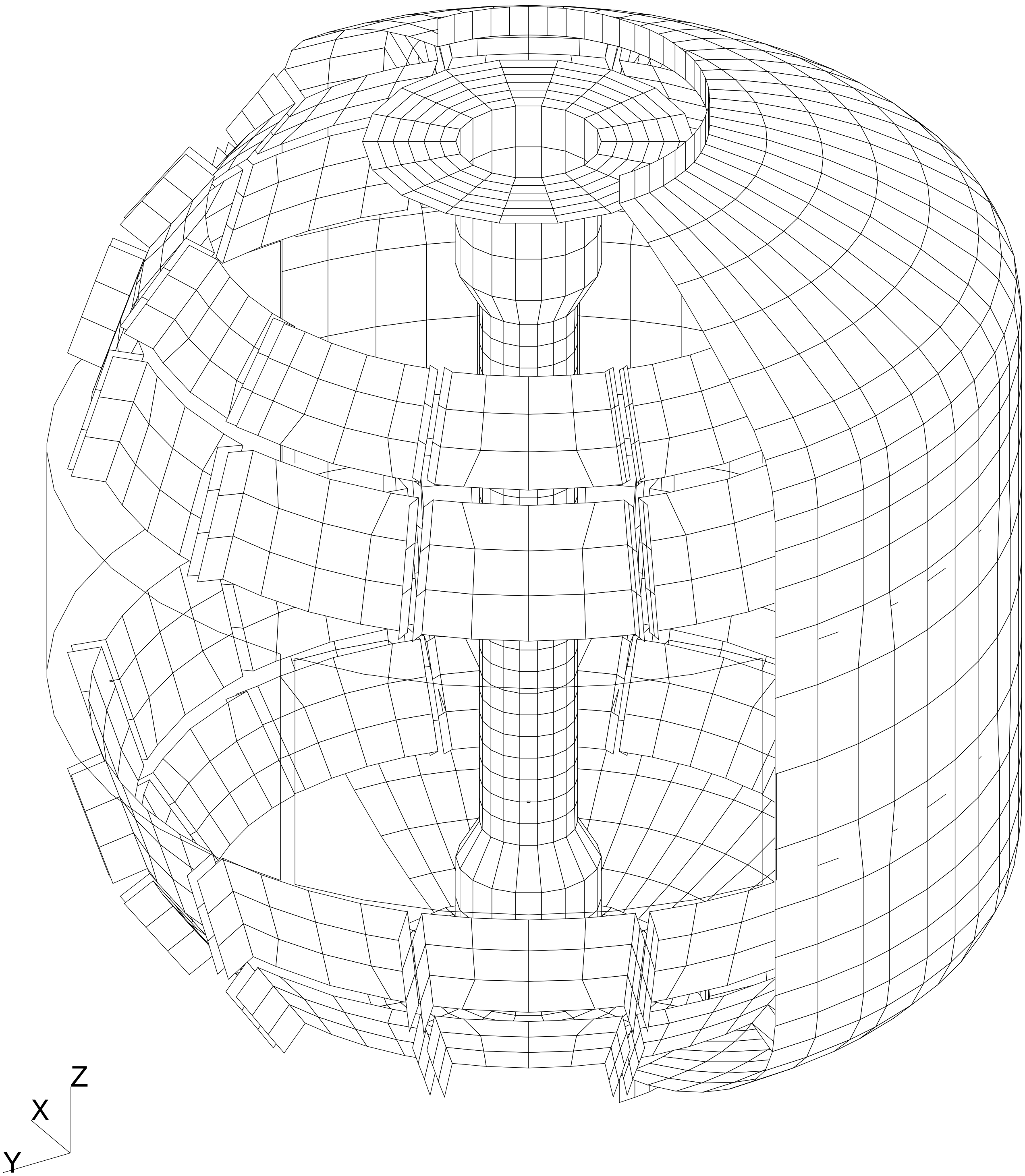
Equivalent Surface Current which produces mode vacuum field
from dcon_surf_Fp2.2_bn6.154 unwrapped inboard cut
Input to VALEN for NSTX 's'= 2.0590e-1



03/14/02 NSTX half of VV removed

VALEN

NSTX geometry (including sensors and ideal control coils)

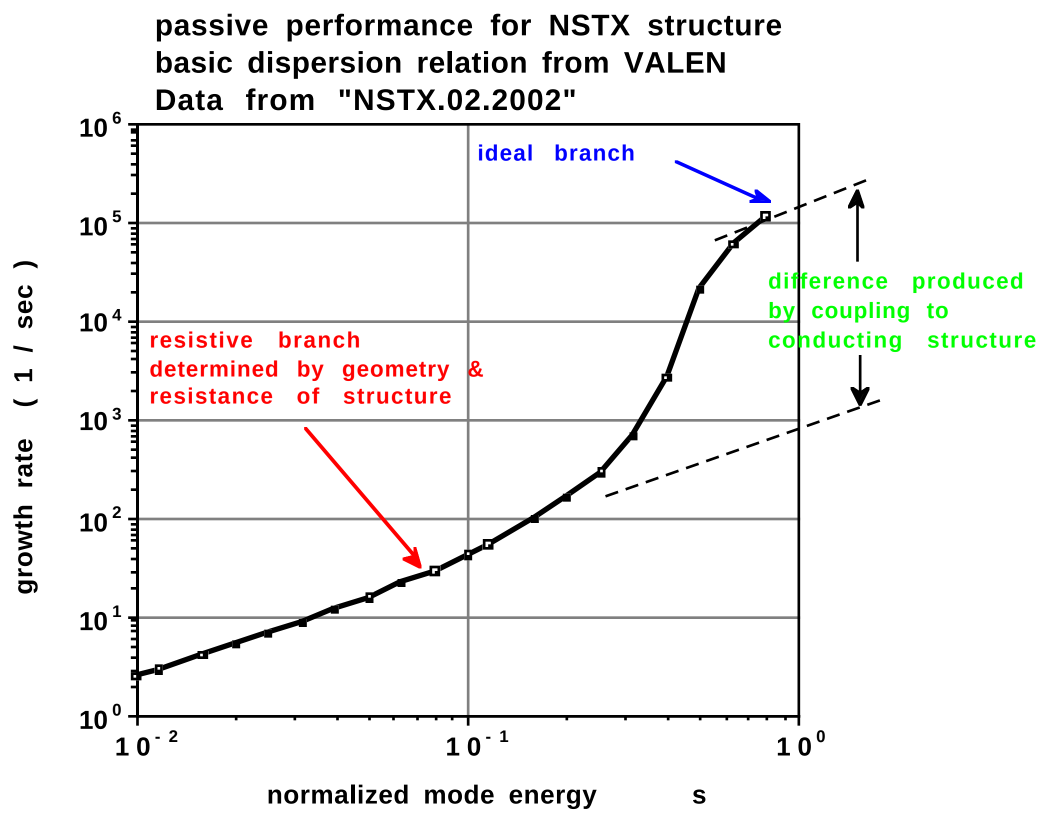


VALEN predicts growth rate for plasma instability as function of the instability strength parameter 's'

- 's' is a normalized mode energy

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

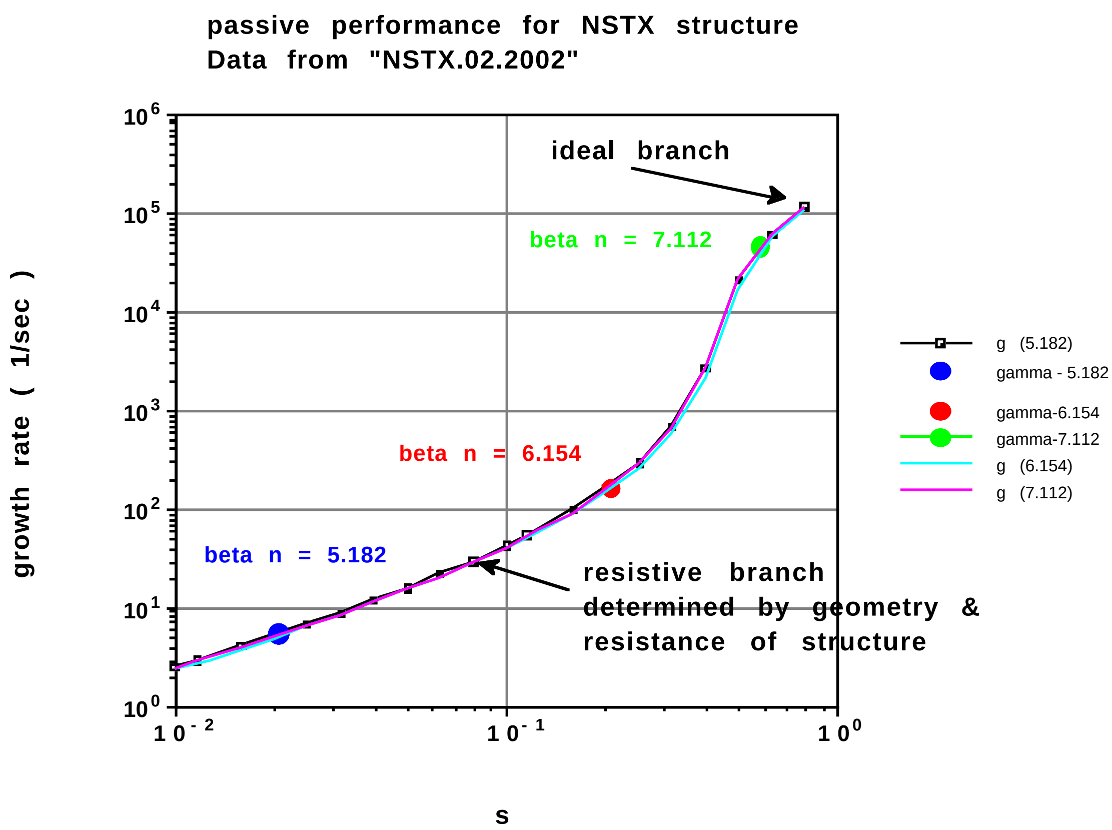
- computed dispersion relation of growth rate vs. 's' is an eigenvalue calculation



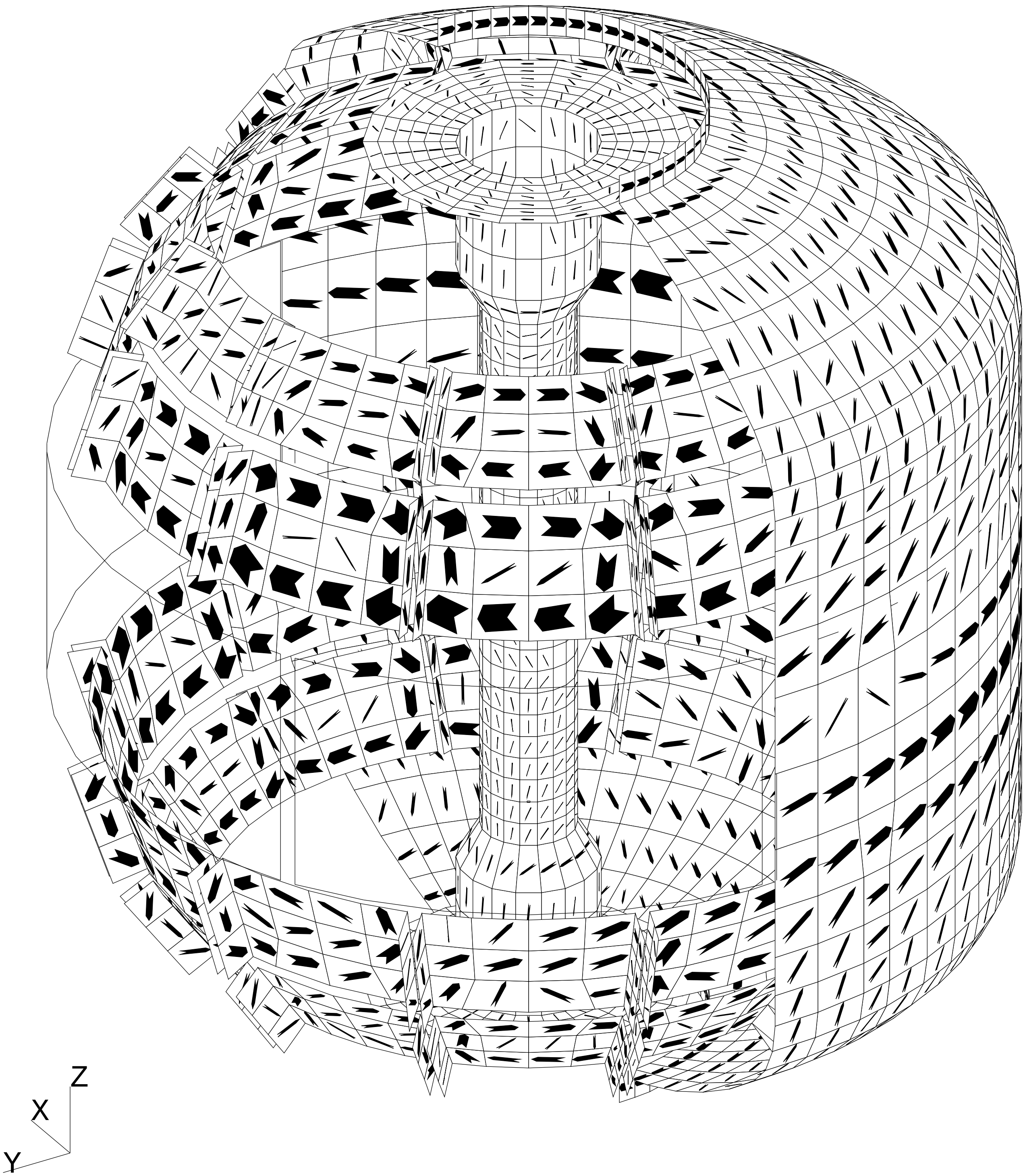
VALEN predicts growth rate for plasma instability as function of 's'

- $s = \dfrac{-\delta W}{\left(\mathrm{LI}^2 / 2\right)}$ a normalized energy

- great agreement for different starting plasma equilibria !

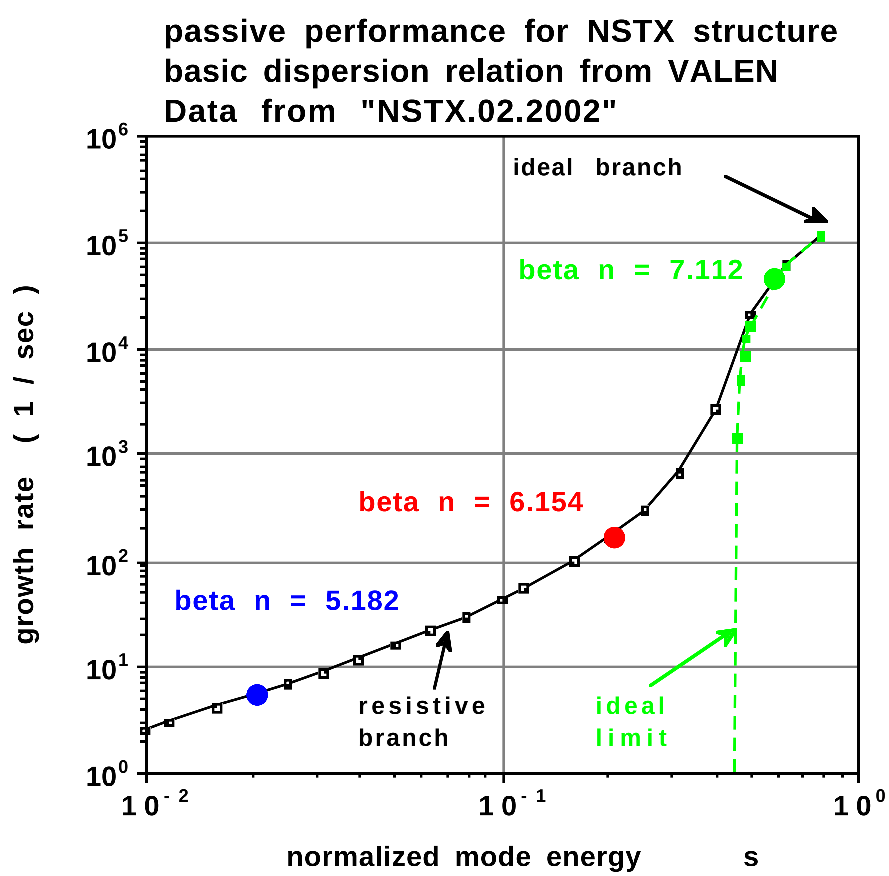


03/01/02   10:05:40 EST artemis executable: xvps6
VALEN s = 0.31623 gamma = 573.3 betan(6.154)driver
eddy currents (passive only) in NSTX structure



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

- examine limit of perfect conductors
- connect s to β_n

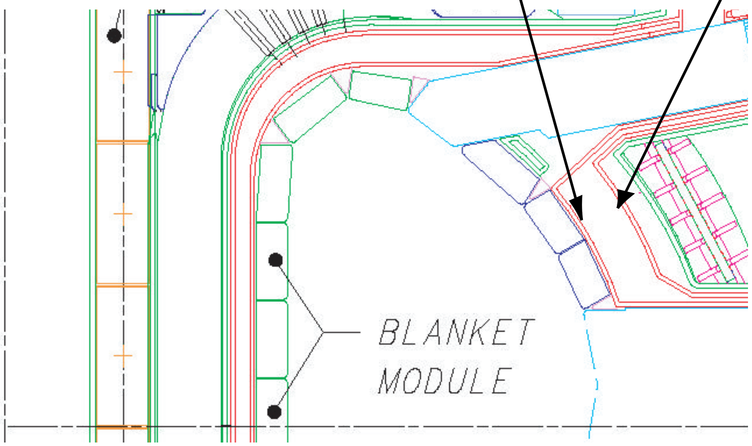


ITER

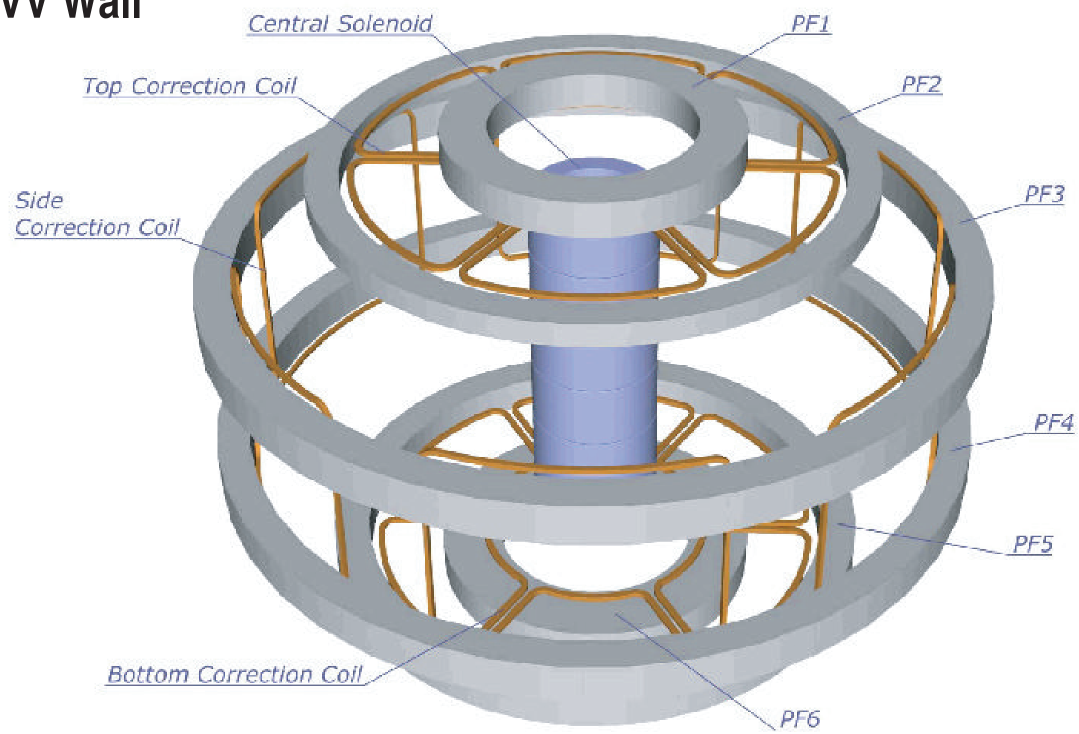
PASSIVE STABILIZER AND ACTIVE CONTROL COILS

Inner Vacuum Vessel Wall (6 cm-thick stainless steel)

Outer VV Wall

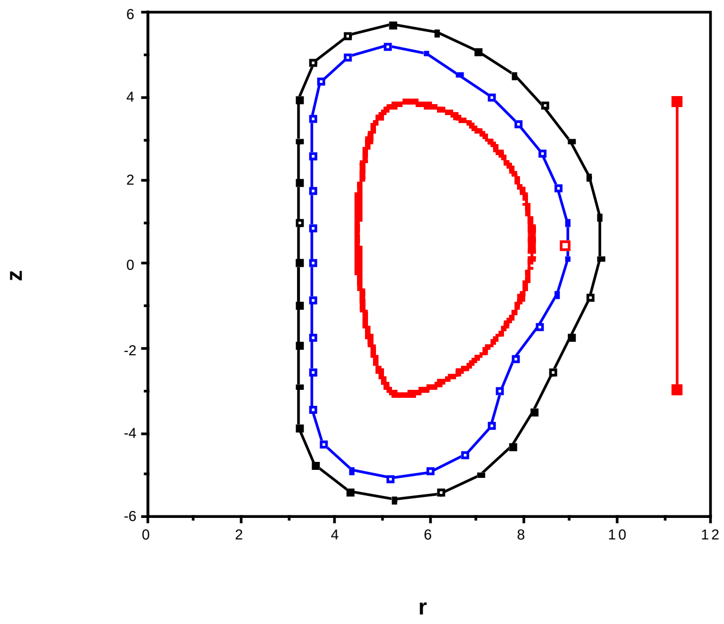


The ITER vessel is modeled as two walls.



Three sets of six saddle coils, outside the vessel, but the upper and lower coils couple weakly to the RWM.

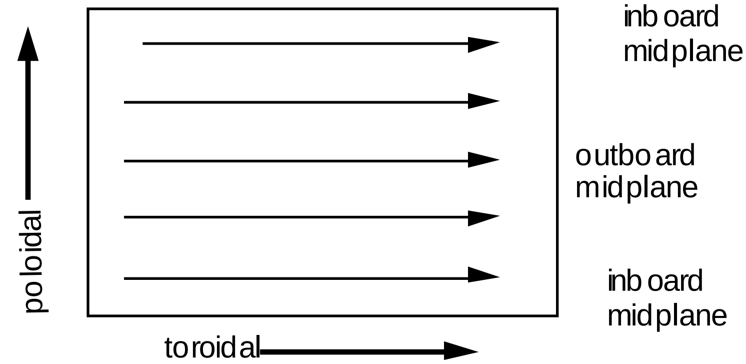
ITER Base Case Feedback Control System Geometry

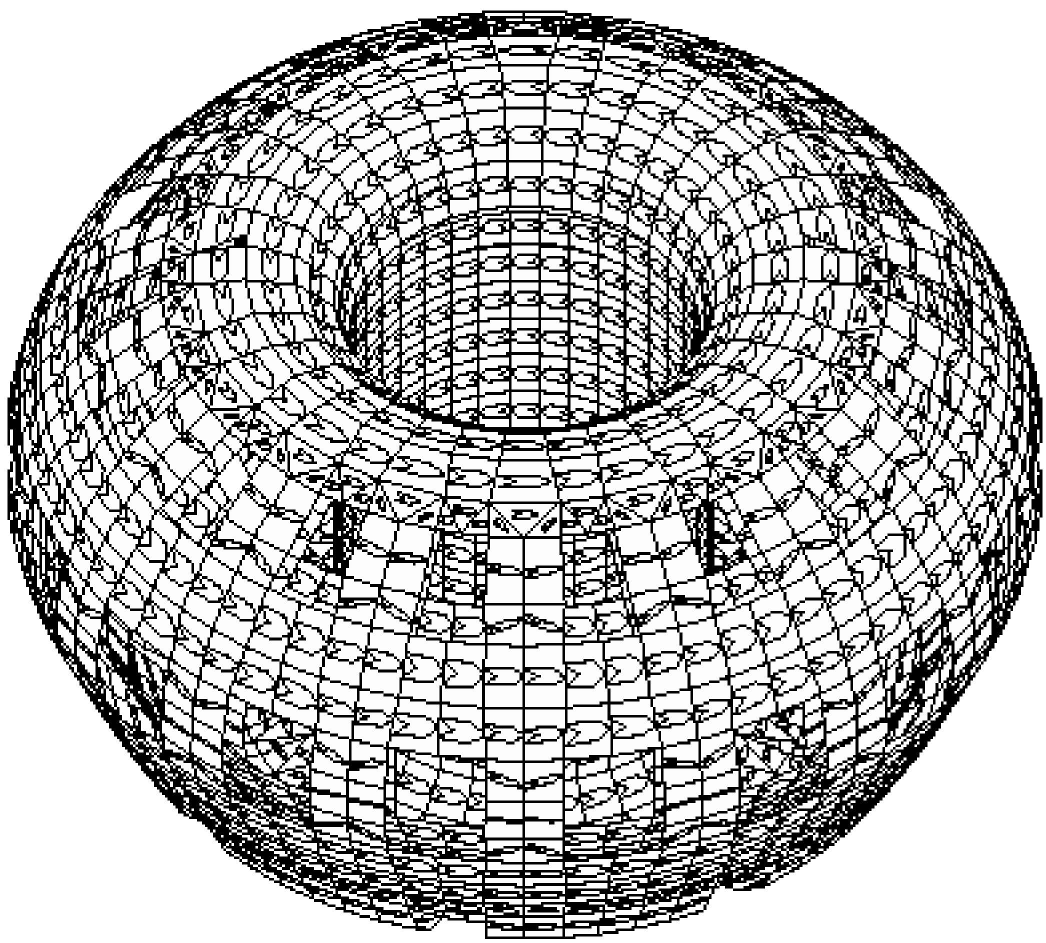


- The ITER vacuum vessel is modeled as a double wall configuration using design data provided by Gribov, with feedback control provided by 3 n=1 pairs of external control coils on the mid-plane.

ITER Vacuum Vessel Mode Analysis

n ~ 0 and m ~ 0

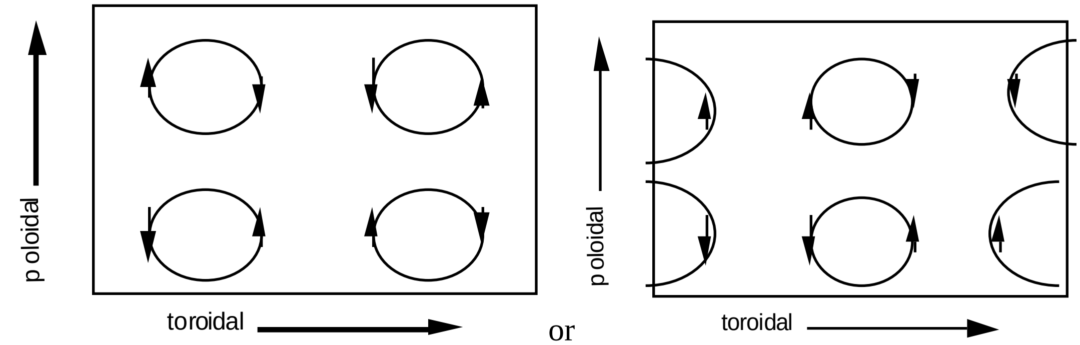


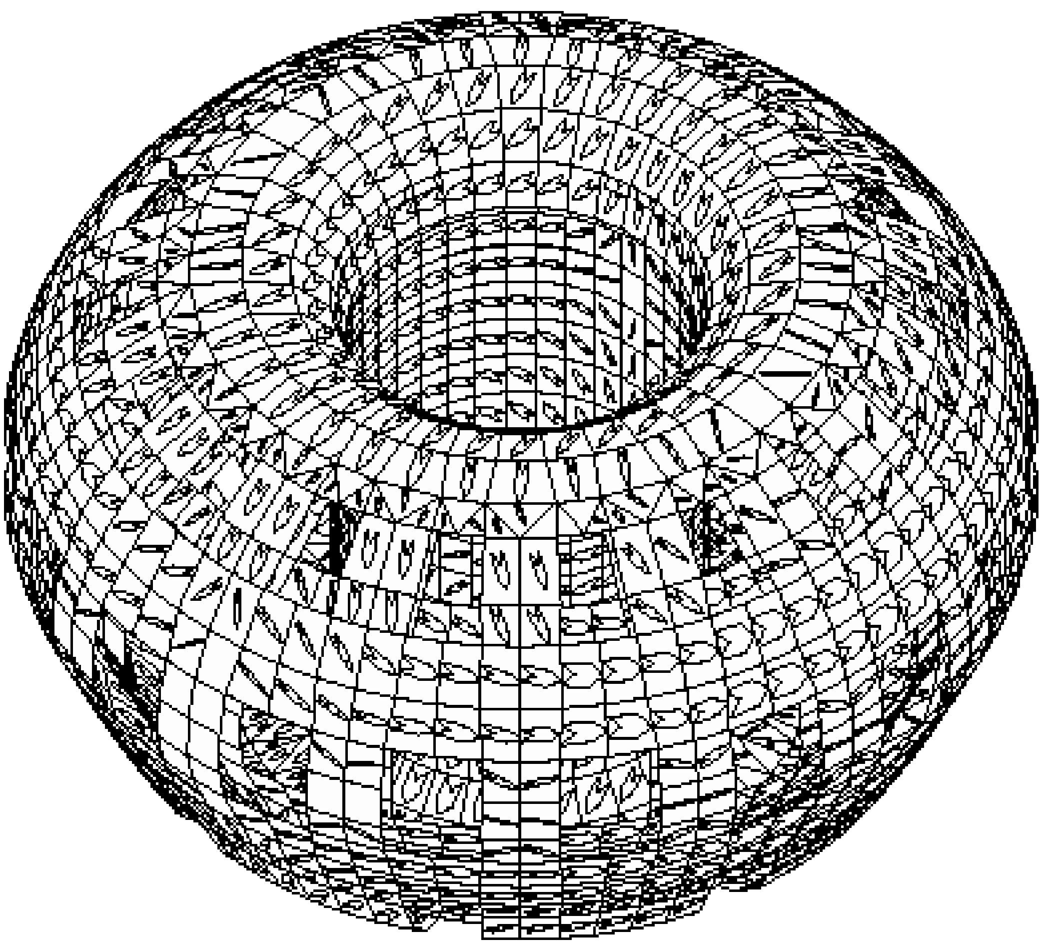


- Modeled with 3906 elements.
- Longest Time Constant: **0.39897 s**

ITER Vacuum Vessel Mode Analysis

n ~ 1 and m ~ 1
(2 fold degenerate)

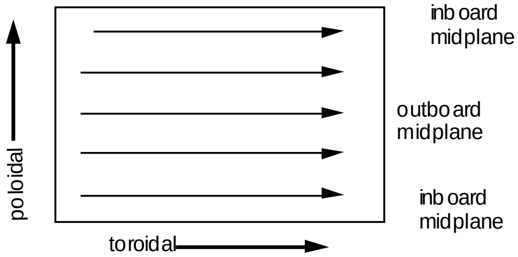




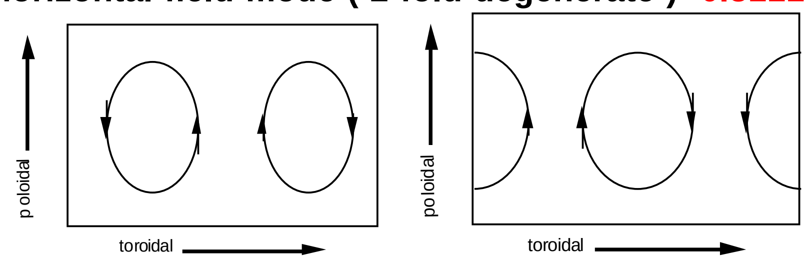
- Modeled with 3906 elements.
- 1/1 Time Constant: **0.18762 s**.

Whole Family of ITER Vessel Modes

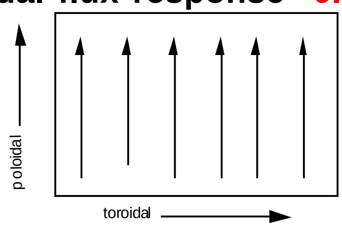
the n=0, m=0 'OH response mode' 0.39897 s, 0.39804 s
[red = 3906 elements ; black = 2970 elements]



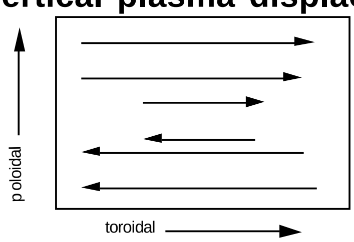
the n=1, m=0 horizontal field mode (2 fold degenerate) 0.31114 s, 0.31729 s



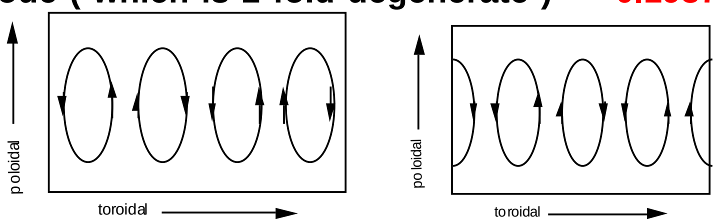
the n=0, m=0 toroidal flux response 0.24513 s, 0.25216 s



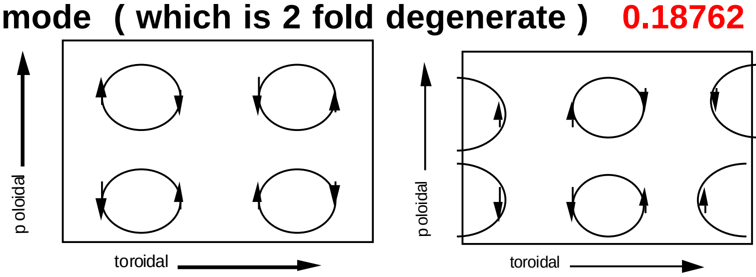
the n=0, m=1 response to vertical plasma displacement 0.23113 s, 0.22753 s



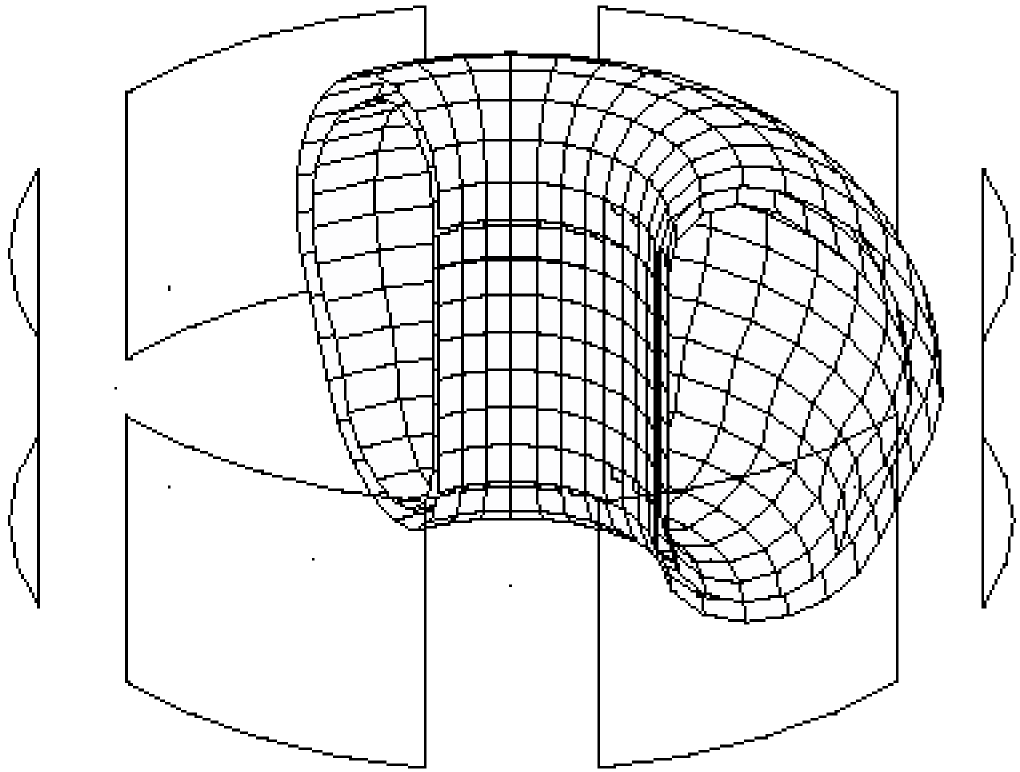
the n=2, m=0 mode (which is 2 fold degenerate) 0.19377 s , 0.20166 s



the n=1, m=1 mode (which is 2 fold degenerate) 0.18762 s, 0.18937 s

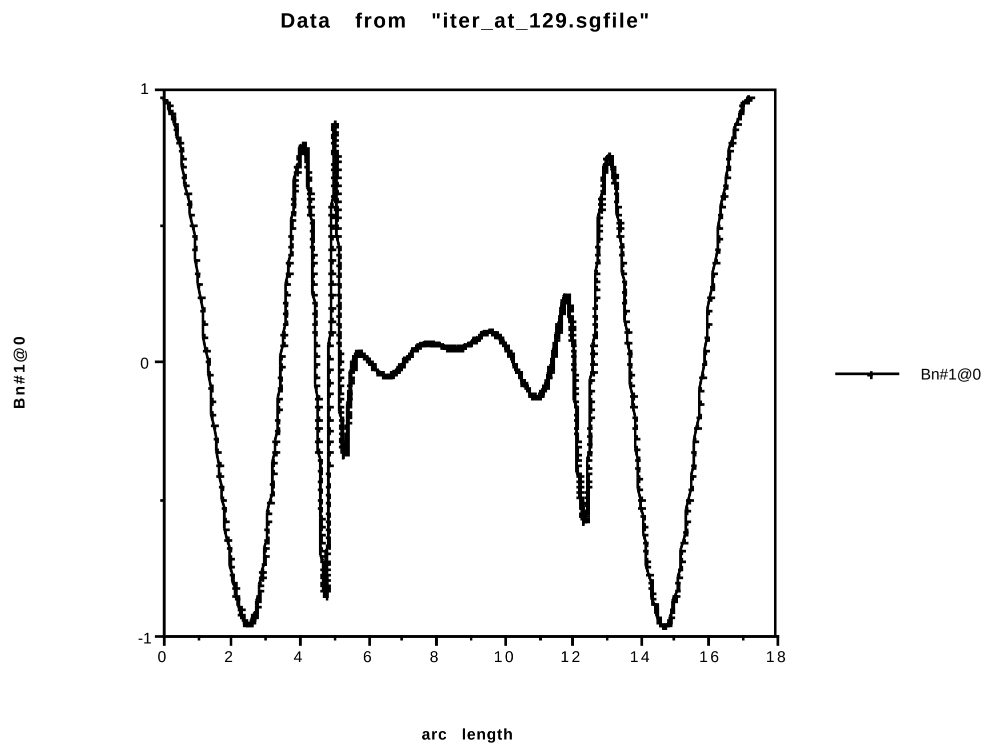


VALEN Model of ITER Vessel and Control Coils: Base Case Feedback Control System

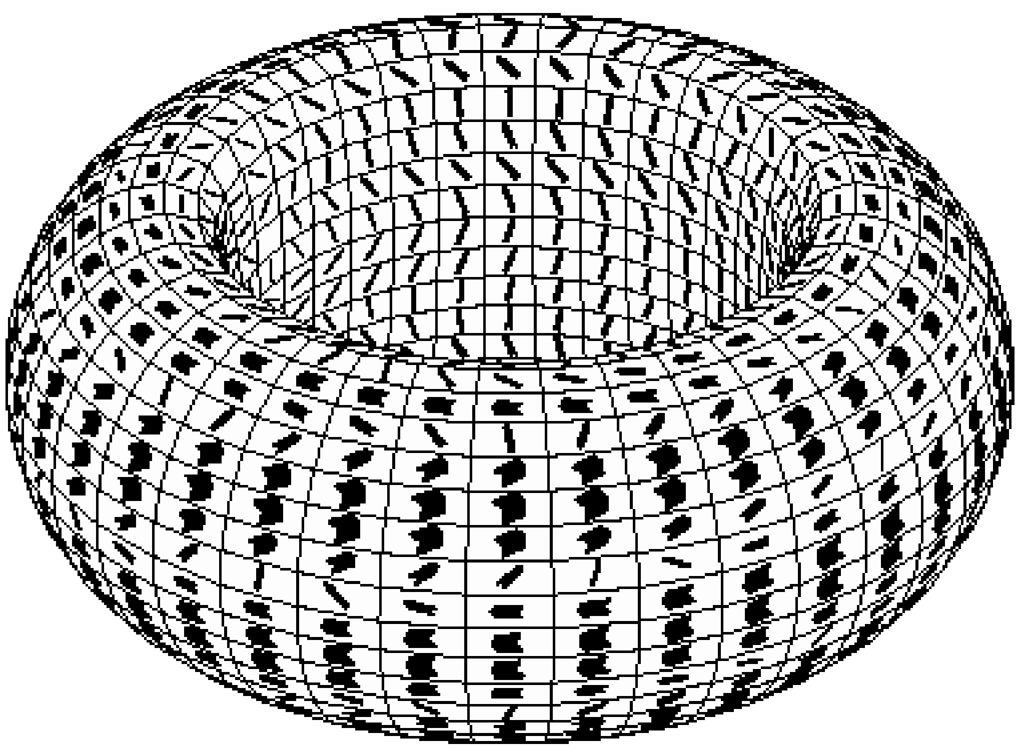


- Vacuum Vessel Modeled with and without wall penetrations.

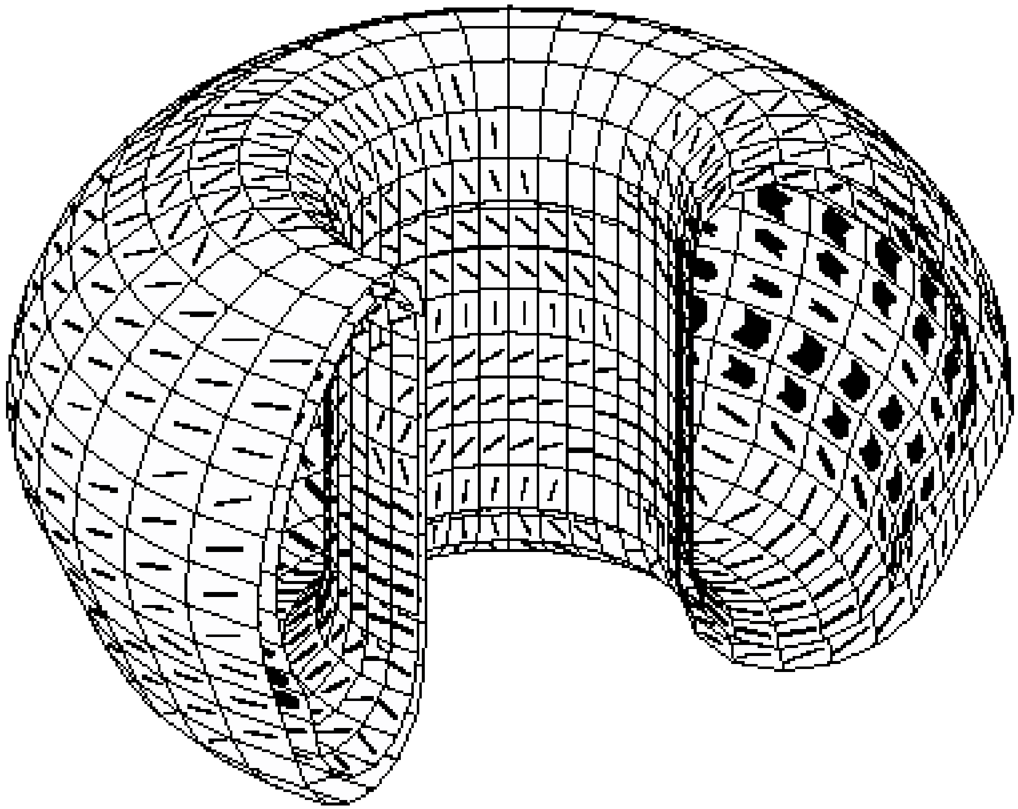
DCON Calculation of ITER RWM: B-normal vs Poloidal Angle



Use B-normal to Compute Equivalent Plasma Surface Current

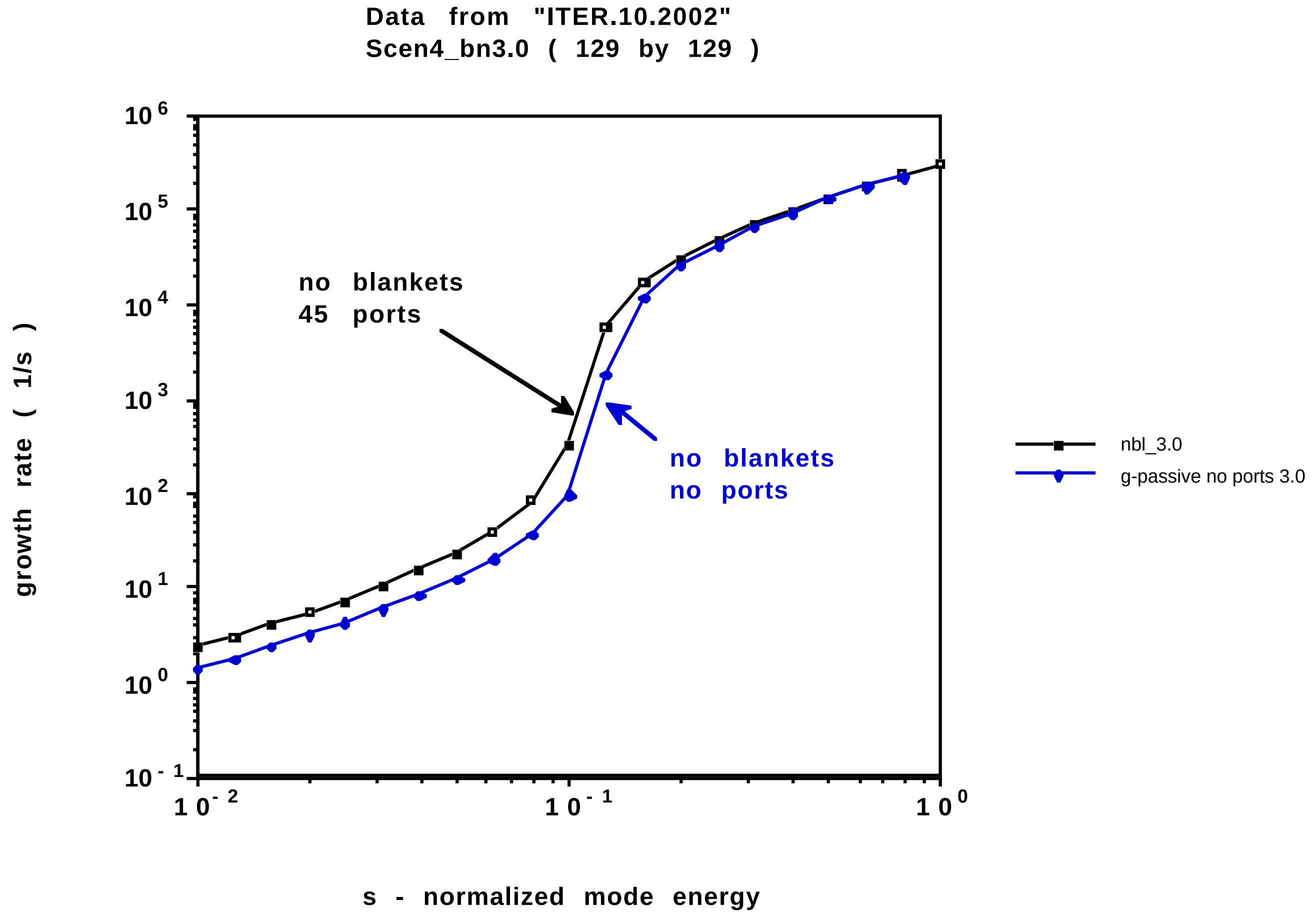


RWM Induces Stabilizing Image Currents Largely on the Inner Vessel Wall



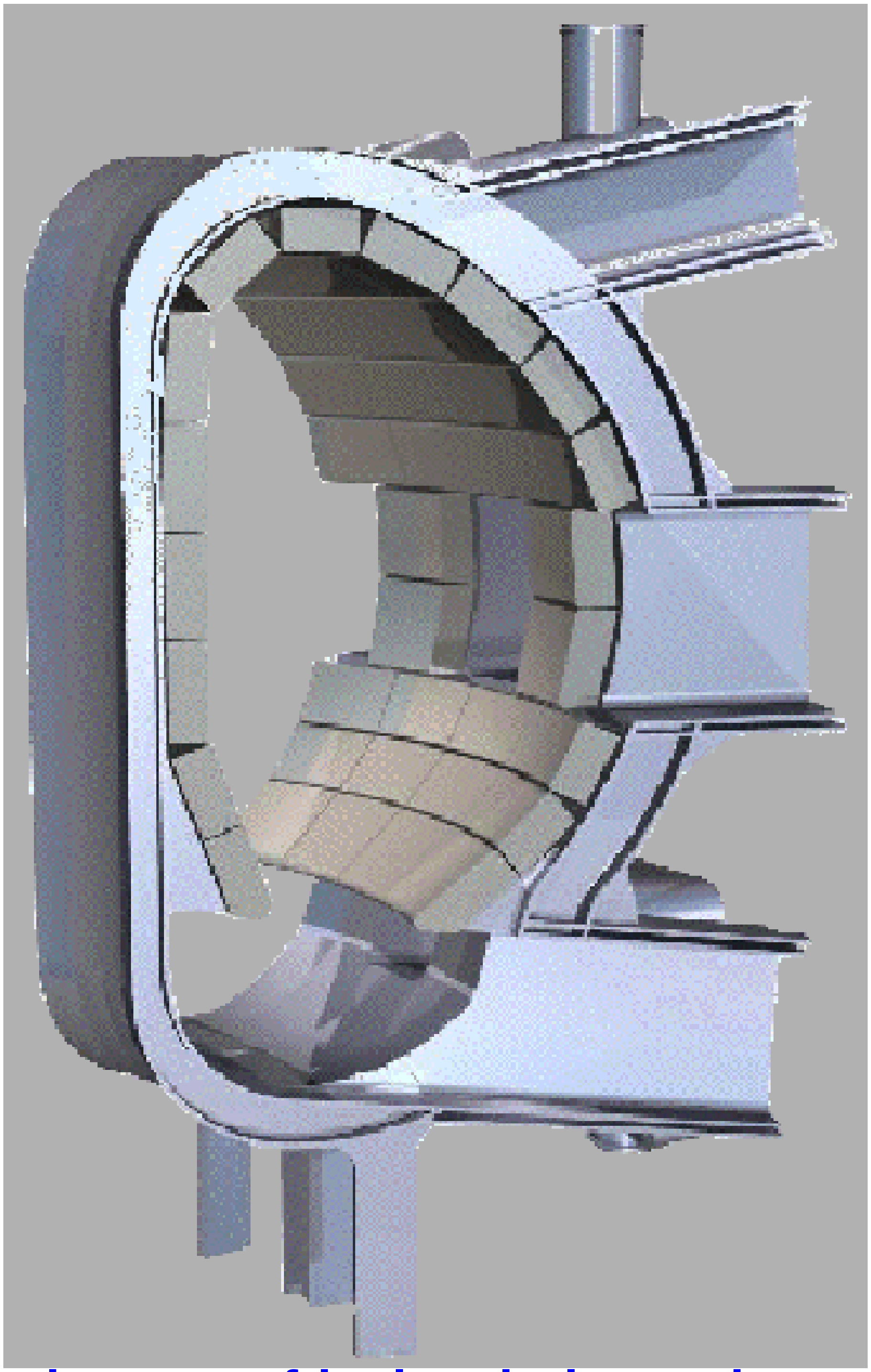
- Vacuum Vessel Modeled with and without wall penetrations.

ITER Vacuum Vessel Penetrations Have Little Effect on Passive RWM Stabilization



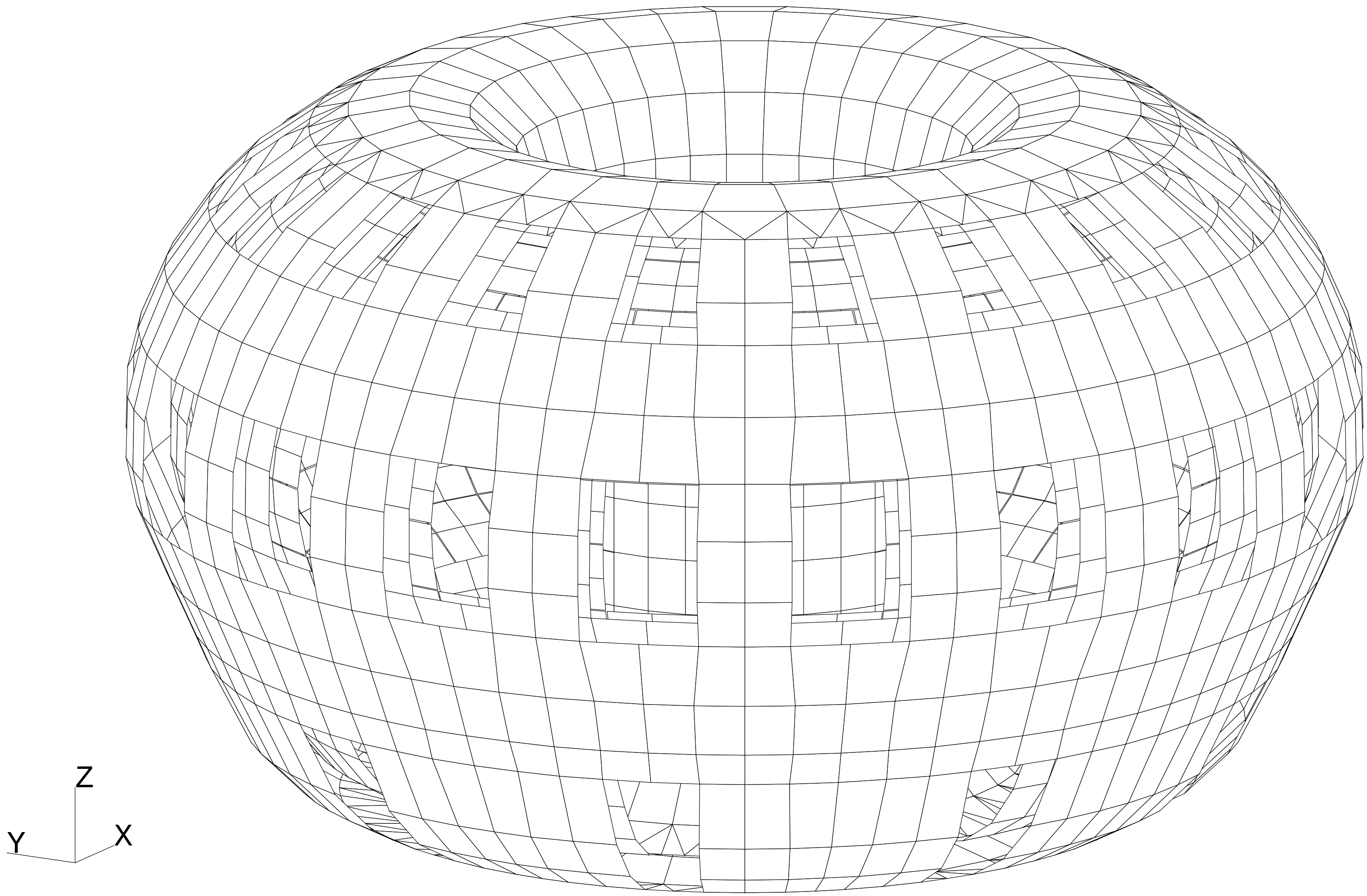
- **Relatively small reduction in the ideal wall beta limit.**

Include ITER Blanket Modules in Passive RWM Stabilization Model

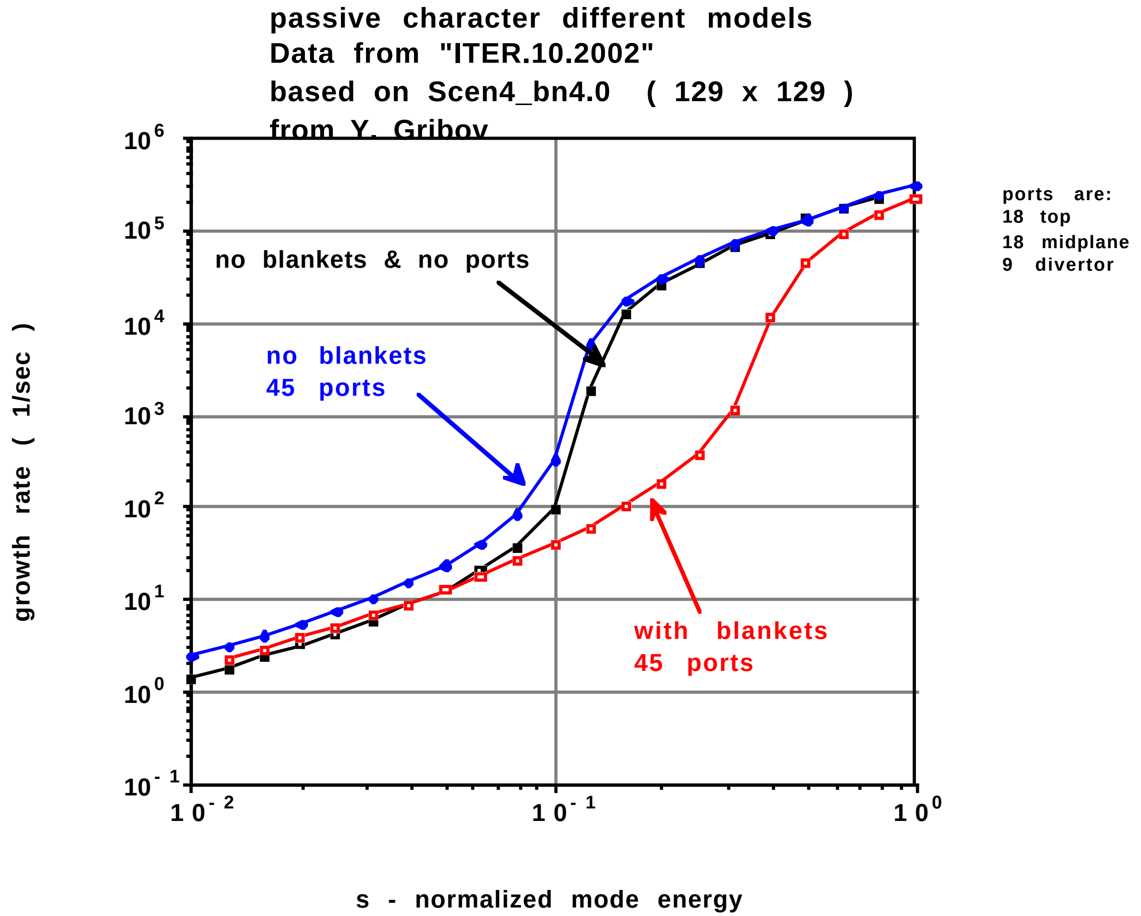


- Modeled as set of isolated plates above the inner vessel wall.
- Each blanket module adjusted to have 9 ms radial field penetration time constant.

VALEN Model of ITER Double Wall Vessel and Blanket Modules

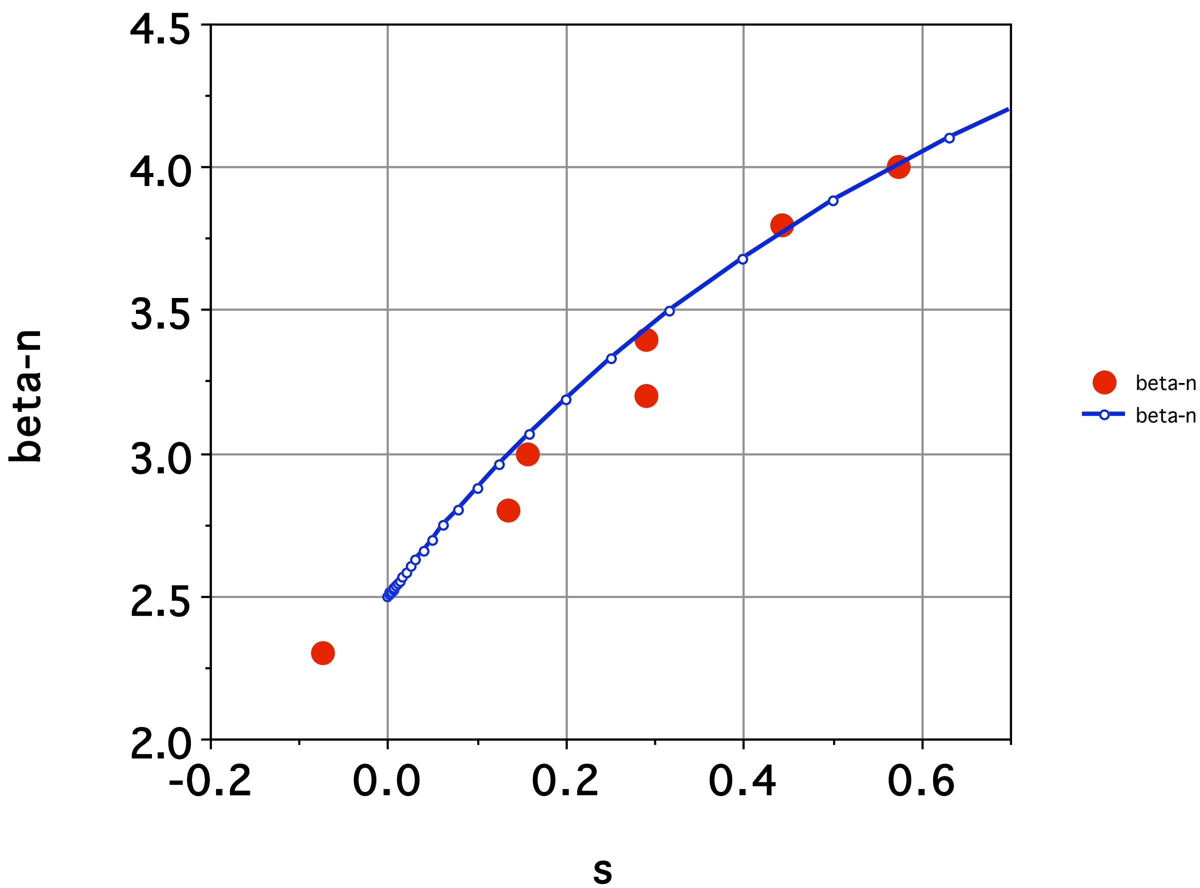


ITER Blanket Modules Substantially Increase the Passive RWM Stabilization Limits



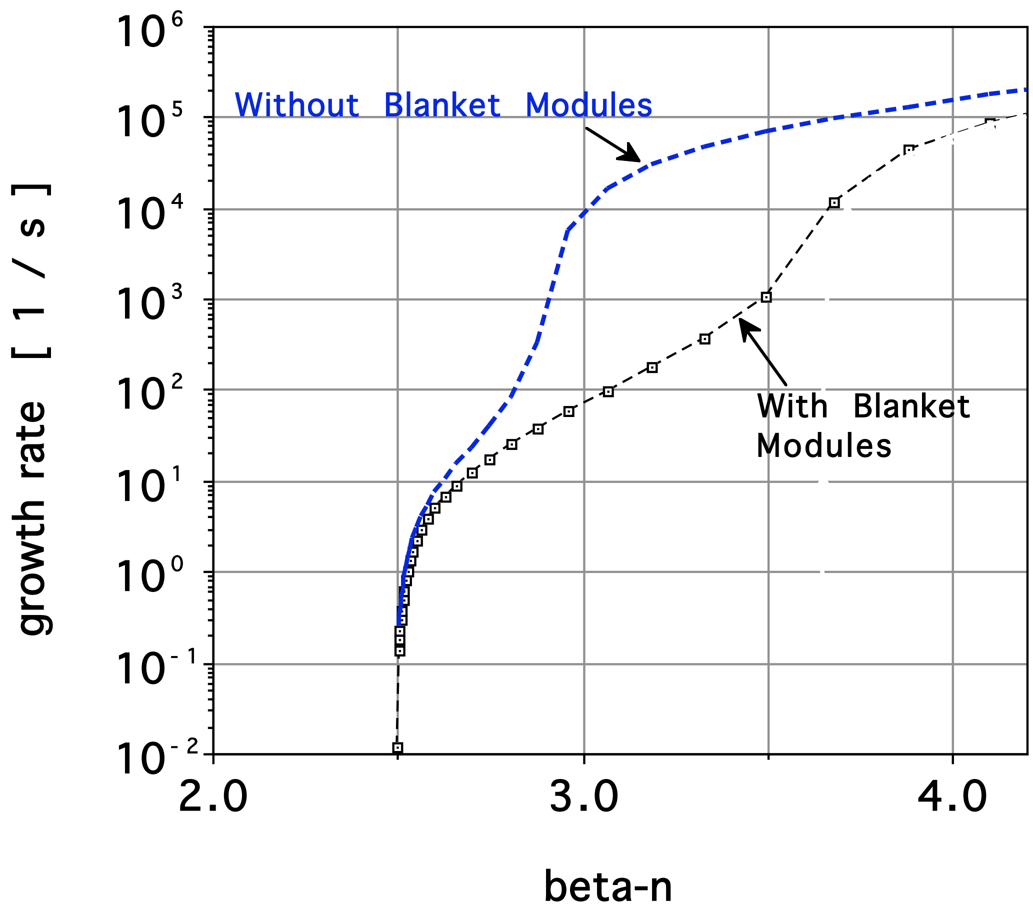
- **Offers prospect of much higher beta limit with an optimized feedback control coil system.**

Use DCON Computation of W to Calibrate s to $_N$



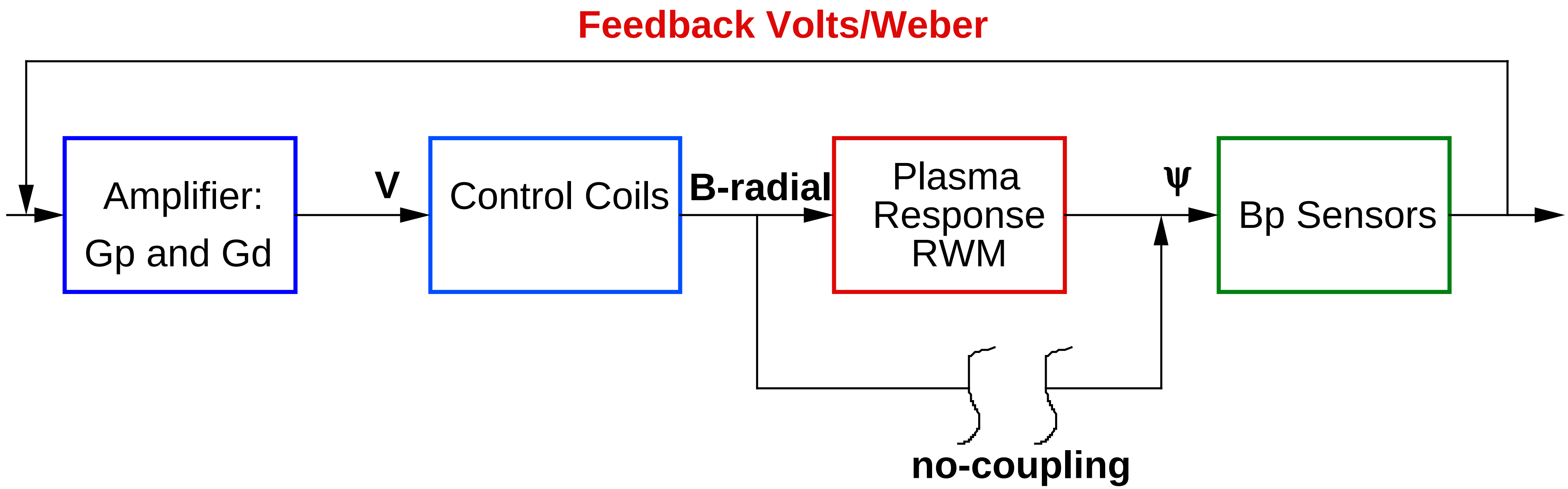
- This calibration can then be used to replot passive response.

ITER Passive Dispersion Relation

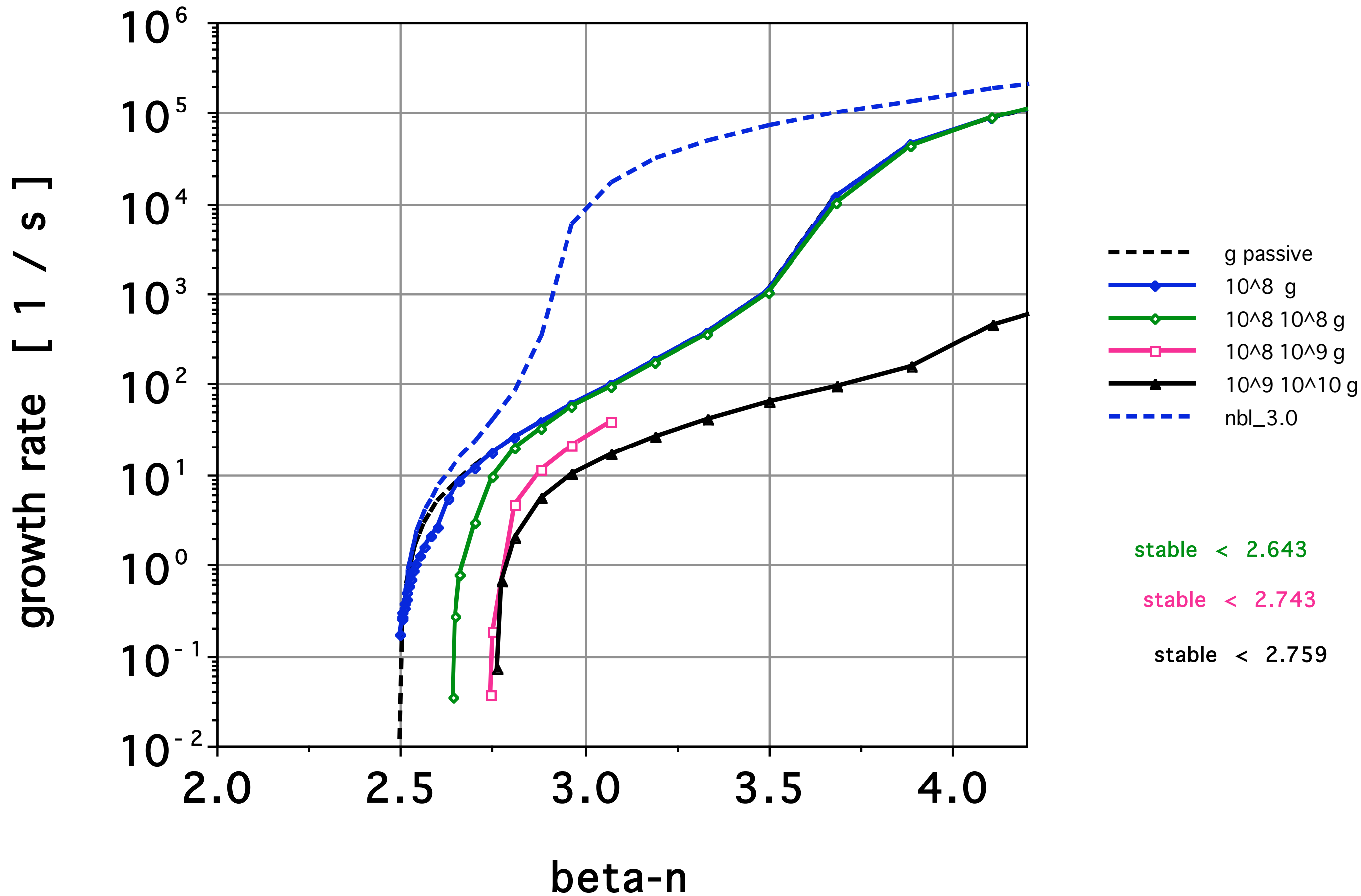


- No wall β_N limit is 2.5; Ideal Wall Limit With Blanket is 3.7

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



ITER Basic Coils: Scan of Proportional & Derivative Gain



- Feedback Saturates at β_N ~ 2.76 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

RWM Dispersion Relation with Mode Control Feedback*

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

Apply Voltage to Control Coil, $V_f(t) = -\dfrac{L_f}{M_{fp}}\left[\square_w G_p + G_d \dfrac{d}{dt}\right]\square\text{sensor}$

G_p = Proportional Gain $\quad$ G_d = Derivative Gain

$\square_w = R_{wall}/L_{wall}$ $\quad$ $\square_f = R_{control\ coil}/L_{control\ coil}$ $\quad$ $\square$ = feedback delay

$$\boxed{a_3\square^3 + a_2\square^2 + a_1\square + a_0 = 0}$$

$$a_0/\square_w = -\square_f + \square_w G_p$$

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

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

<u>For Stability all four Coefficients must be Positive!</u>

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

At Ideal Wall $\square$ 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 $\square$ 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 $\beta_N \sim 3.7$]

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: $c_f = -3.39$

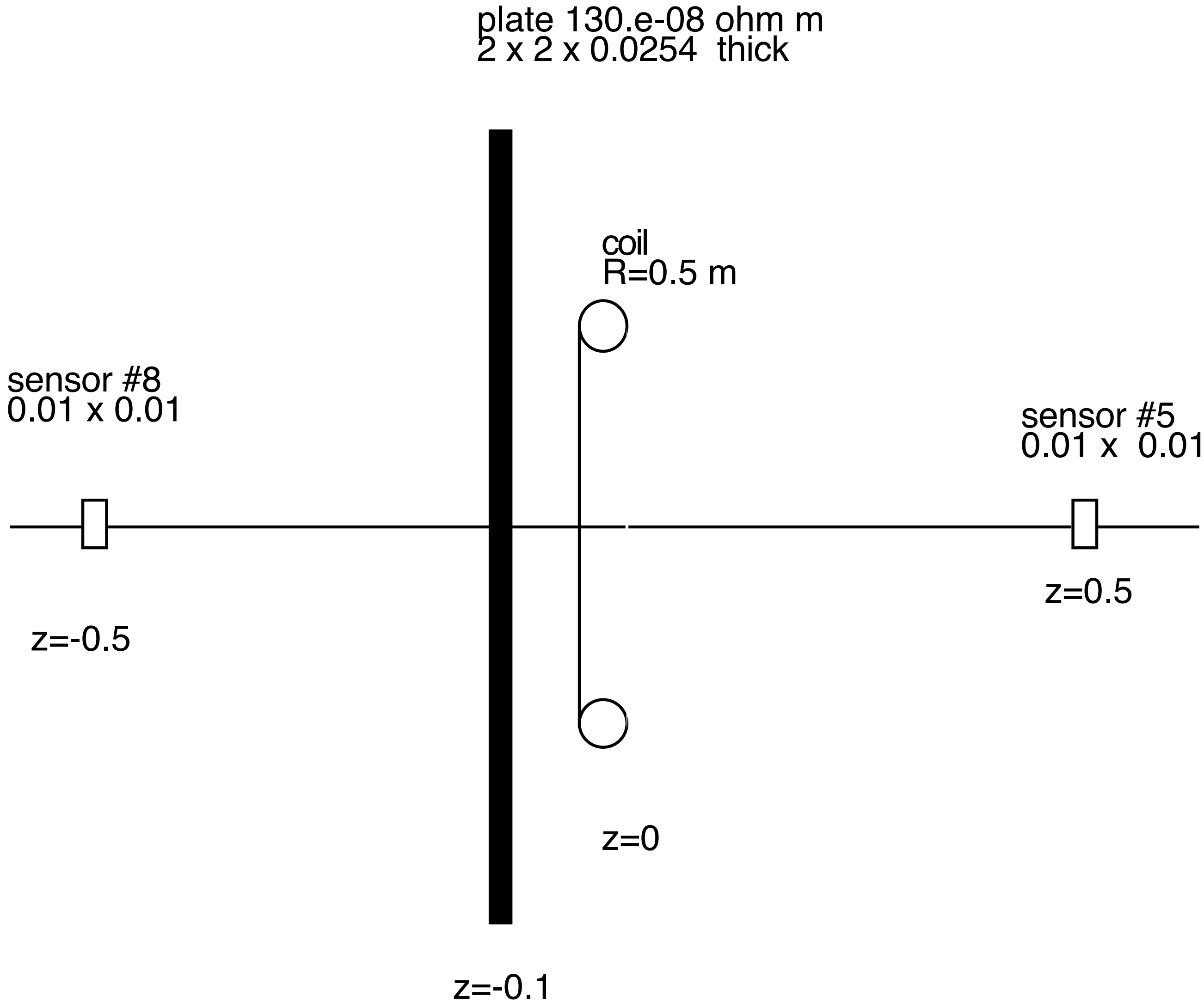
Physically:

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

Says Plasma Mode is more than 4 times better coupled to wall eddy currents than external Basic ITER Control Coils.

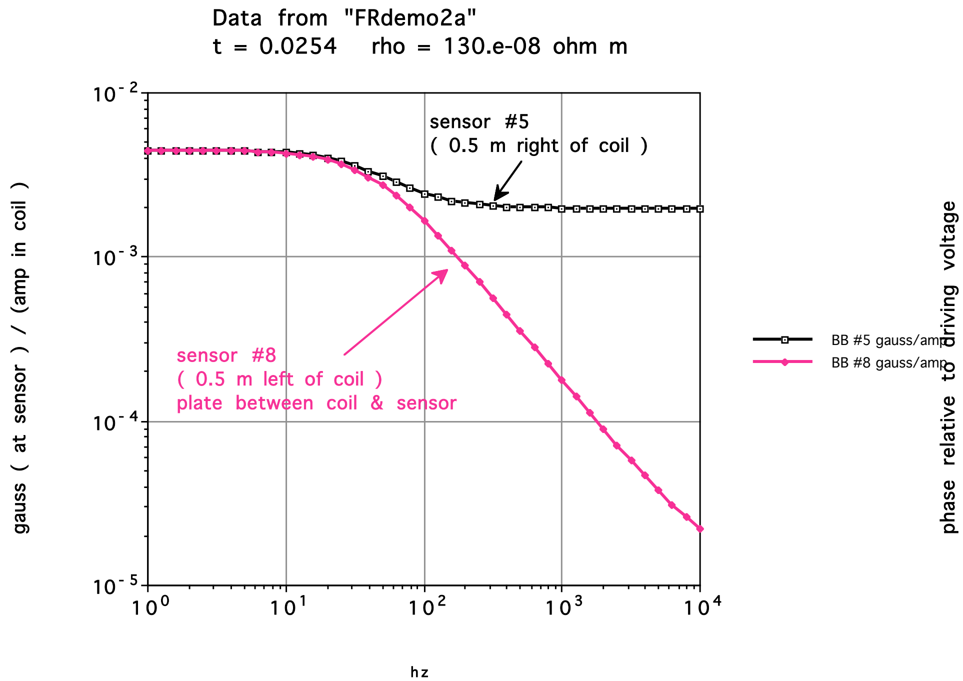
VALEN Model Geometry: Resistive Wall & Control Coil

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

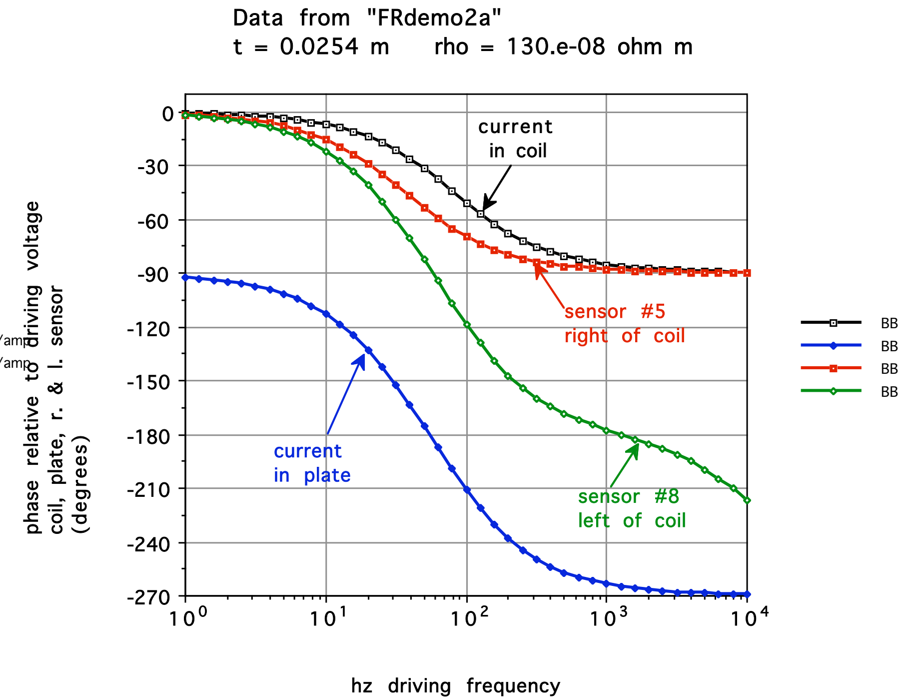


Frequency Dependence of Control Field

Magnitude of Control Field vs Frequency

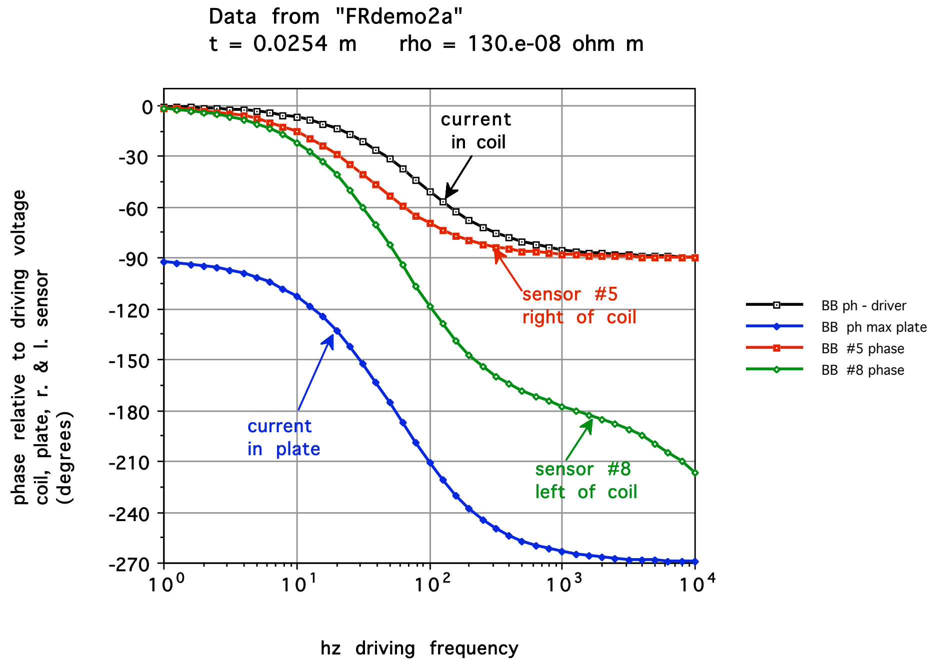


Phase of Control Field vs Frequency

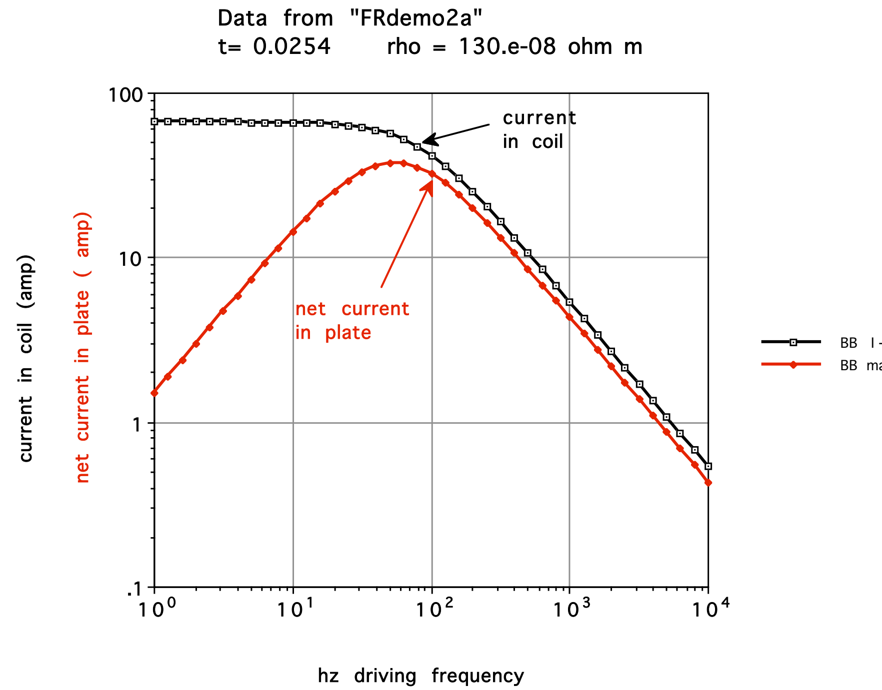


At High Frequency: Destabilizing Wall Image Currents

Phase of Control Field vs Frequency

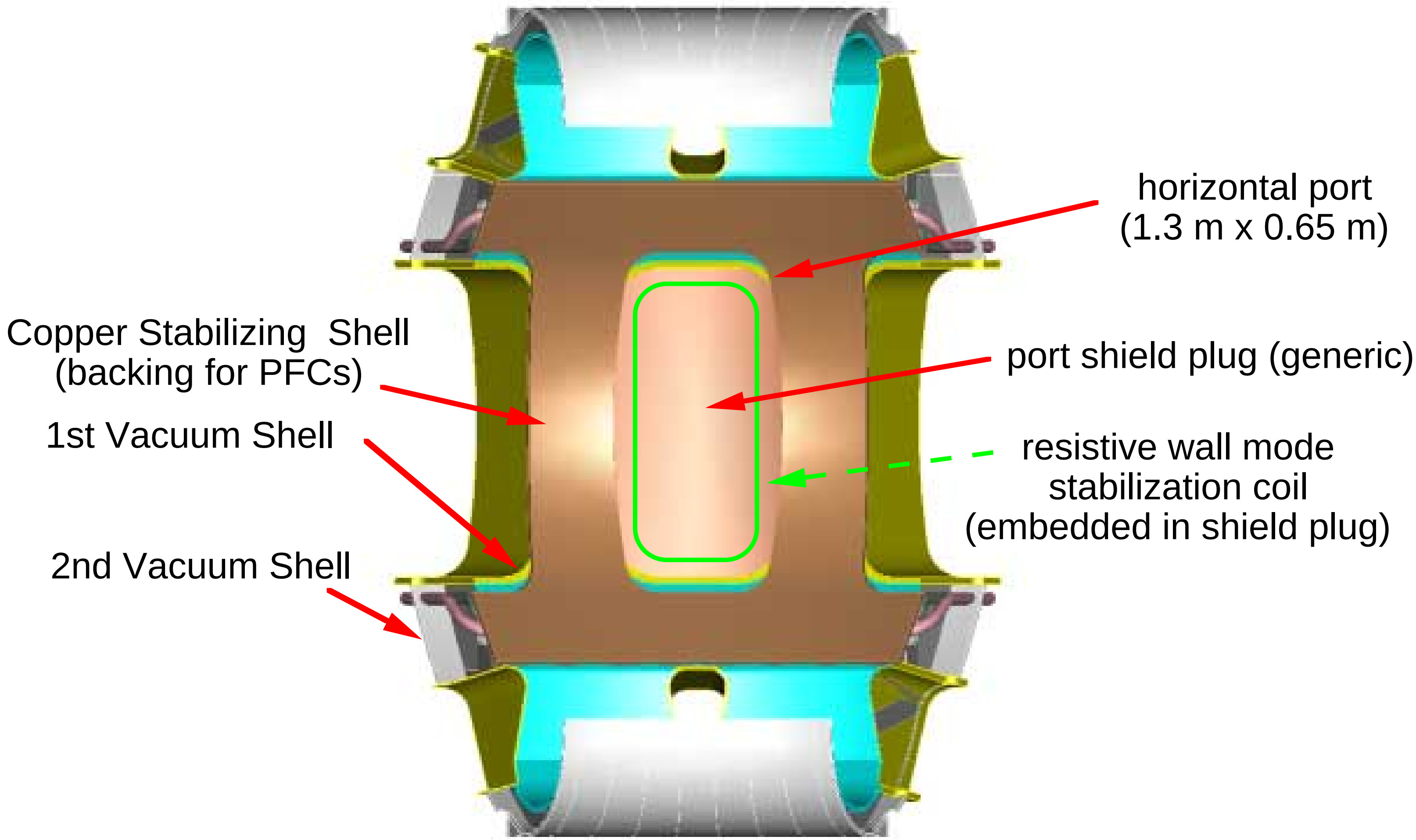


Magnitude of Currents vs Frequency

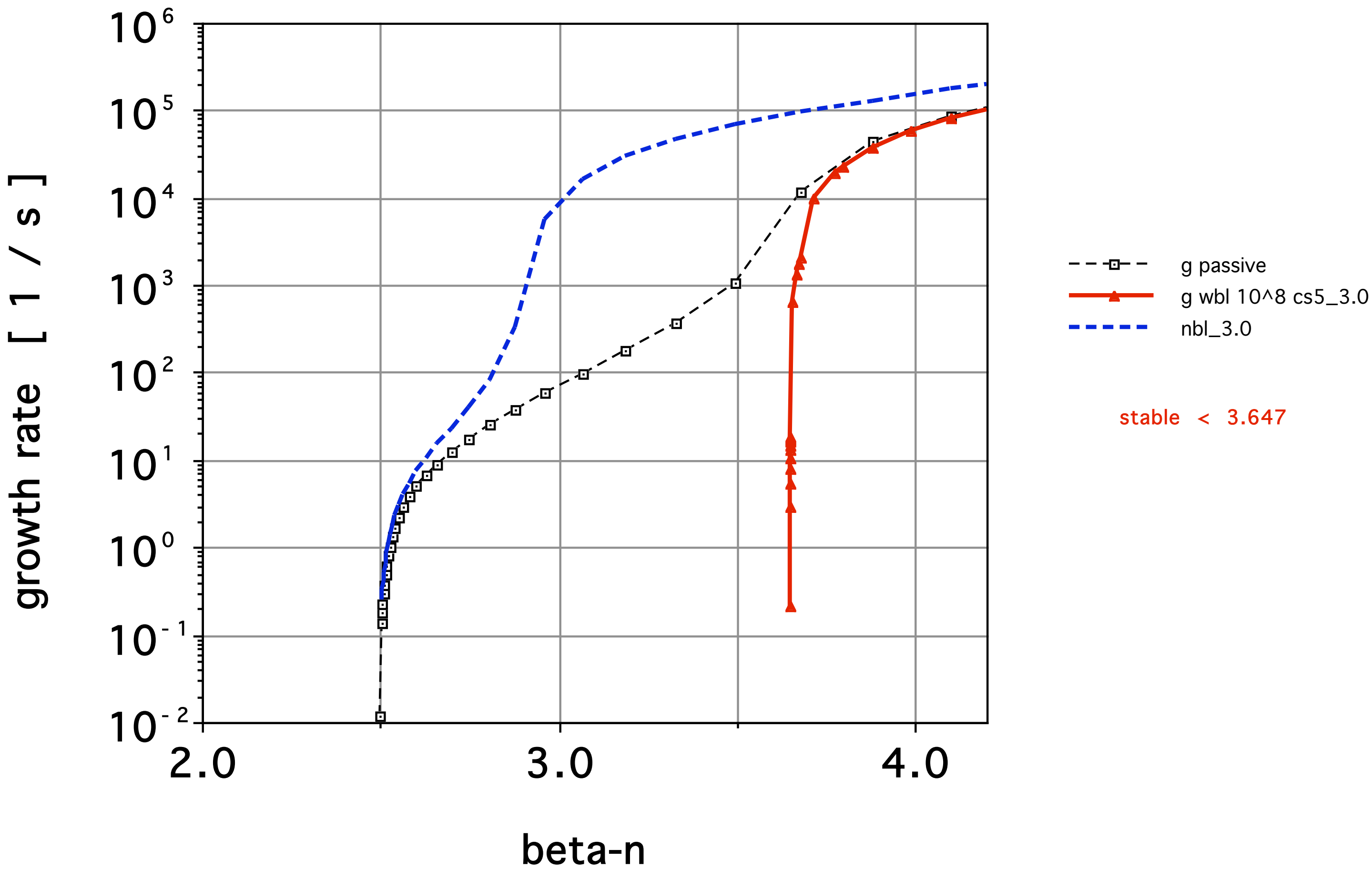


Optimizing Resistive Wall Mode Control: FIRE Approach

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

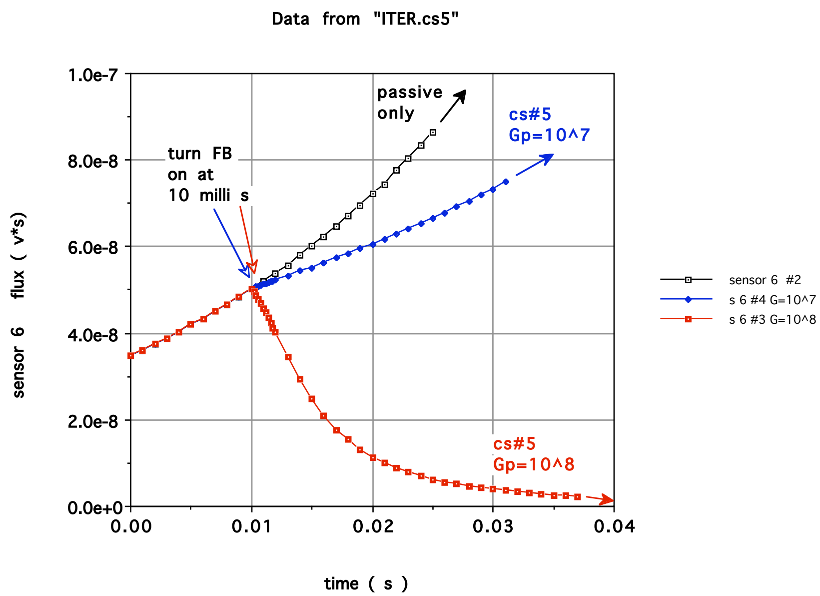


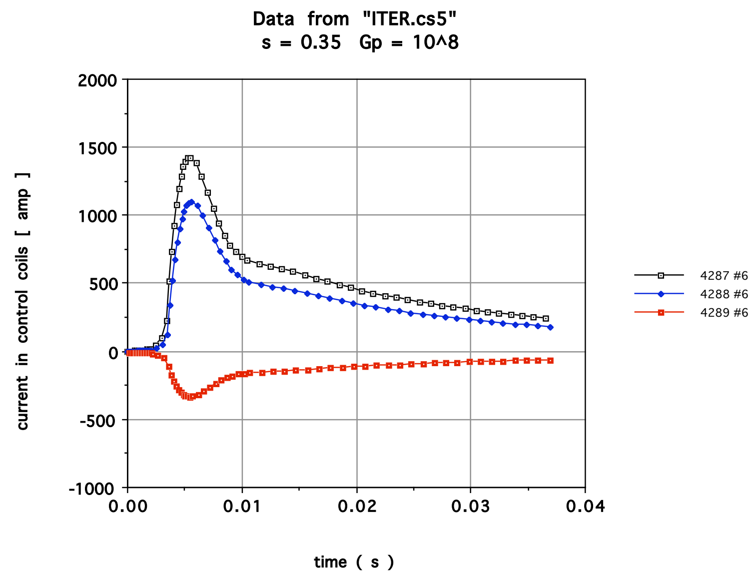
ITER Internal Coils in Port Plugs Easily Reach Ideal Limit



- Ideal Beta Limit Reached with pure Proportional Gain $G_p=10^8$ V/W
- Control Coils use only three n=1 pairs in 6 port plugs!

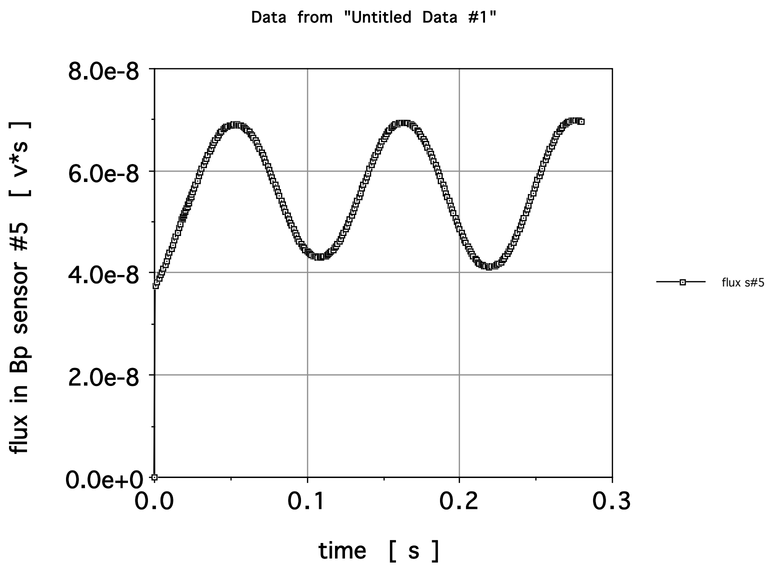
Time Dependent Feedback Model of ITER Internal Coils

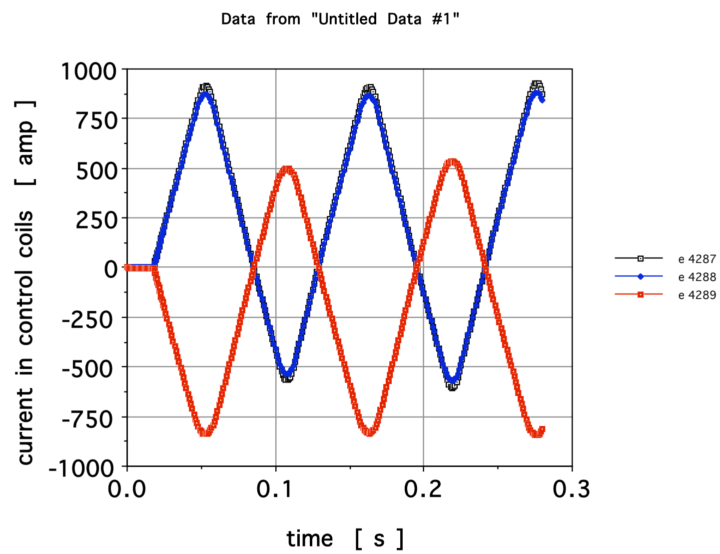




- At Ideal Beta Limit simple damped suppression in 20 to 30 ms
- Peak Current in Control Coils reaches peak of only 1.5 kA
- Peak Voltage on single turn control coils is only 5 volts
- Reactive power requirements only 7.5 kW in each coil pair

Time Dependent Feedback Model of Basic ITER Coils

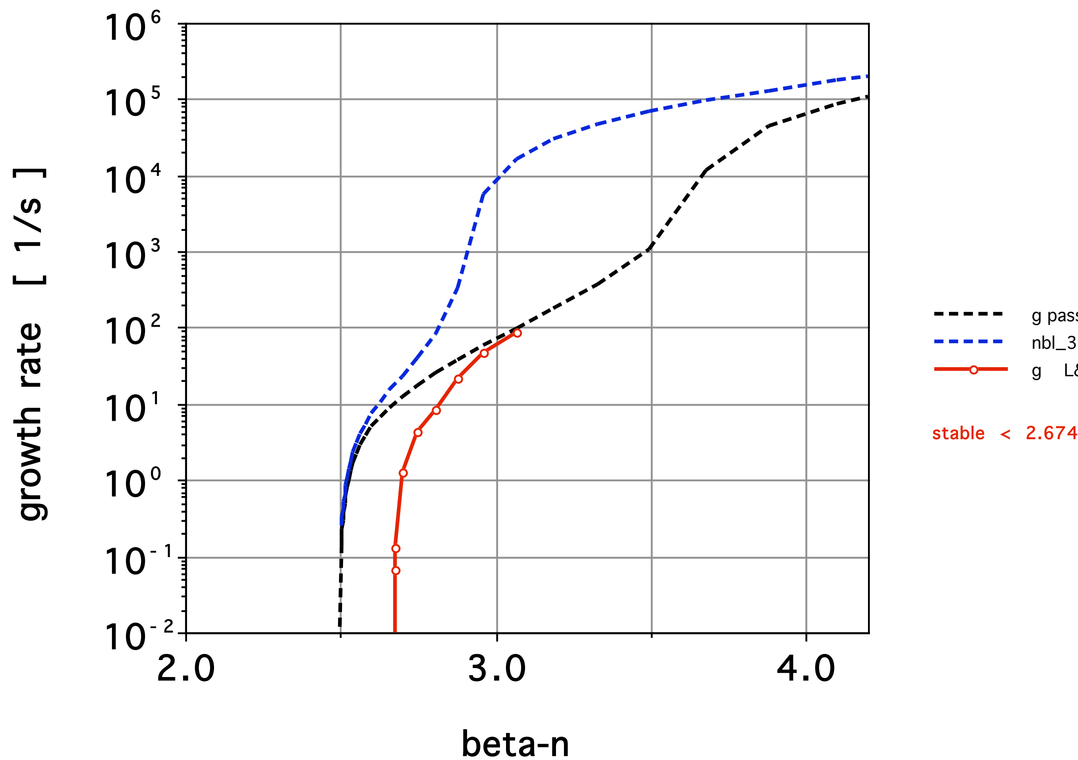




- Beta chosen to be near predicted limit of $\beta_N \sim 2.7$ which is only about 20% between no-wall limit and ideal limit.

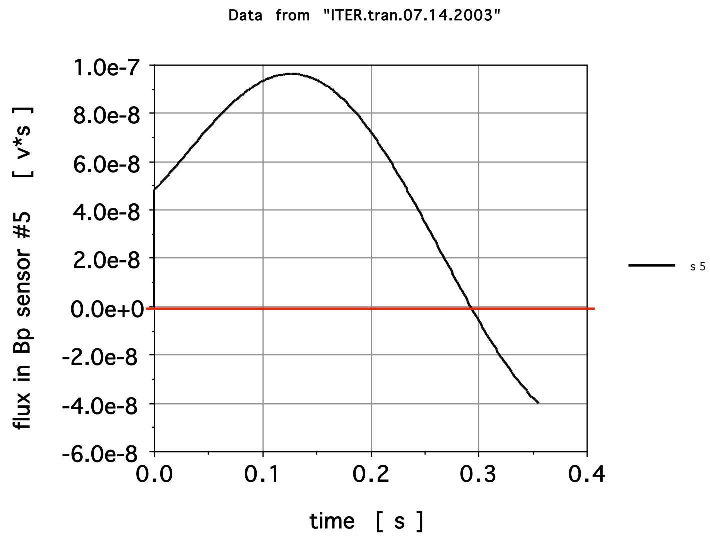
- Voltage limited to 40 V/turn times 28 turns = 1120 Volts
- Peak Current in Control Coils reaches peak of 28 kA-Turns
- Reactive power requirements exceed 1 MW per coil pair

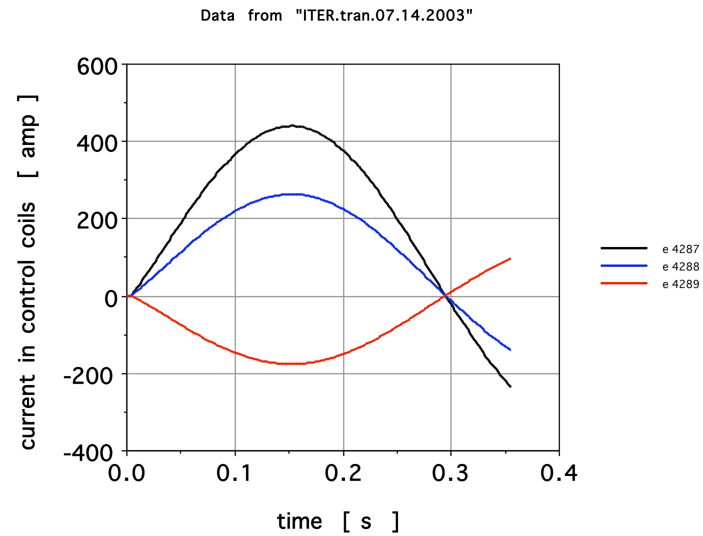
ITER Basic Coils: Use Liu & Bondeson Gain Parameters



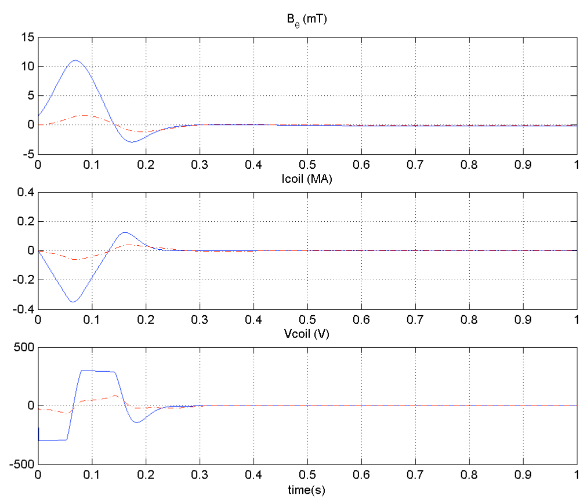
- Liu uses $V_f = - L_f\ b_s/b_o s[K_i/s+K_p]$; $b_o=28x10^{-7}T/A$; $L_f=0.04H$; $b_s=\Phi_s/A_s$
- VALEN uses $V_f = - L_f/\ b_oA_s\ [K_i+K_p d/dt\ ]\ \Phi_s = -1.4x10^8[K_i+K_p d/dt\ ]\Phi_s$
- $G_p= 6x10^8$ V/W is Liu's K_i=4.318 and $G_d= 2x10^8$ V/V is Liu's K_p=1.5
- These values reduce best $\beta_N \sim 2.67$

Time Dependent Feedback With Liu, et al. Parameters



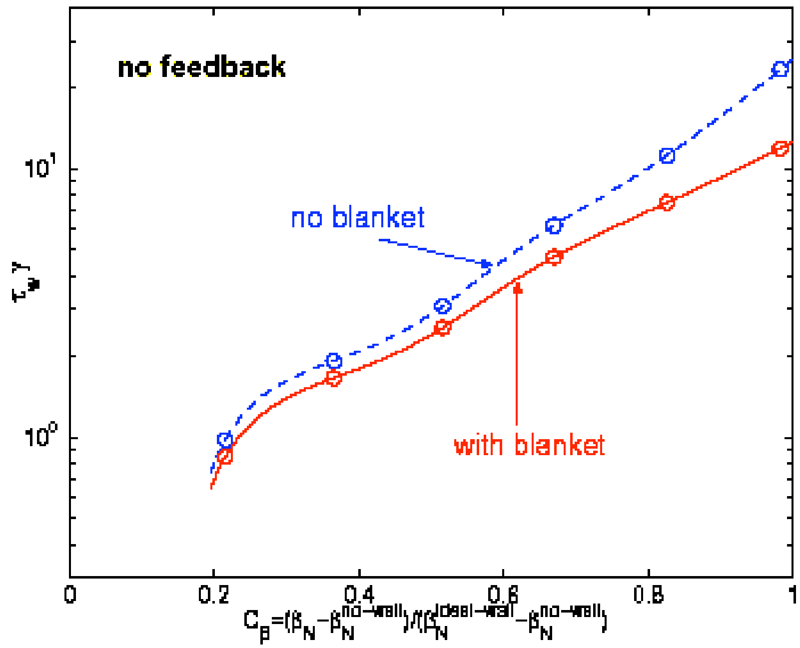


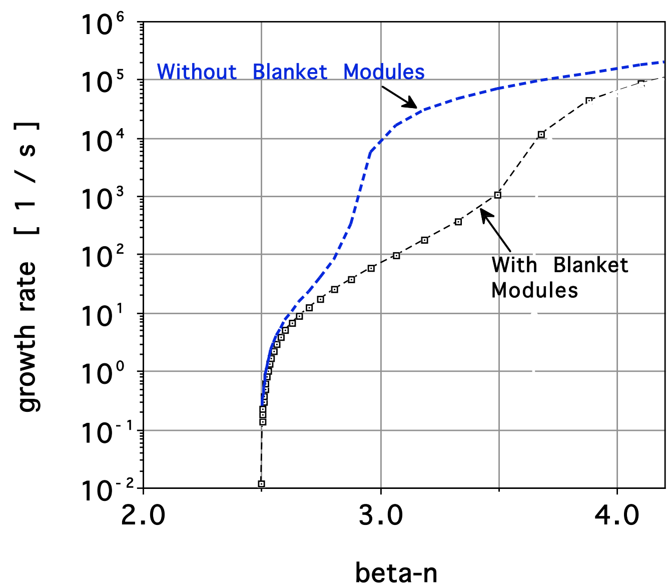
- Beta chosen to be near predicted limit of $\beta_N \sim 2.6$ which is only about 10% between no-wall limit and ideal limit. $V_{max} \sim 200$ V



- Time history similar to Liu, et al.

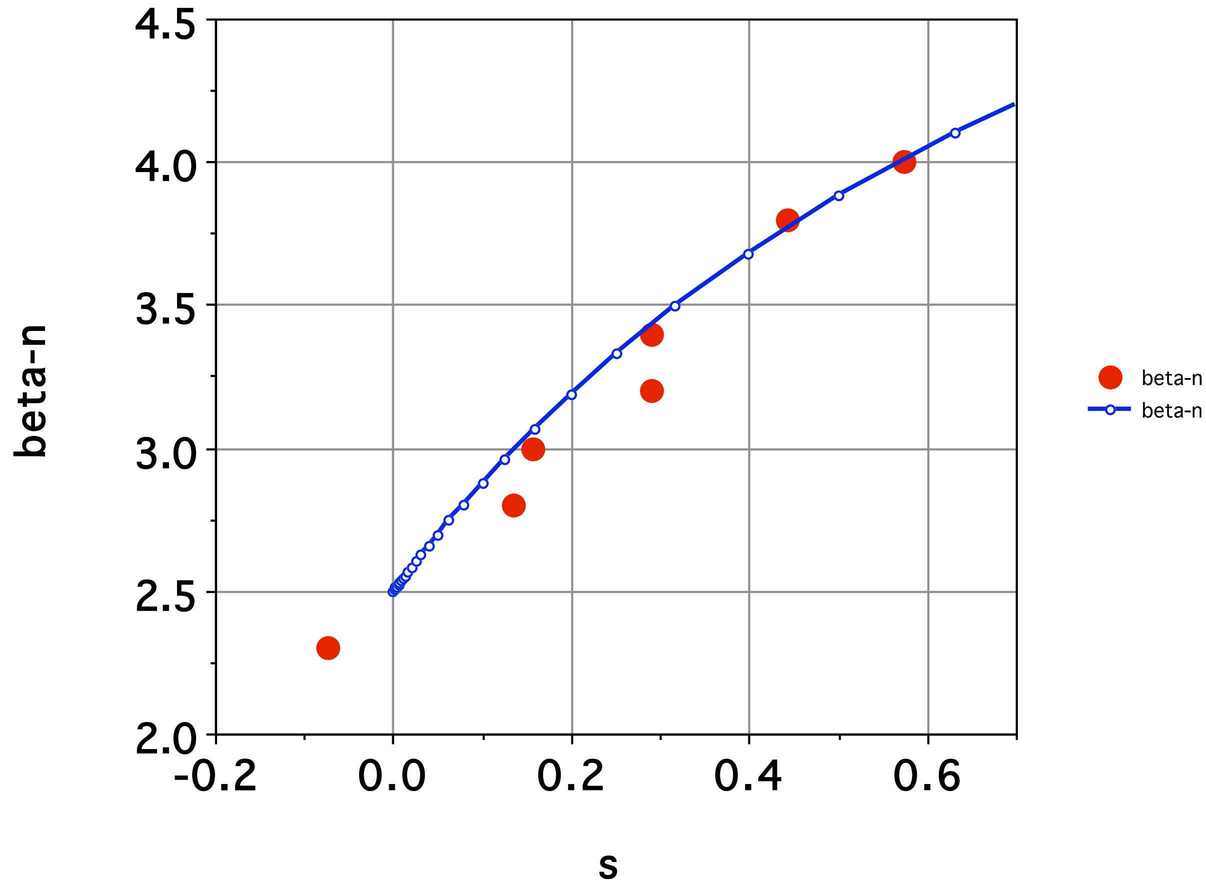
Physics of Ideal Kink Transition Seems Absent in Liu, et al.





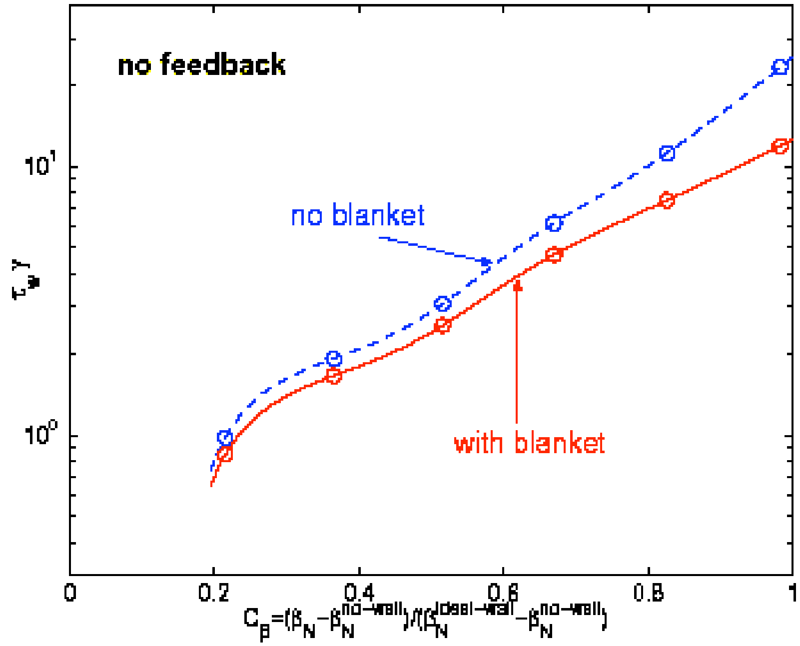
- Note absence of Ideal Kink Branch Transition when $C_\beta \sim 1$
- In Liu, et al. $\tau_{wall} \sim 0.188$ s so γ at $C_\beta \sim 1$ is between 53 to 120 s^{-1}
- In VALEN modeling γ at $C_\beta \sim 1$ is between 1000 to 10^4 s^{-1}
- Growth rate disparity consistent with $\gamma\tau_{wall}$ in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

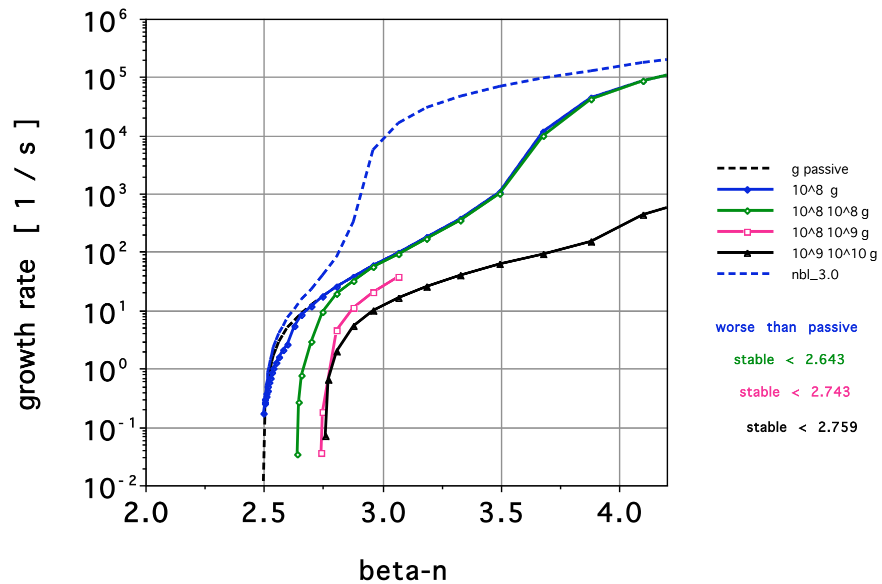
Use DCON Computation of □W to Calibrate s to □$_N$



- Liu, et al. analysis seems constrained to small s values.

Limitation of Performance Due to c_f Effects Seems Absent





- $c_f = 1 - [M_{pw}M_{fw}]/[L_{wall}M_{fp}] = 1 - [V_{plasma}$ **from** $I_w]/[V_{plasma}$ **from** $I_f]$
- For ITER Basic External Coils is clear that **c_f < 0** [est. was –3.4]
- Effect of Coil Toroidal Discreteness + Wall Modes May Play Role
- Growth rate disparity consistent with □□$_{wall}$ in Liu, et al. too small for claimed values of C□

Summary & Conclusions

- 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 MW reactive power required.
- Inclusion of Blanket Modules Significantly Increases Ideal Wall Beta Limit from about β_N of ~2.7 to ~3.7
- 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.
- Unresolved discrepancies exist between VALEN analysis and Liu & Bondeson MARS analysis of Basic ITER External Control Coils:
  + Program to benchmark two codes against common equilibria and geometry needs to be established.
  + A common set of transfer functions needs to be established.