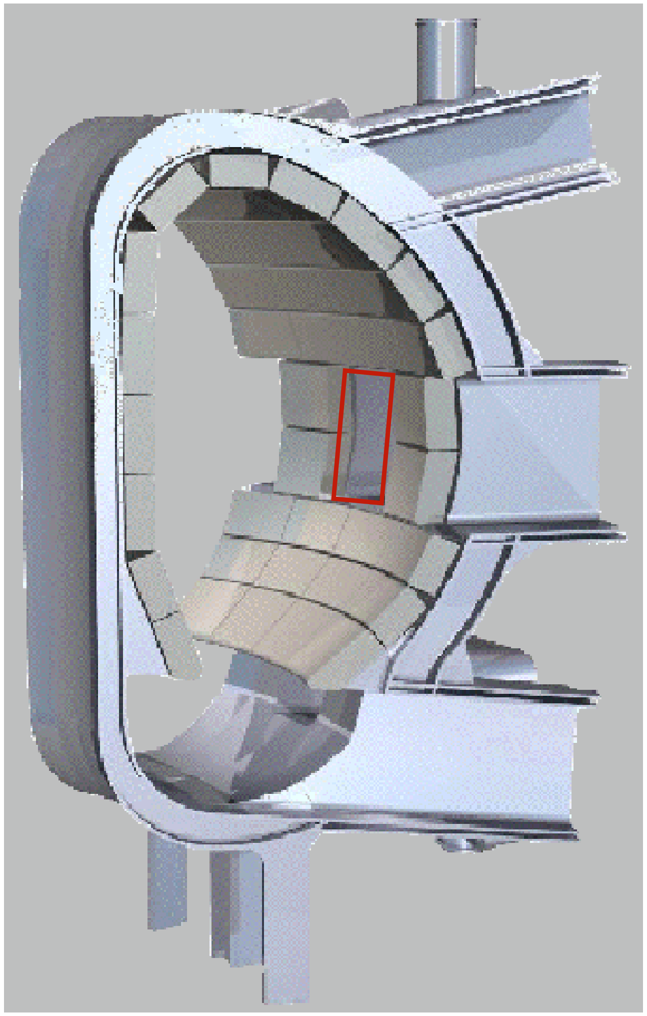
RWM Control in ITER



Presented by

Gerald A. Navratil

Including analysis by

Jim Bialek &

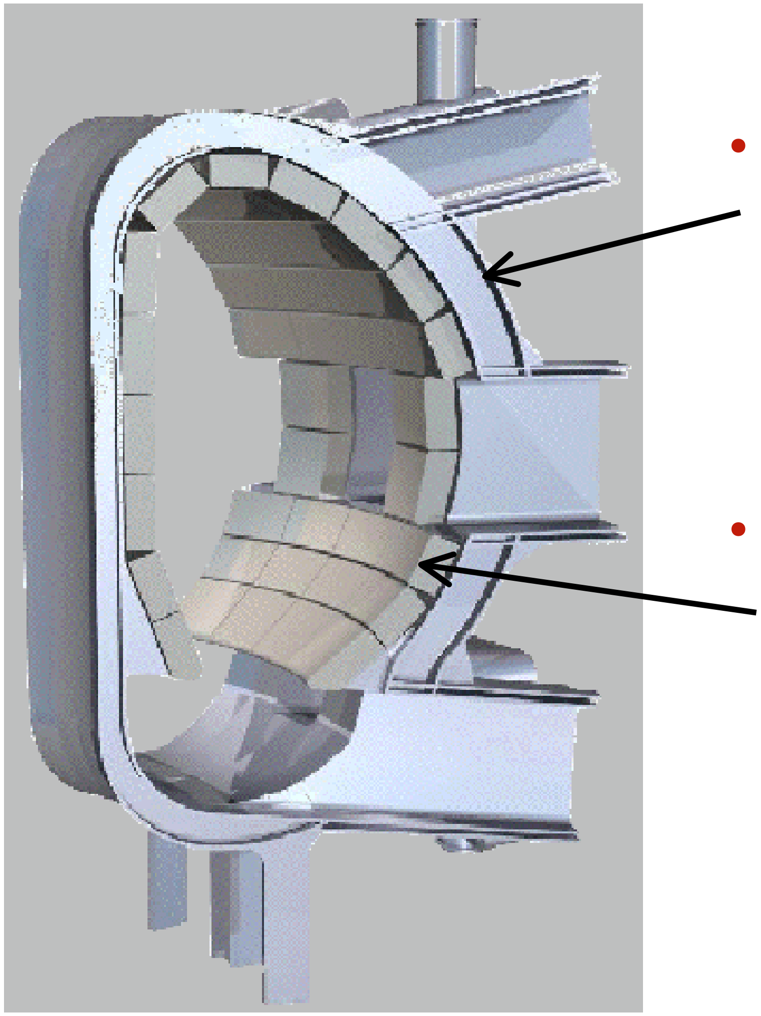
Oksana Katsuro-Hopkins

Columbia University

OUTLINE

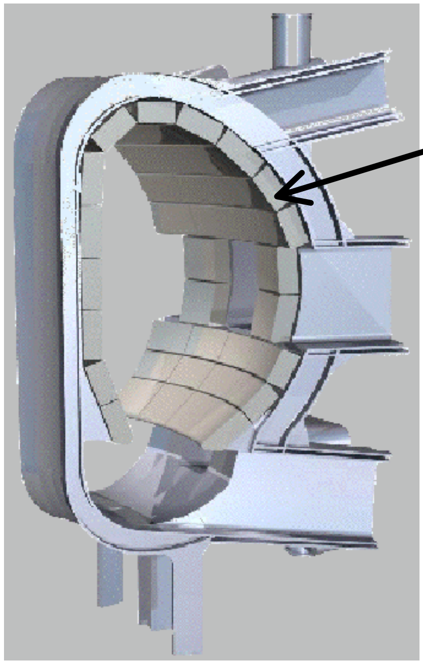
- PASSIVE STABILIZATION OF RWM IN ITER
  - **ITER PASSIVE STABILIZER PERFORMANCE: IMPORTANT ROLE OF THE BLANKET MODULES**
- ACTIVE CONTROL OF RWM WITH BASELINE ERROR CORRECTION COILS
  - **BENCHMARKING OF MARS, VALEN/DCON, AND KINX**
- IMPROVED COIL DESIGN OPTIONS & ADVANCED CONTROL ALGORITHMS
  - **EXTERNAL ON-VESSEL COILS**
  - **INTERNAL COILS**
  - **OPTIMAL CONTROLLER AND OBSERVER**

Passive Stabilizing Structures in ITER



- Double Wall Vacuum Vessel with ~190 ms time constant for each wall for 1/1 field pattern.
- Blanket/Shield Modules <u>Specified</u> to have 5 ms to 9 ms time constant for normal B-field soak through

ITER Blanket/Shield Plays Important MHD Role



- Blanket/Shield Modules Specified to have 5 to 9 ms time constant
- Ulrickson finds longer time constants: 40 ms to 100 ms
  Should be ITER Issue to Clarify

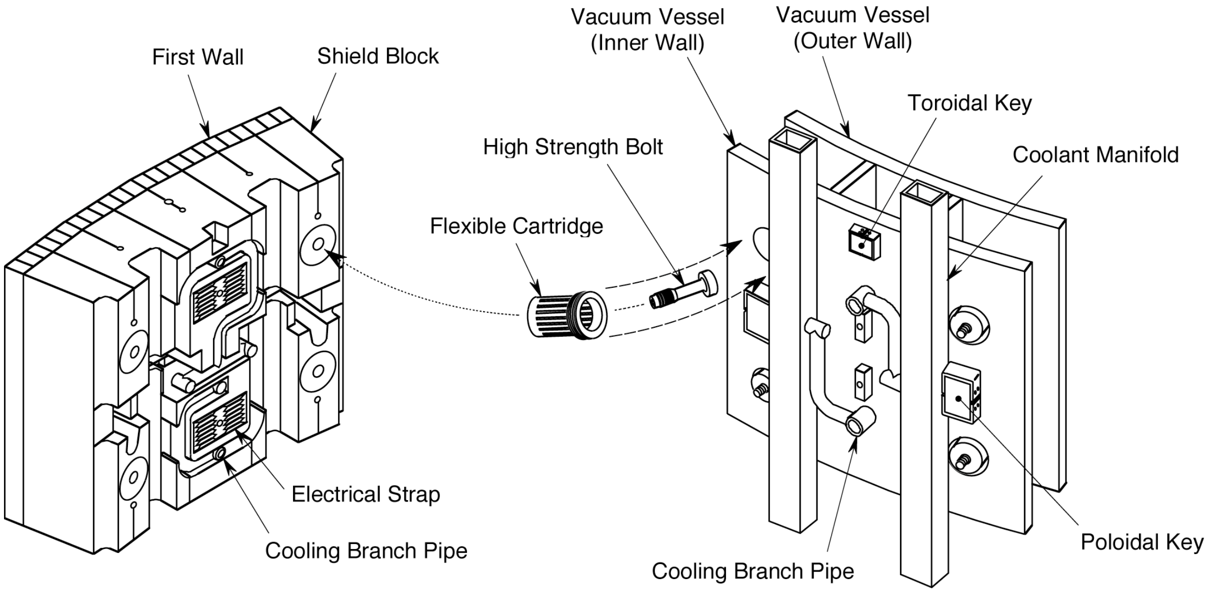


Table 4.3.3-1 ITER Parameters for the Non-Inductive Scenario

Parameter	WNS	Parameter	WNS	Parameter	WNS
R/a (m/m)	6.35/1.85	β_N	2.95	f_{He} (%)	4.1
B_T (T)	5.18	β_p	1.49	f_{Be} (%)	2
I_p (MA)	9.0	P_{fus} (MW)	356	f_{Ar} (%)	0.26
κ_{95}/δ_{95}	1.85/0.4	$P_{L-H} + P_{NB}$ (MW)	29 + 30	Z_{eff}	2.07
$<n_e>$ ($10^{19} m^{-3}$)	6.7	Q	6.0	P_{rad} (MW)	37.6
n/n_G	0.82	W_{th} (MJ)	287	P_{loss} (MW)	92.5
$<T_i>$ (keV)	12.5	$P_{loss}/P_{thr.\ L\text{-}H}$	2.59	τ_E (s)	3.1
$<T_e>$ (KeV)	12.3	β_T %	2.77	τ_α^*/τ_E	5.0
I_{CD}/I_p (%)	51.9	l_i (3)	0.72	$H_{H98\,(y2)}$	1.57
I_{bs}/I_p (%)	48.1	$q_{95}/q_o/q_{min}$	5.3/3.5/2.2		
I_{OH}/I_p (%)	0				

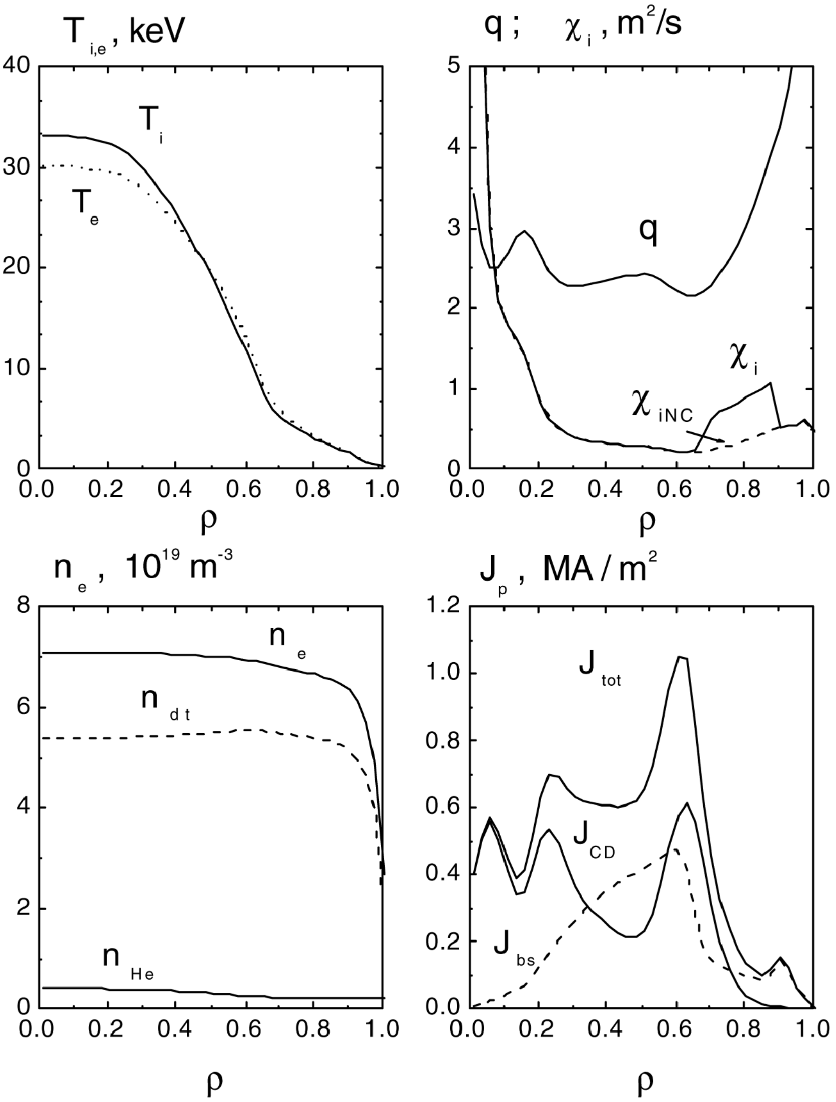
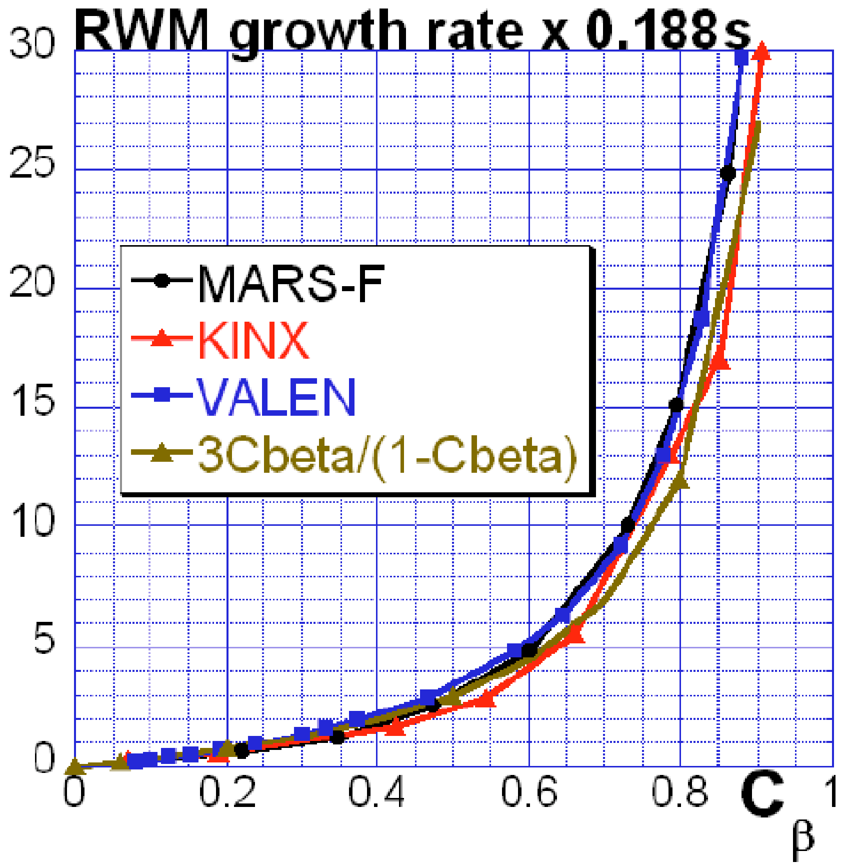


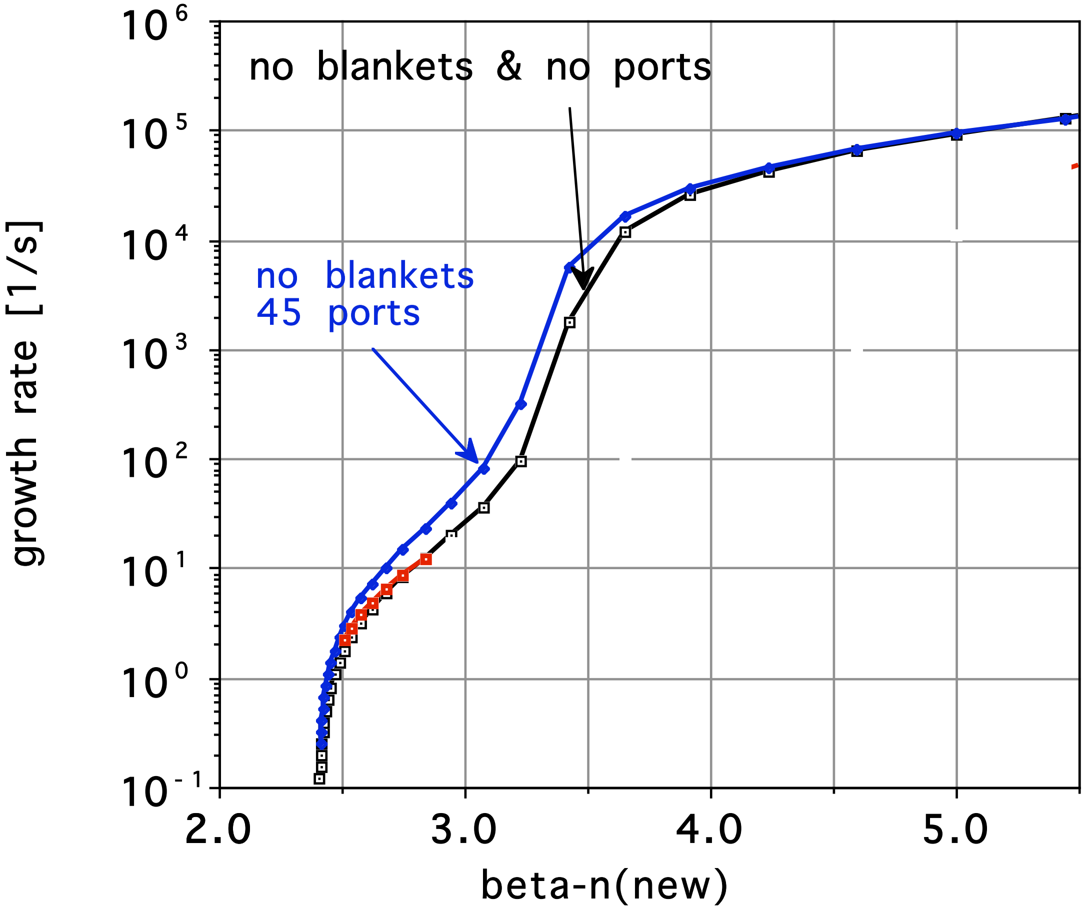
Figure 4.3.3-1 Plasma Parameter Profiles at the Current Flat-top Phase (t > 1000 s) for the Steady State WNS Operational Scenario

ITPA Benchmark Study Shows Good Agreement Among Codes



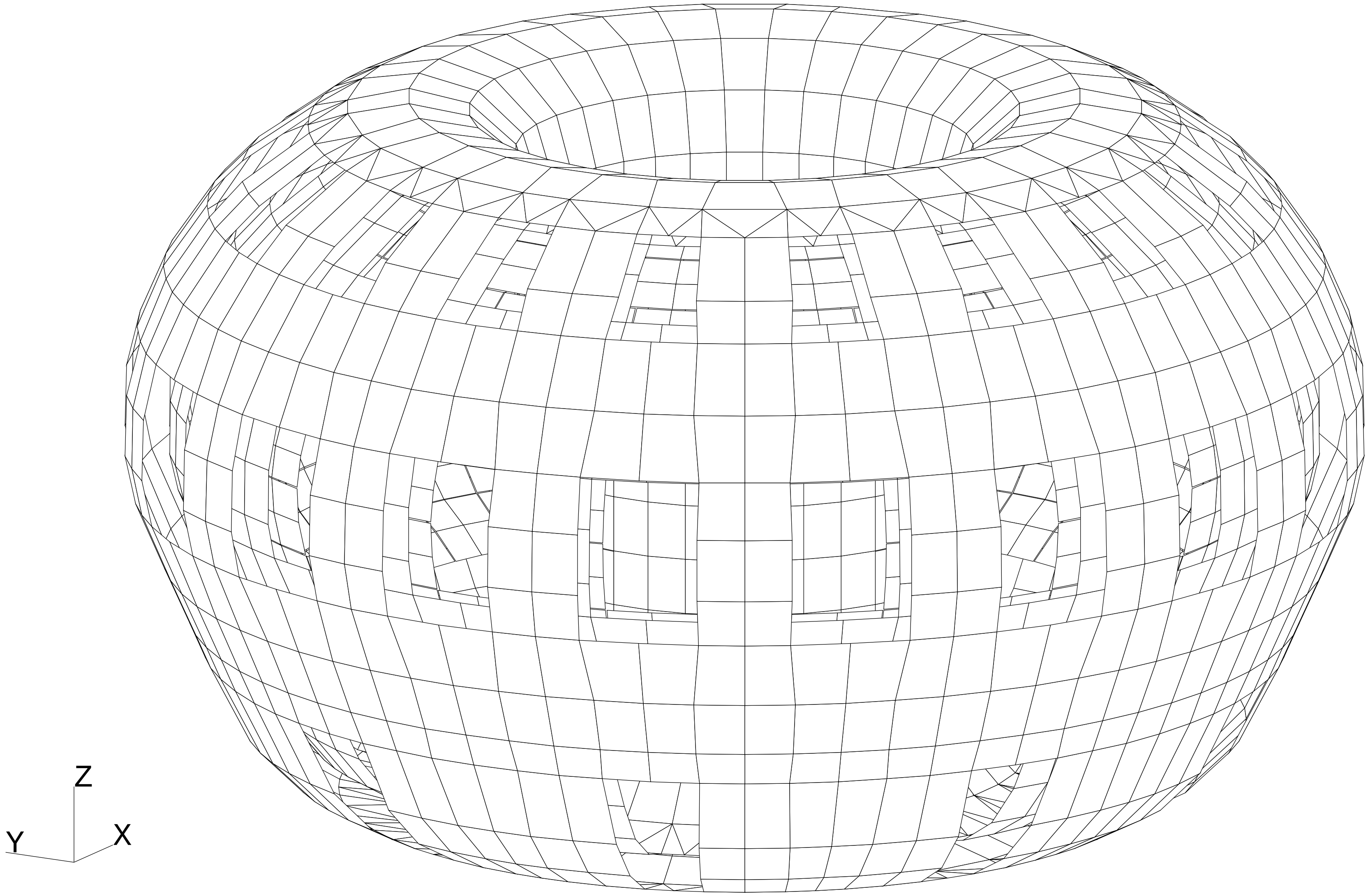
- RWM Dispersion Relation for 2D axisymmetric ITER Vacuum Vessel without ports or Blanket/Modules

ITER Ports Cause Small Reduction in Ideal Limit

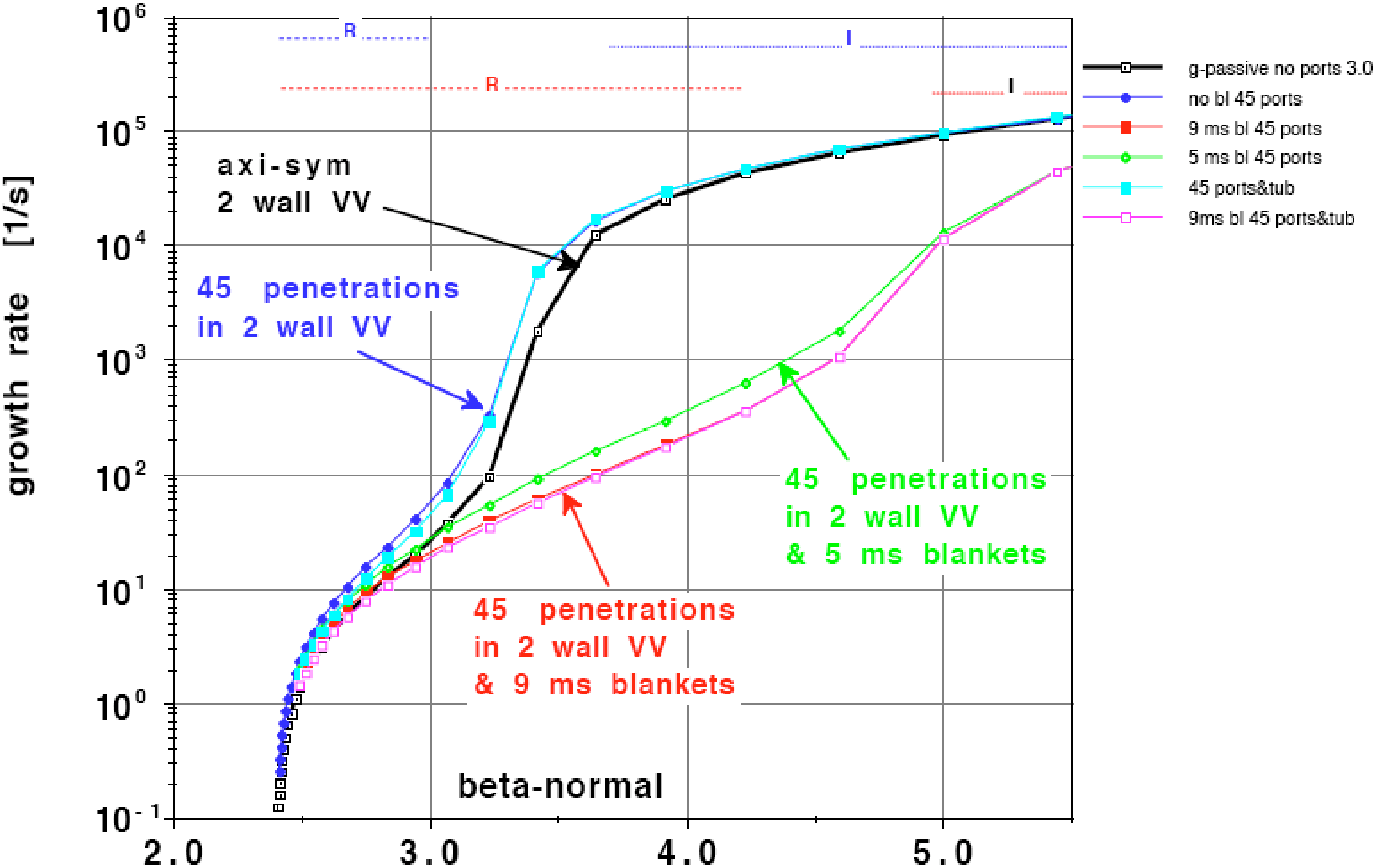


- No wall β_N limit is 2.4; Ideal Wall Limit Drops to β_N ~ 3.3

VALEN Model of ITER Double Wall Vessel and Blanket Modules



ITER Blanket Opens Up Large AT Regime



axi-sym
2 wall VV

45 penetrations
in 2 wall VV

45 penetrations
in 2 wall VV
& 5 ms blankets

45 penetrations
in 2 wall VV
& 9 ms blankets

Data from "ITER.01.2004.w.betan"

- No wall β_N limit is 2.4; **Ideal Wall Limit With Blanket is ~ 5**

Active Control in ITER:

Baseline External Error Correction Coils

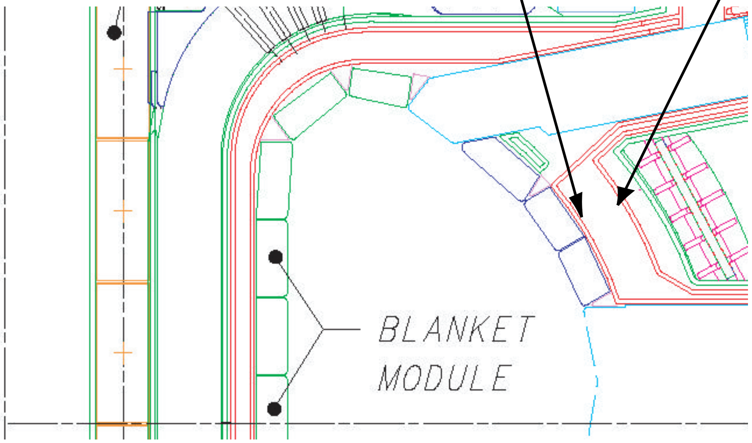
ITPA MARS/VALEN Benchmarking

ITER

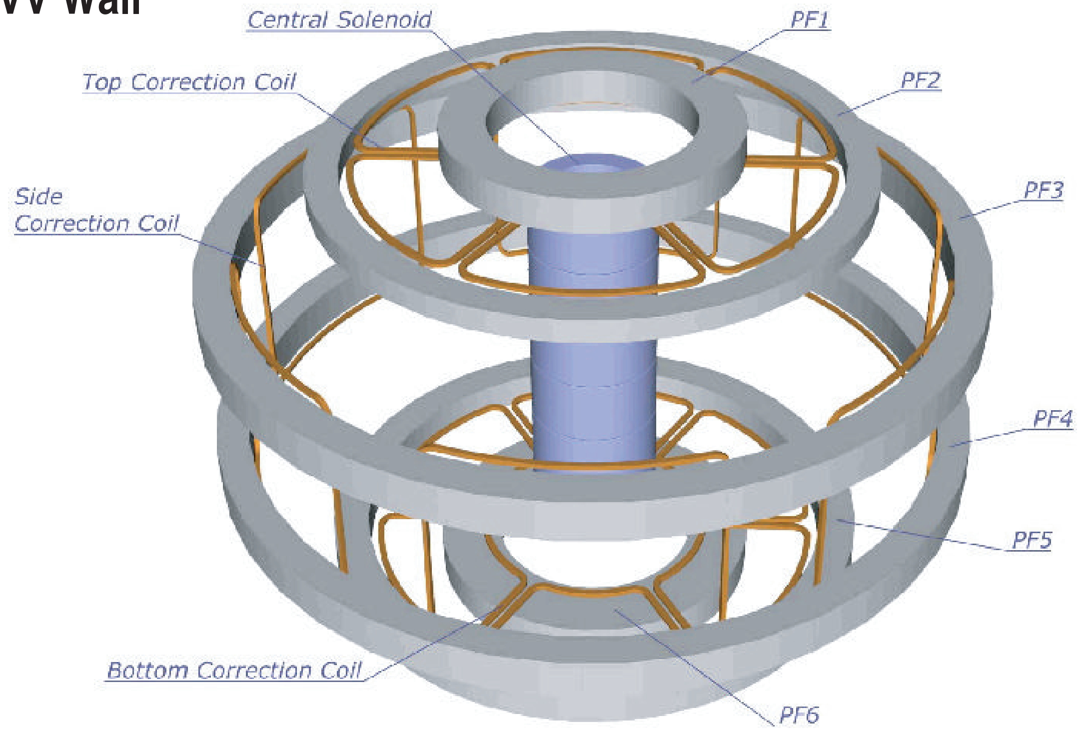
PASSIVE STABILIZER AND ACTIVE CONTROL COILS

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.

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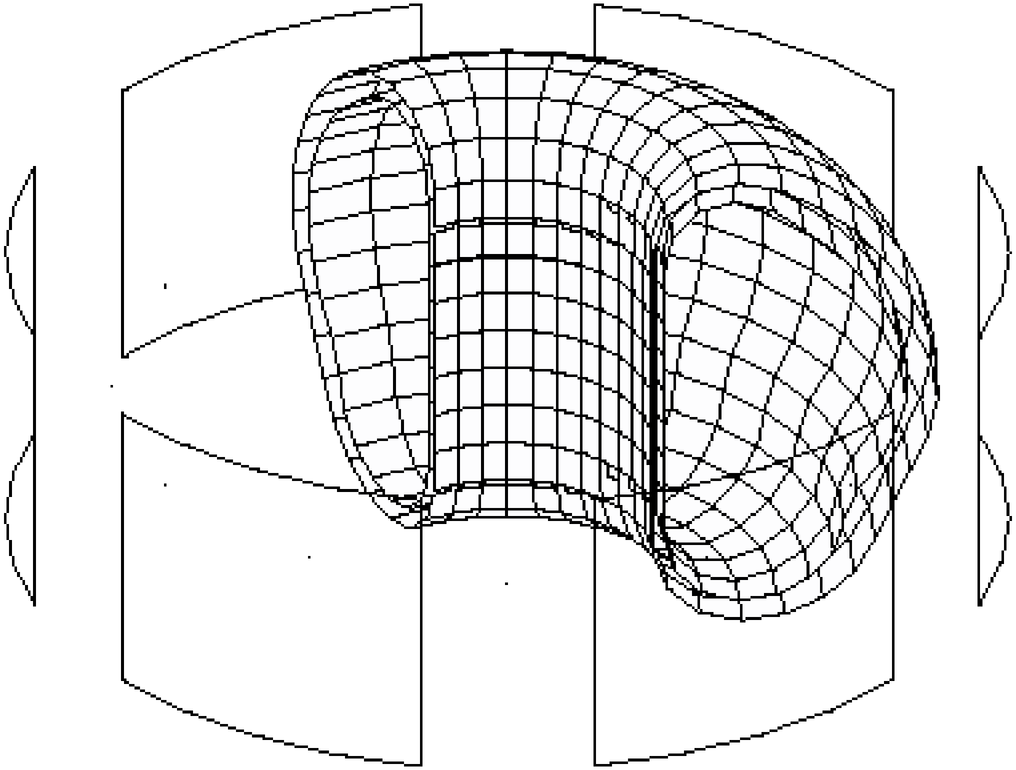
University

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



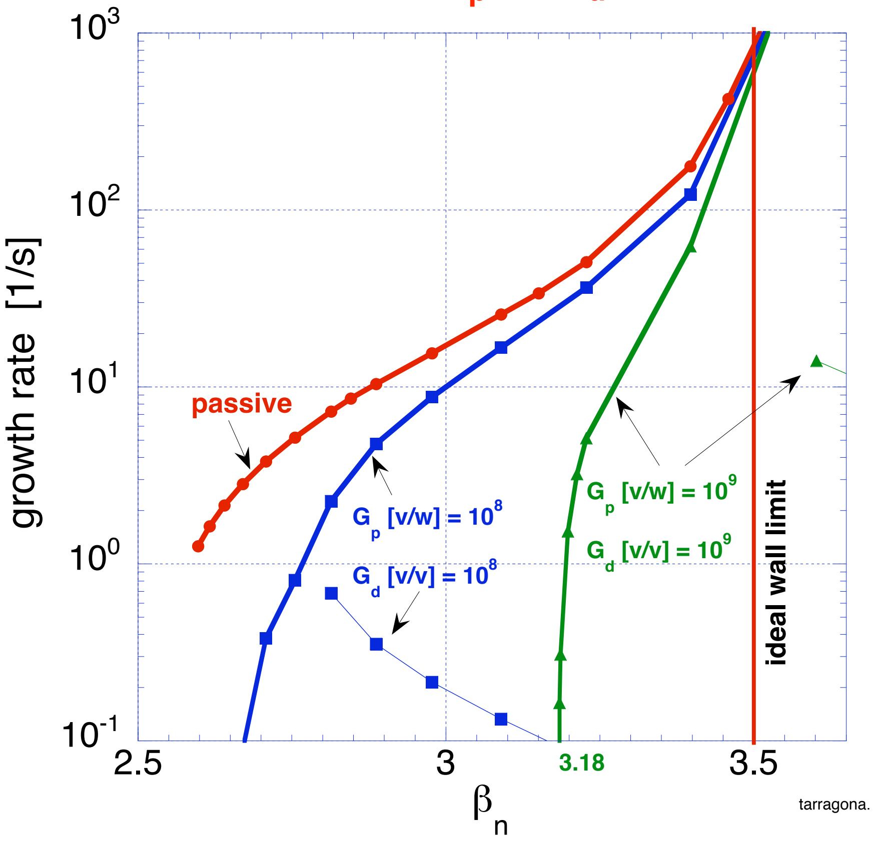
- Vacuum Vessel Modeled with and without wall penetrations.

ITER Baseline Six External Coils with 10 s time Constants

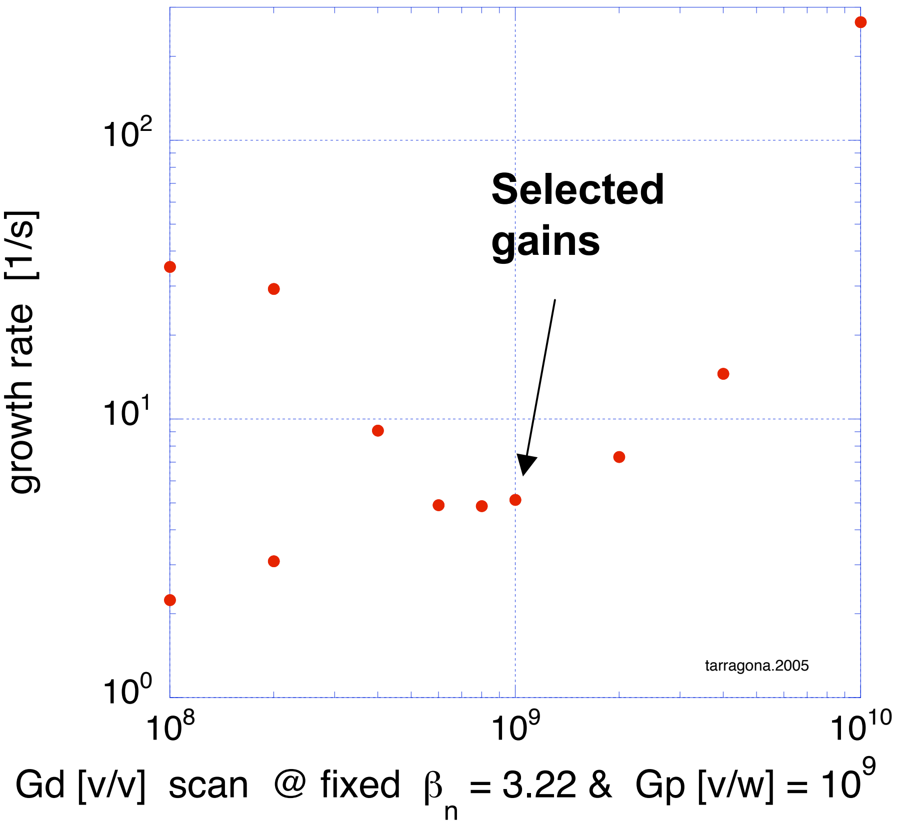
Investigate combined G_p [v/w] & G_d [v/v] gain

$V_{cc} = G_p$ x(sensor flux) + G_d x(sensor voltage)

Stabilized to $\beta_n = 3.18$ When both G_p & G_d used



Could not reach $\beta_n = 3.22$ with different G_d



RWM stabilization with PD controller: Results obtained in 2005

All codes have shown that proportional control algorithm for the current in feedback coils can stabilize RWM up to **C_β = 0.6-0.7**.

However effect of the feedback derivative gain (***k_2***) on RWM stabilization was different. It is significant in MARS-F and KINX and very minor in VALEN.

A proper choice of ***k_1*** and ***k_2*** in MARS-F and KINX allows stabilization of RWMs with **$C_\beta \approx$ 0.85**.

To clarify the reason of differences, comparison of the RWM response to the coil current was proposed (Y.Liu).

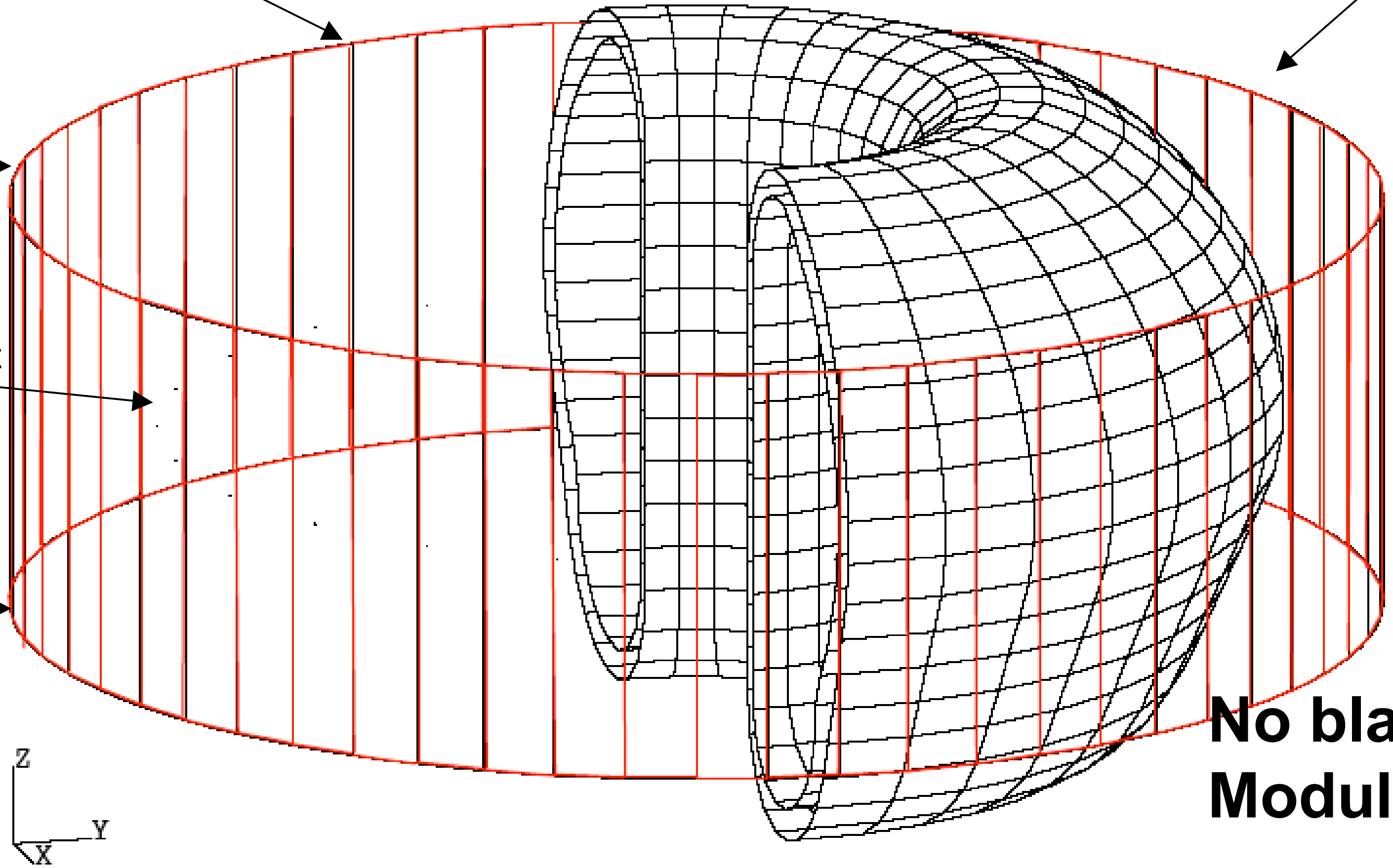
Benchmarking model used in this analysis .

below we show a cut away view of axisymmetric vacuum vessel (2 walls) and VALEN approximation of continuous RWM coil

60 picture frame coils with no overlap. The total gap between all Coils = 1 toroidal degree

This models the Idealized n=1 RWM coil

Each coil has a different current, this results in a n=1 distribution of current



Coil top
+3.9 m

Br & Bz sensors at
r,z = 8.85,0.45 m

Coil bottom
-3.0 m

No blanket Modules

RWM response to coil current (transfer function)

The RWM response to the coil current can be expressed via transfer function:

$$P(s) = \frac{b_\vartheta(s)}{b_0 \, j(s)} \, ,$$

$b_\vartheta(s)$, $j(s)$ – Laplace transformations of the amplitudes of poloidal magnetic field, $B_\vartheta(t)$, and current in 2D coils, $J_0(t)$.

b_0 - amplitude of radial component of magnetic field produced by unit DC current of the sinusoidal coil mode on the magnetic sensors.

VALEN / MARS quantitative comparison of ‘M_{sf} ‘

MARS

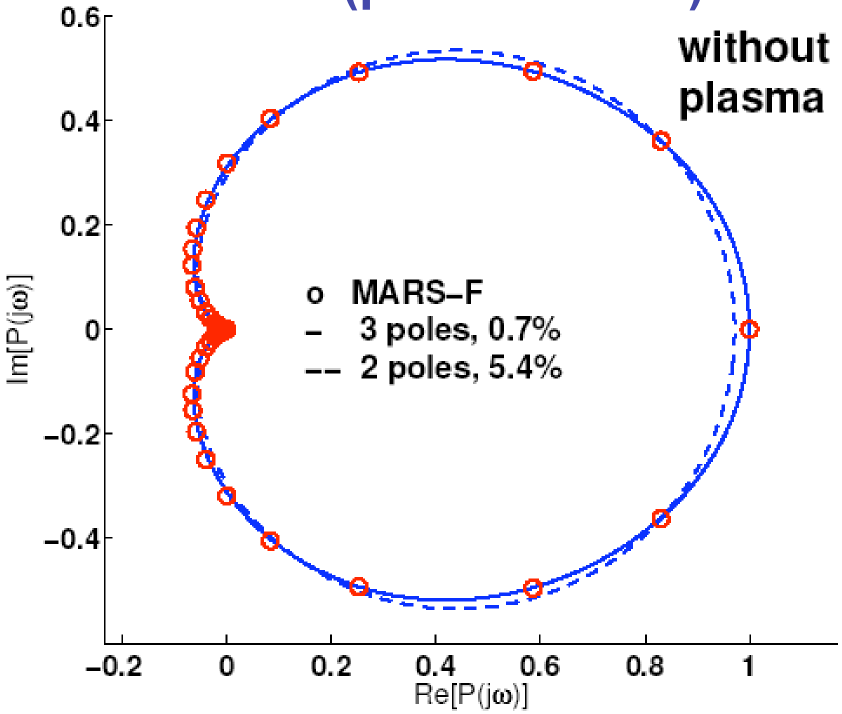
br = 3.63e-8 [T/A] gaussian distribution

br = 8.02e-8 [T/A] cylindrical approximation

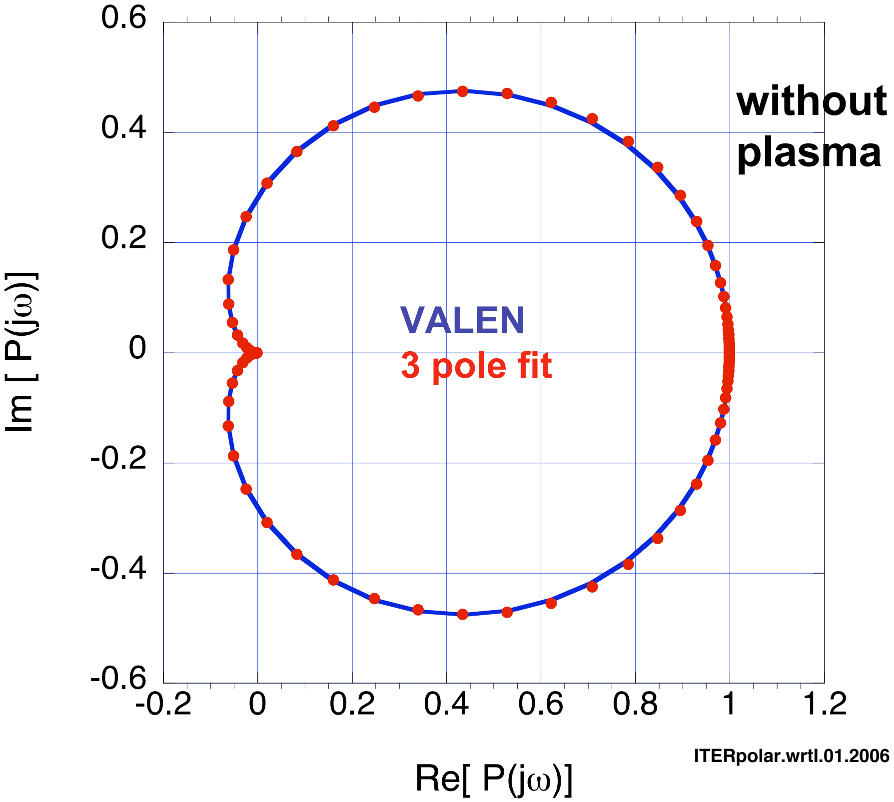
VALEN

br = 9.369e-8 [T/A]

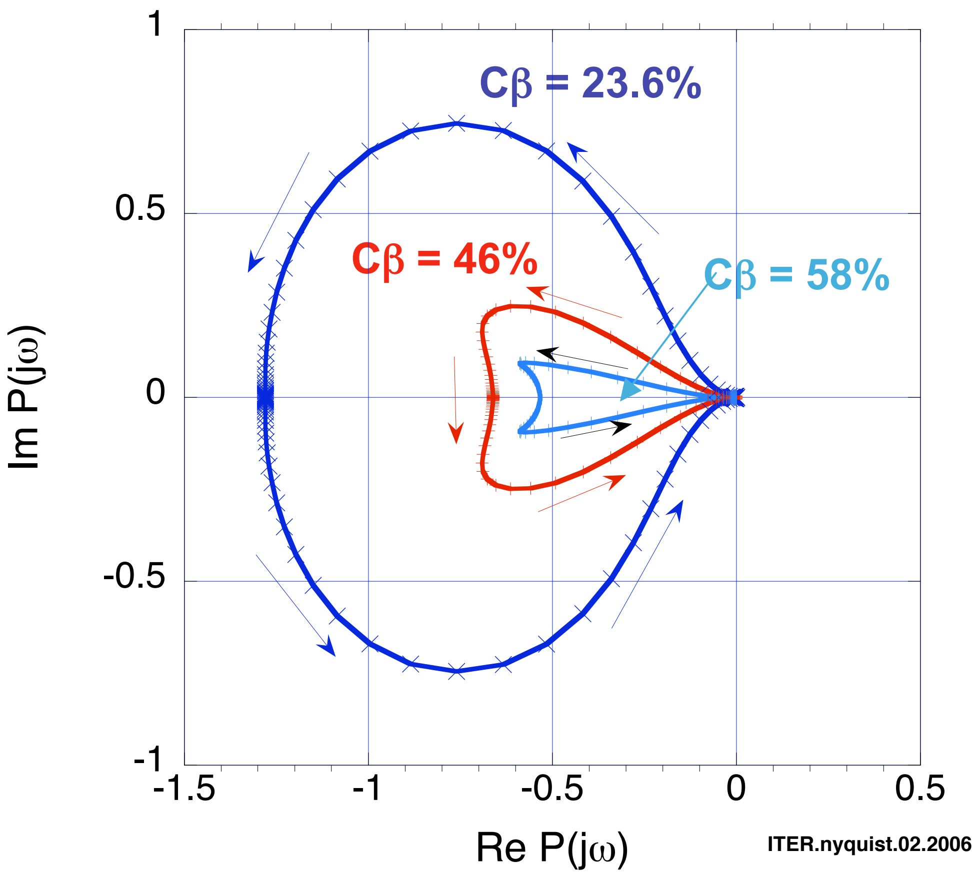
MARS
(previous talk)



VALEN



Nyquist plots are consistent with previous VALEN closed loop (feedback) calculations. Nyquist diagrams predict stability up to C_β > 58%. All Nyquist plots are up/down symmetric (as expected from model).



ITER.nyquist.02.2006

All curves shown have a single counter clockwise closed path as jω is mapped from -infinity to +infinity.

Simple scaling by a positive constant (K_p) will make all these curves enclose the point (-1,0).

More scaling (gain) is needed for higher C_β

Curves shown are VALEN transfer functions, not curve fits

VALEN Nyquist analysis as a function of C_β is very similar to published MARS results.

[*Nucl. Fusion* 44 (2004) 232-242 by Liu, Bondeson, Gribov & Polevoi]

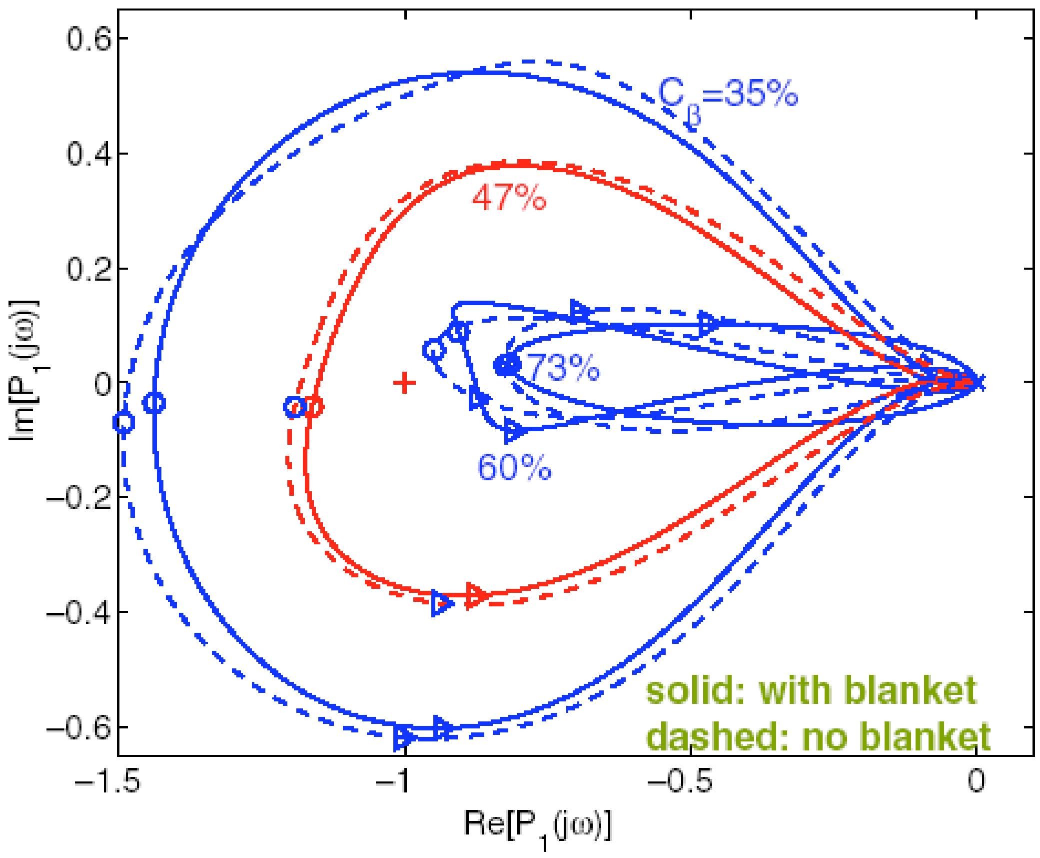
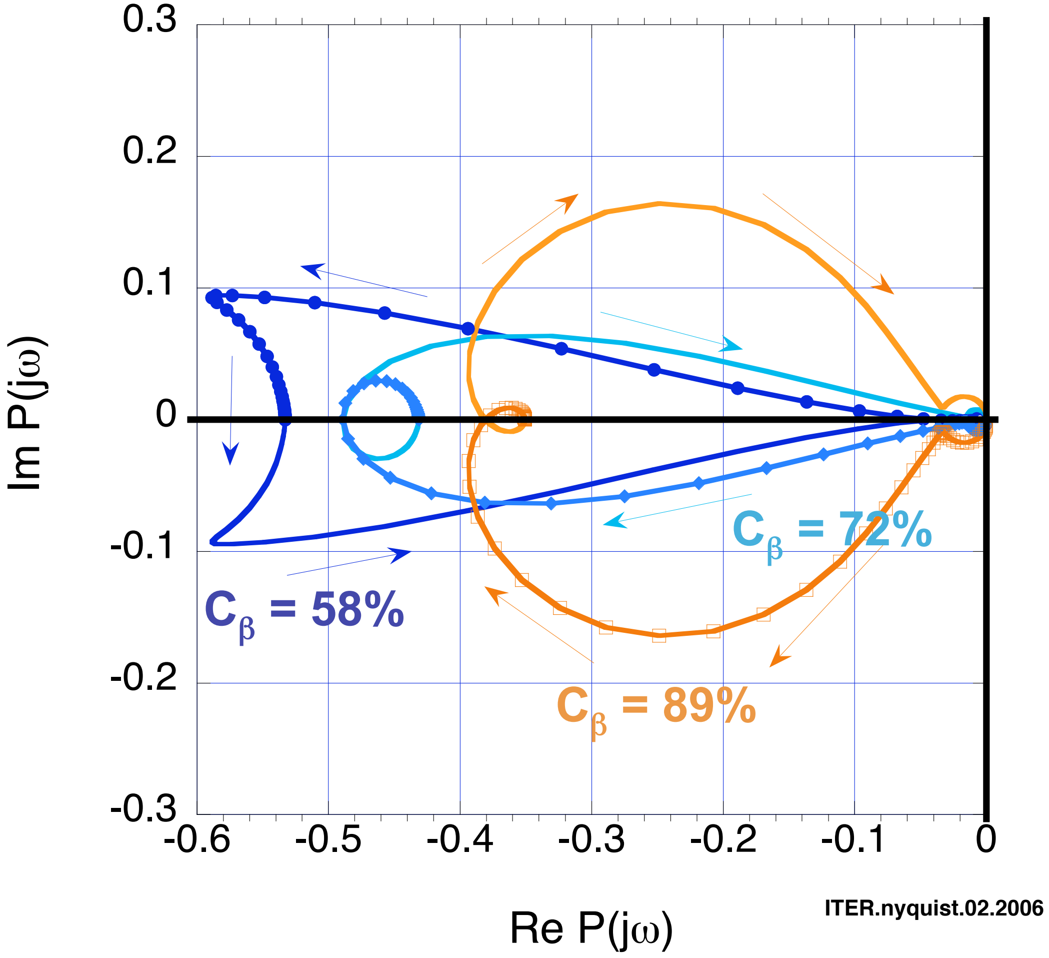


Figure 8. Nyquist diagrams of the transfer function, $P_1(s)$, for different plasma pressures. Poloidal sensors are used.

VALEN Shows More Complex Unstable Transfer Function at High C_β

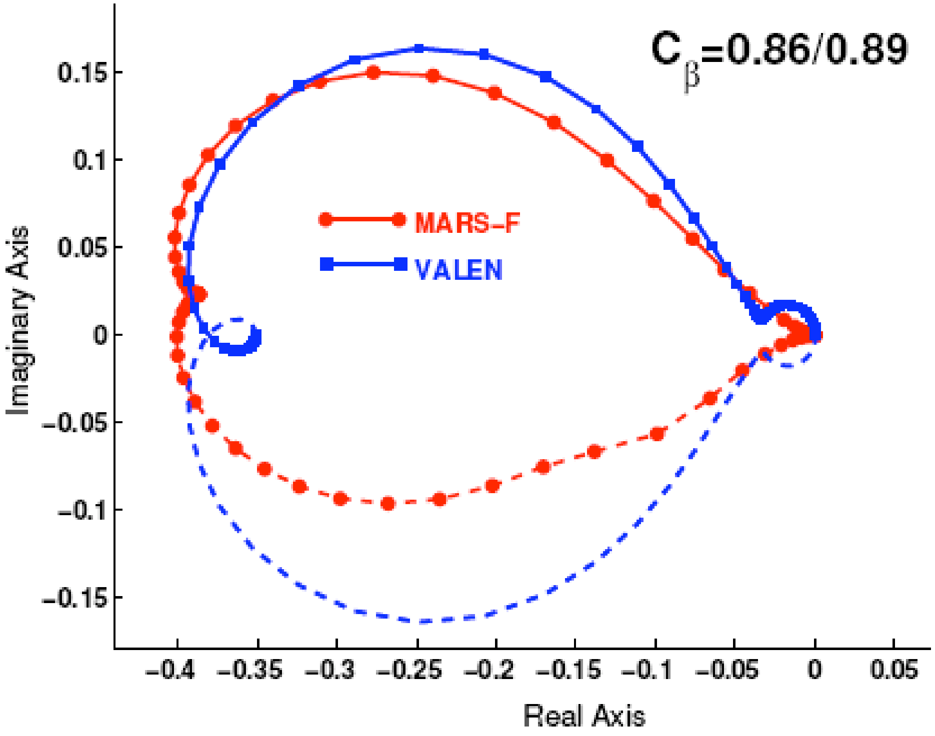


Nyquist plots derived from VALEN are consistent with previous VALEN closed loop feedback calculations and MARS Nyquist analysis at lower C_β.

The direction of the curves has changed at C_β = 72%, where we observe two clockwise rotations (unstable) as we map the line jω - <u>not seen in MARS analysis</u> maybe 3D eddy effect.

'Simple' feedback no longer works!

VALEN Shows More Complex Unstable Transfer Function at High C_β



[Y. Liu, 22 March 2006 Report]

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The direction of the curves has changed at C_β = 72%, where we observe two clockwise rotations (unstable) as we map the line jω - not seen in MARS analysis maybe 3D eddy effect.

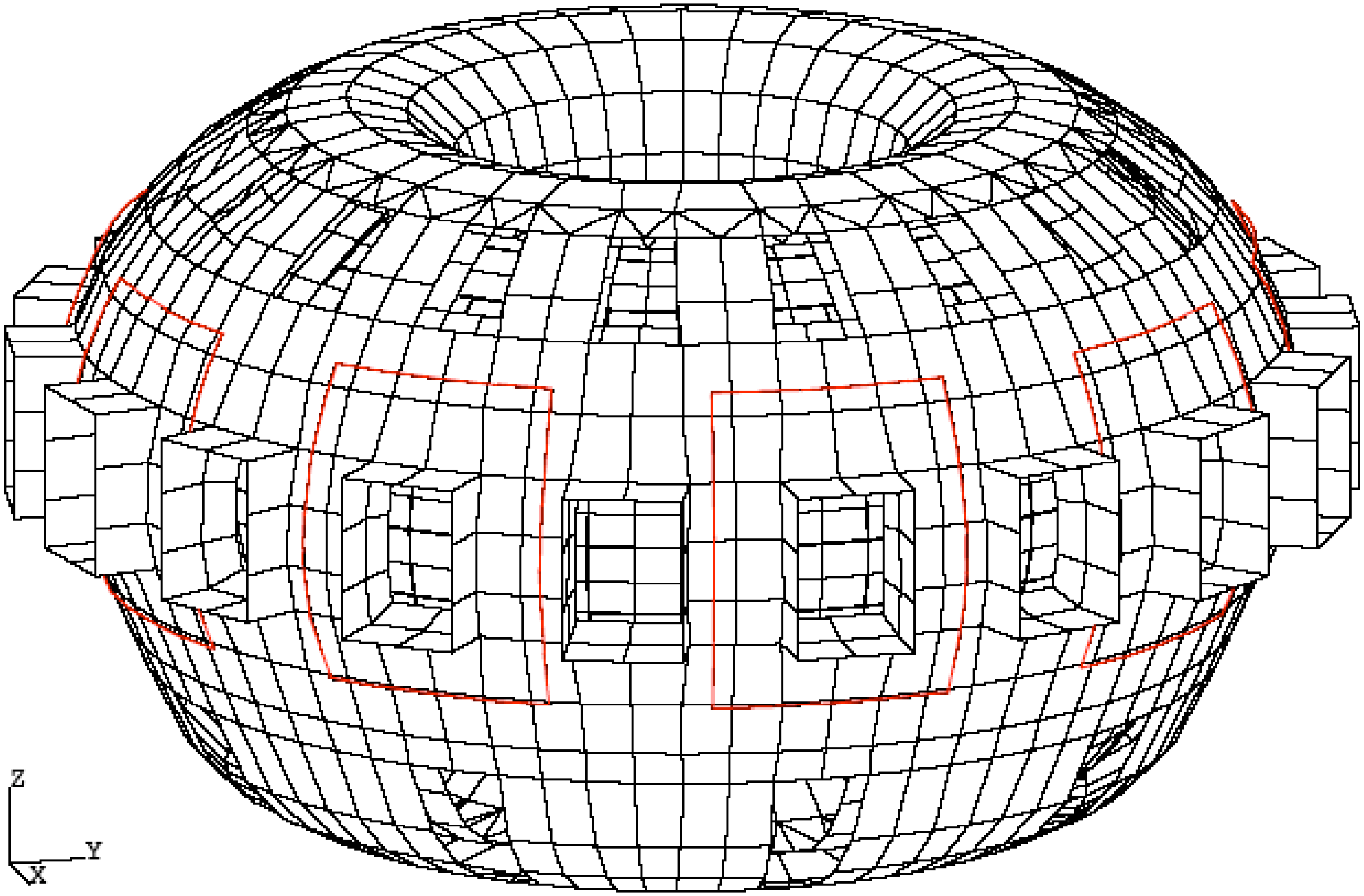
Lead/Lag Compensation in feedback does not work!

Improved Active Control in ITER:

Improved Coil Geometry

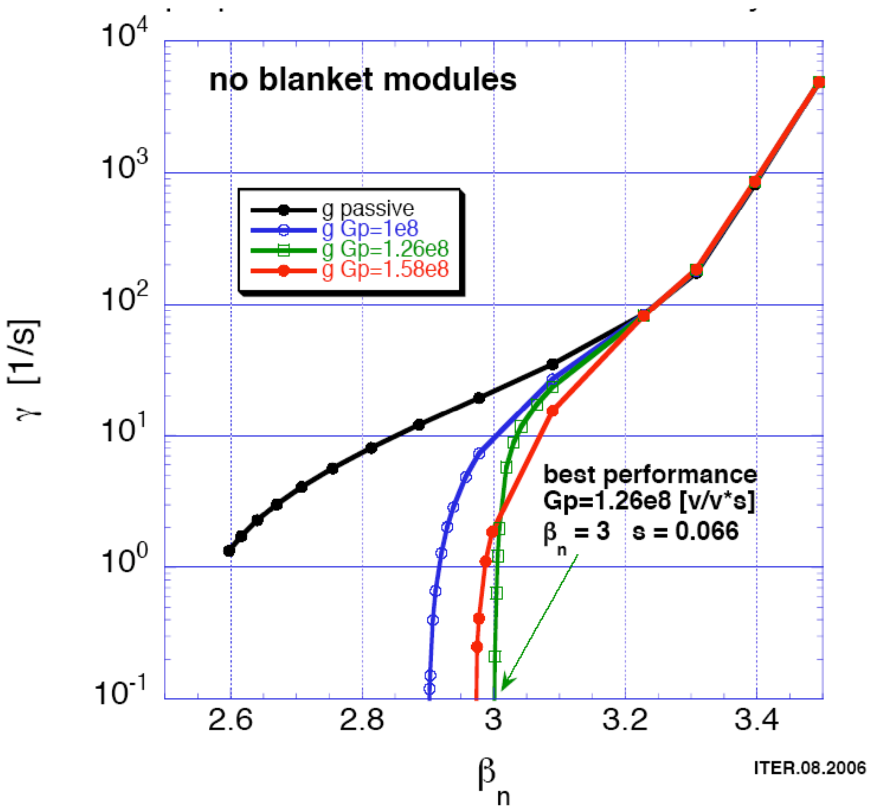
Improved Control Algorithms Beyond PID

Proposed Alternative ITER RWM Control Coil Set: Nine Coils Located on Outer VV Wall



- Compare Performance with ITER Baseline Design both <u>with</u> and <u>without</u> Blanket/Shield Modules

VALEN Model of Alternative Control Coils With G_p



no blanket modules

best performance
Gp=1.26e8 [v/v*s]
$\beta_n = 3 \quad s = 0.066$

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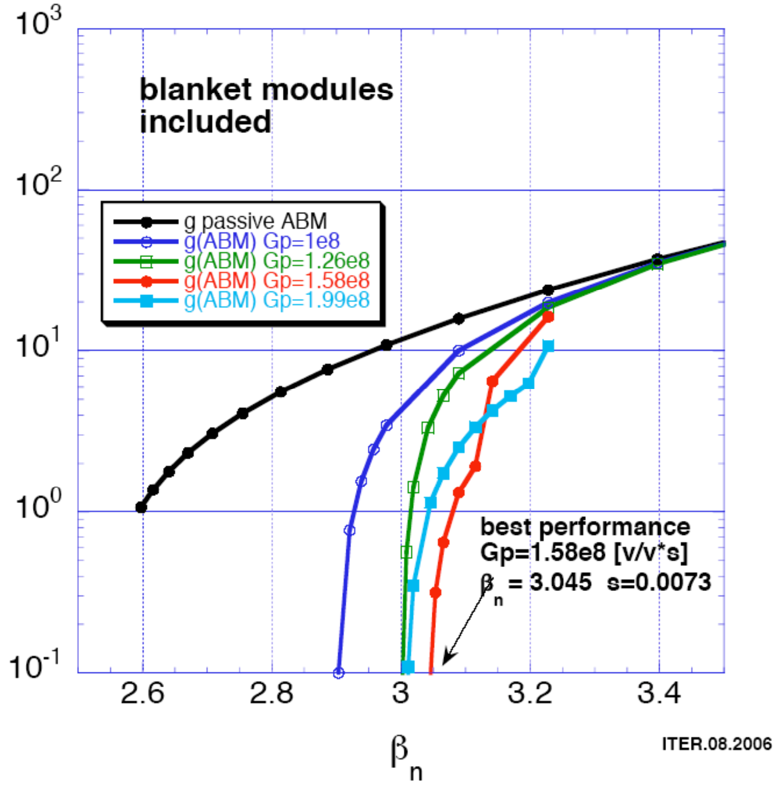

blanket modules
included

best performance
Gp=1.58e8 [v/v*s]
$\beta_n = 3.045 \quad s=0.0073$

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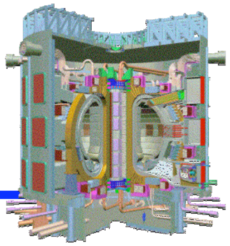
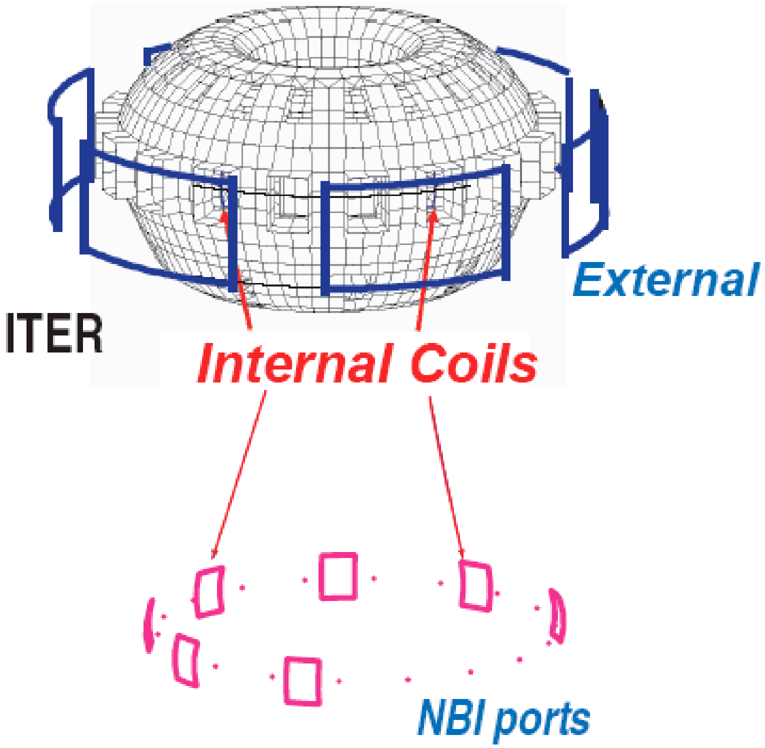
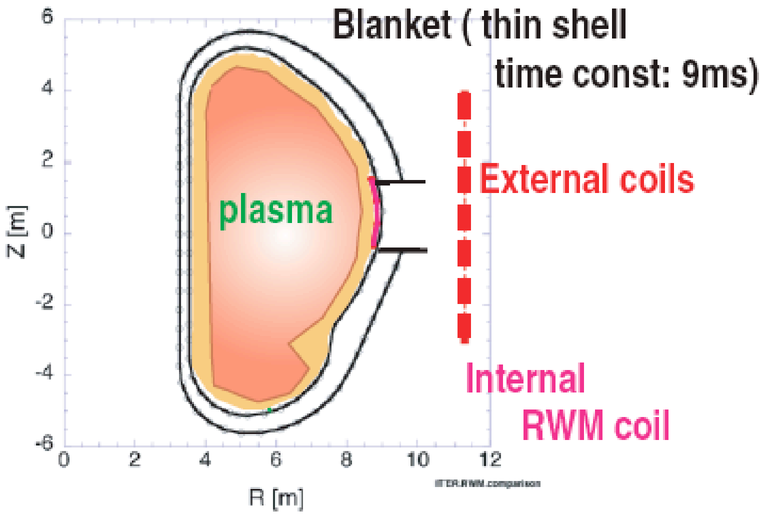
Performance Comparable to Baseline ITER Coil Set where Best Stabilized β_n with Proportional Gain ~ 3.18

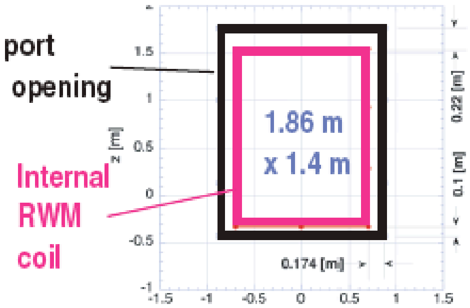
Internal vs External RWM Coils on ITER





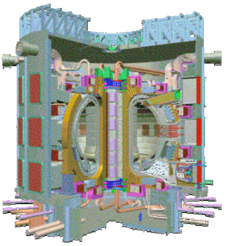
- RWM coils are located at every 40 degrees except NBI ports (toroidally asymmetric 7 coils)



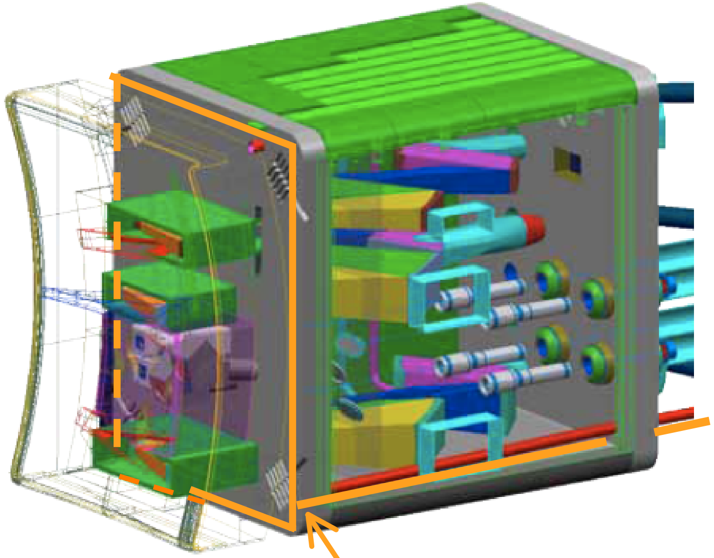


- The study analyses the effect of a single turn coil in the 10 cm gap between the blanket shield module (BSM) and the port extension of a mid-plane port plug.

Applying Internal RWM Feedback Coils to the Port Plugs in ITER Increases β–limit for n = 1 from $\beta_N = 2.5$ to ~ 4

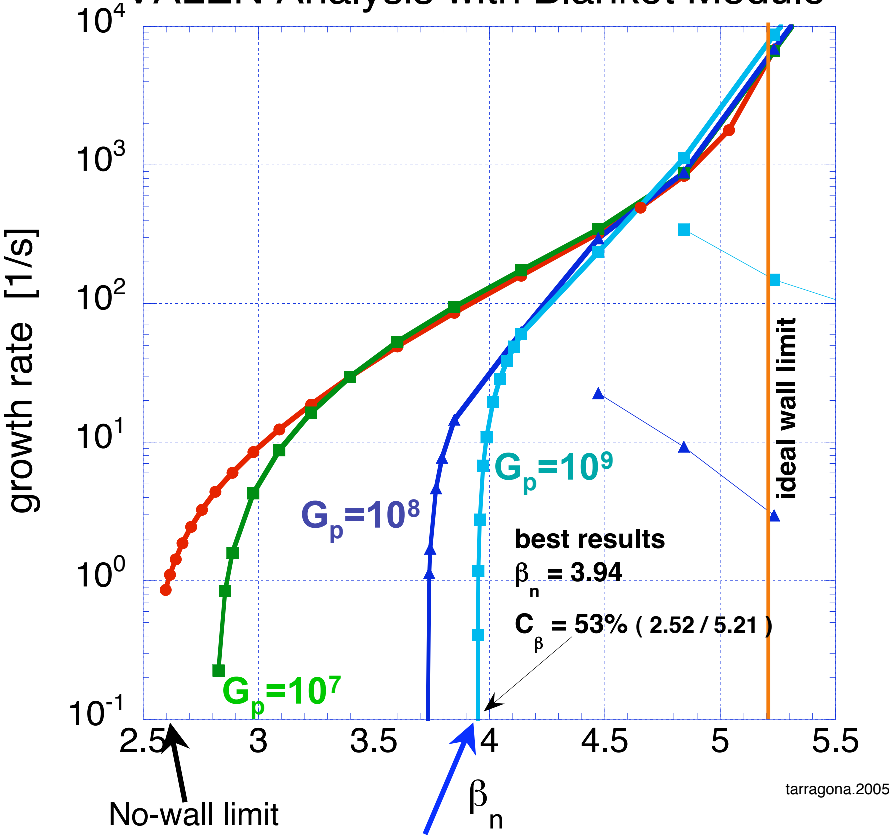


RWM Coil Concept for ITER



- Baseline RWM coils located outside TF coils
- **Internal RWM coils would be located inside the vacuum vessel behind shield module but inside the vacuum vessel on the removable port plugs.**

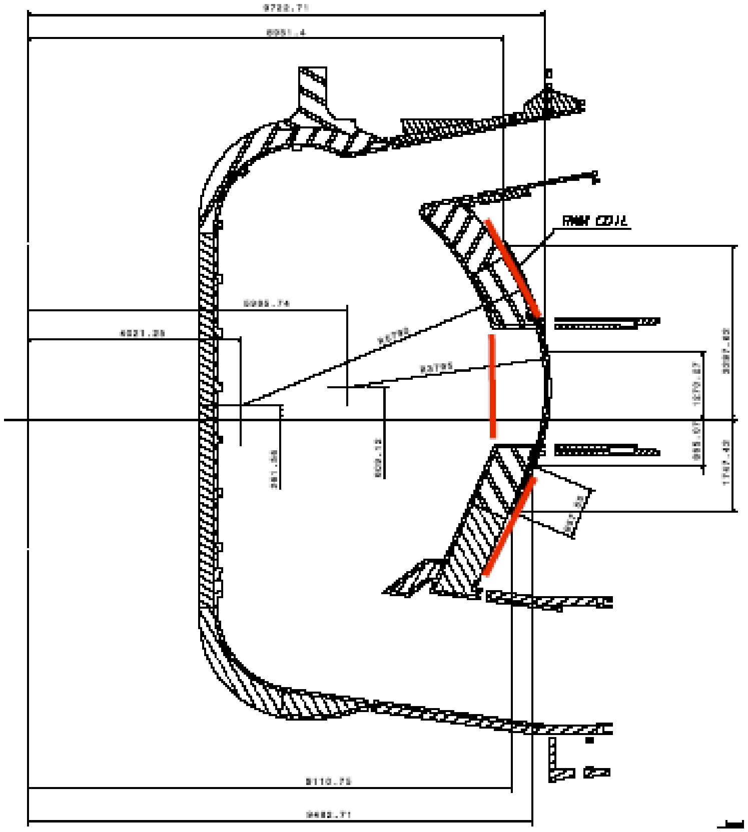
VALEN Analysis with Blanket Module

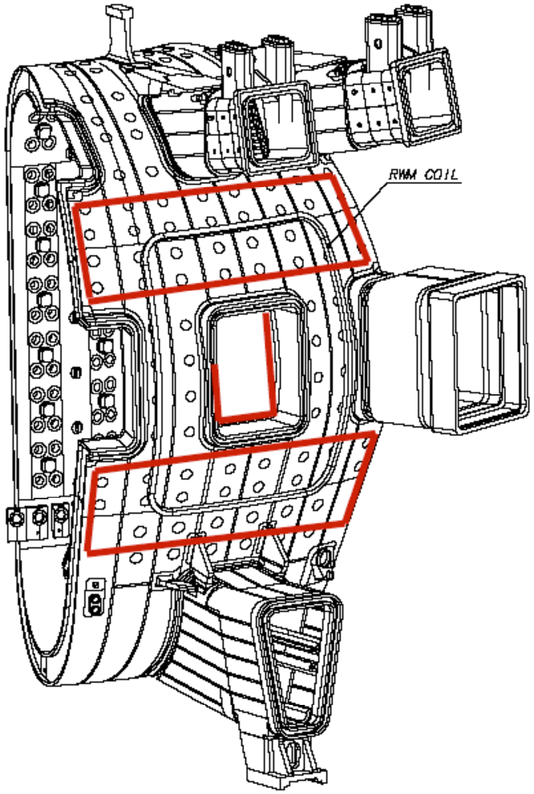


- **7 RWM Coils mounted behind Port Plug Blanket Module with simple proportional gain G_p feedback control loop**
- **Ulrickson “split” Blanket/Shield analysis Suggests $\beta_n > 4$ possible**

Proposed Approach to Combined RWM/ELM Control Coil

- ITER Engineering VERY OPPOSED to any in-vessel coils behind the blanket and shield modules.
- Explore RWM and ELM Control performance of a hybrid internal port plug set combined with an on-vessel (but external) set similar to DIII-D I-Coil set.





Next Step: Go Beyond PID and Lead-Lag Compensation

- At 2005 ITPA MHD Group Meeting in Tarragona Joe Lister advocated use of modern ‘state-space’ feedback control methods to better understand and optimize our modeling of ITER RWM active stabilization.

- Formulation of RWM Control Model in ‘State Space’ form is entry point to modern control theory that offers:

  + Improved performance control loop using pure proportional gain

  + Reduced noise using Optimal Observer and Kalman Filter

  + Reduced dimension model for real-time application.

- This approach has been used in fusion modeling of n=0 stability, e.g.:

  D. J. N. Limebeer and J. P. Wainwright, IEEE Symposium on Industrial Electronics, p21-27 (1998).

  Al-Husari, Hendel, Jaimouka, Kasenally, Limebeer, Portone, 30th Conf. On Decision and Control, p 1165-1170 (1991)

State Variables: A Dynamical Systems Approach

- Basic “state variable” or phase space representation using 1st order ODEs rather than transfer functions to describe system

$\dot{\vec{x}} = \overset{\leftrightarrow}{A} \cdot \vec{x}$ unforced system dynamics (open loop γ)
$\vec{y} = \overset{\leftrightarrow}{C} \cdot \vec{x}$ output equations (what you what controlled)

- Can be nonlinear, $\dot{\vec{x}} = f(\vec{x})$, also

- Add feedback input control vector $\vec{u}$ (but do not close the loop yet)

$\dot{\vec{x}} = \overset{\leftrightarrow}{A} \cdot \vec{x} + \overset{\leftrightarrow}{B} \cdot \vec{u}$ $\overset{\leftrightarrow}{B}$ gives coupling of $\vec{u}$ to system states
$\vec{y} = \overset{\leftrightarrow}{C} \cdot \vec{x} + \overset{\leftrightarrow}{D} \cdot \vec{u}$ $\overset{\leftrightarrow}{D}$ represents direct coupling of control $\vec{u}$

What can we say about the open loop system dynamics without specifying a feedback law?

Controllability and Observability (solvability conditions)

VALEN Circuit Equations Have A Built-in State Space

After including plasma stability effects the fluxes at the wall, plasma, and feedback coils are given by (J. Bialek, et al., PoP 2001)

$$\vec{\Phi}_w = \overleftrightarrow{\mathcal{L}}_{ww} \cdot \vec{I}_w + \overleftrightarrow{\mathcal{L}}_{wf} \cdot \vec{I}_f + \overleftrightarrow{\mathcal{L}}_{wp} \cdot I_d$$

$$\vec{\Phi}_f = \overleftrightarrow{\mathcal{L}}_{fw} \cdot \vec{I}_w + \overleftrightarrow{\mathcal{L}}_{ff} \cdot \vec{I}_f + \overleftrightarrow{\mathcal{L}}_{fp} \cdot I_d$$

$$\Phi = \overleftrightarrow{\mathcal{L}}_{pp} \cdot I_d + \overleftrightarrow{\mathcal{L}}_{pw} \cdot \vec{I}_w + \overleftrightarrow{\mathcal{L}}_{pf} \cdot \vec{I}_f$$

Using Faraday and Ohms law yields equations for system evolution

$$\begin{bmatrix} \overleftrightarrow{\mathcal{L}}_{ww} & \overleftrightarrow{\mathcal{L}}_{wf} & \overleftrightarrow{\mathcal{L}}_{pw} \\ \overleftrightarrow{\mathcal{L}}_{fw} & \overleftrightarrow{\mathcal{L}}_{ff} & \overleftrightarrow{\mathcal{L}}_{fp} \\ \overleftrightarrow{\mathcal{L}}_{pw} & \overleftrightarrow{\mathcal{L}}_{pf} & \overleftrightarrow{\mathcal{L}}_{pp} \end{bmatrix} \cdot \frac{d}{dt} \begin{Bmatrix} \vec{I}_w \\ \vec{I}_f \\ I_d \end{Bmatrix} = \begin{bmatrix} \overleftrightarrow{R}_w & \overleftrightarrow{0} & \vec{0} \\ \overleftrightarrow{0} & \overleftrightarrow{R}_f & \vec{0} \\ \vec{0} & \vec{0} & R_d \end{bmatrix} \begin{Bmatrix} \vec{I}_w \\ \vec{I}_f \\ I_d \end{Bmatrix} + \begin{Bmatrix} \vec{0} \\ \vec{V}_f \\ \vec{0} \end{Bmatrix}$$

This can easily be put in state space form…

VALEN Mesh Current State Feedback

- The VALEN code, interestingly enough, has a "natural" intrinsic set of state variables. They are the circuit mesh currents used in the finite element model of the plasma,conducting wall, and feedback coil structures.

VALEN equations can be naturally written as, $\dot{\vec{x}} = \overleftrightarrow{A}\cdot\vec{x} + \overleftrightarrow{B}\cdot\vec{u} = \left(\overleftrightarrow{A} + \overleftrightarrow{B}\cdot\overleftrightarrow{K}\right)\cdot\vec{x}$

The state vector of the system is given by: $\vec{x} = \left\{\vec{I}_w, \vec{I}_f, I_d\right\}$

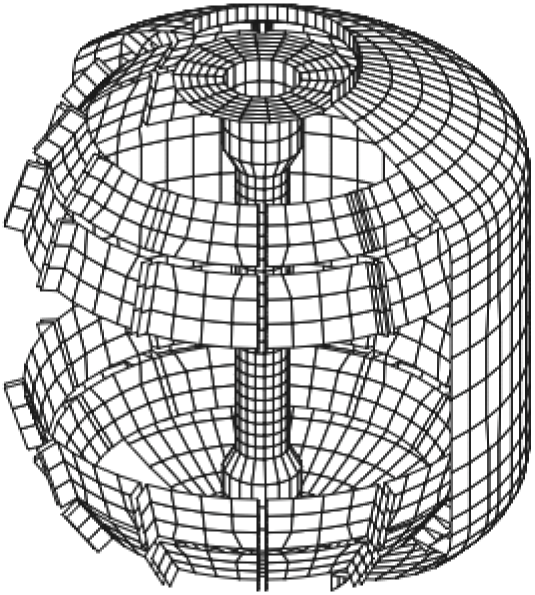
The control vector is the feedback coil voltages: $\vec{u} = \left\{\vec{0}, \vec{V}_f, 0\right\}$

And with, $\overleftrightarrow{A} = \overleftrightarrow{\mathcal{L}}^{-1}\cdot\overleftrightarrow{R}$ and $\overleftrightarrow{B} = \overleftrightarrow{\mathcal{L}}^{-1}$

Sensor flux as output $\vec{y} = \vec{\Phi}_s$

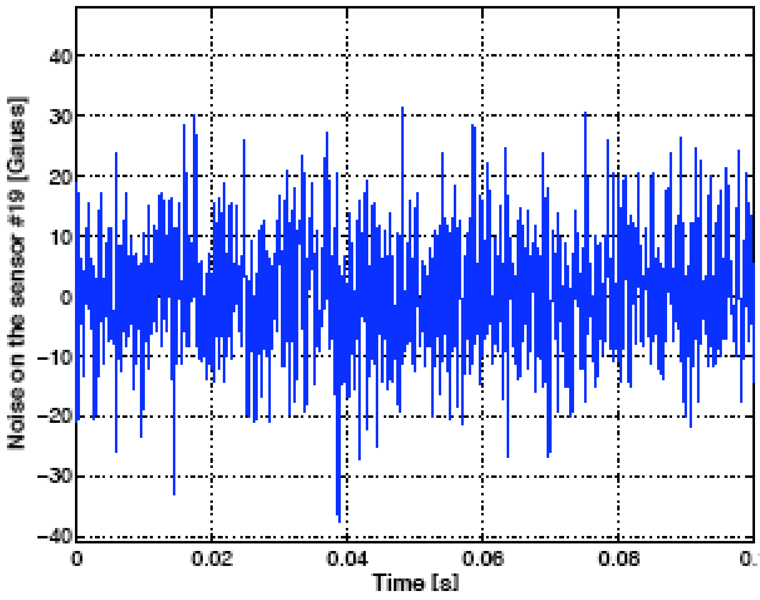
with $\vec{V}_f = \overleftrightarrow{G}_p^{\Phi}\cdot\vec{\Phi}_s \equiv \overleftrightarrow{K}\cdot\vec{x}$ and

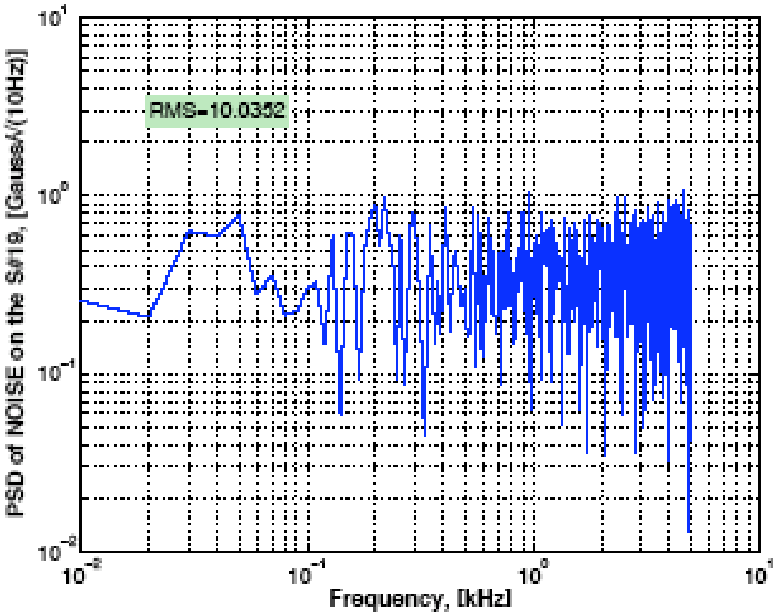
$$\vec{V}_f = \overleftrightarrow{G}_p^{\Phi}\cdot\left[\overleftrightarrow{\mathcal{L}}_{sw} \quad \overleftrightarrow{\mathcal{L}}_{sf} \quad \overleftrightarrow{\mathcal{L}}_{sp}\right]\begin{Bmatrix}\vec{I}_w \\ \vec{I}_f \\ I_d\end{Bmatrix}$$



VALEN model of the NSTX vacuum vessel, passive plates, and conducting center stack

Apply DIII-D Noise Spectrum to ITER Baseline





Broadband white noise with amplitude of 10 Gauss
[about 7 times level in DIII-D – ratio of I_{ITER}/I_{DIII-D}]

No ELMs in applied noise spectrum

Large G_d Leads to Very High Voltage Applied to Coils

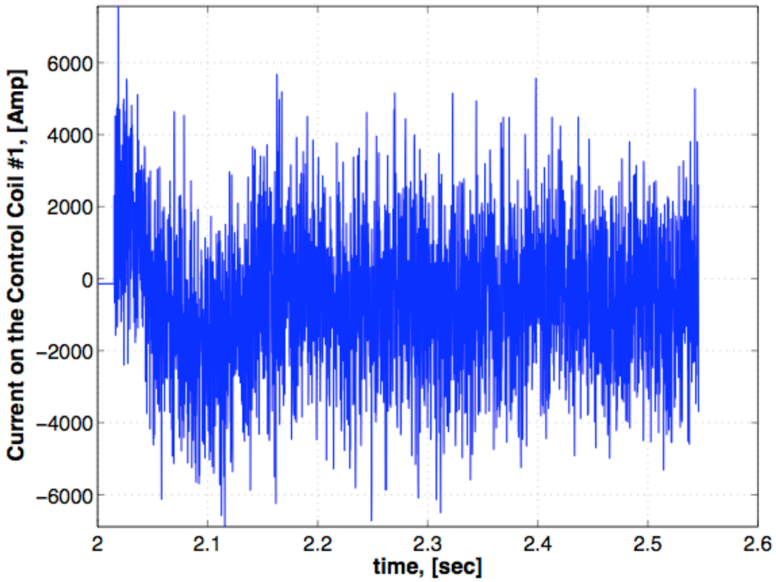


Figure 3: ITER transient run with noise, current on the control coils

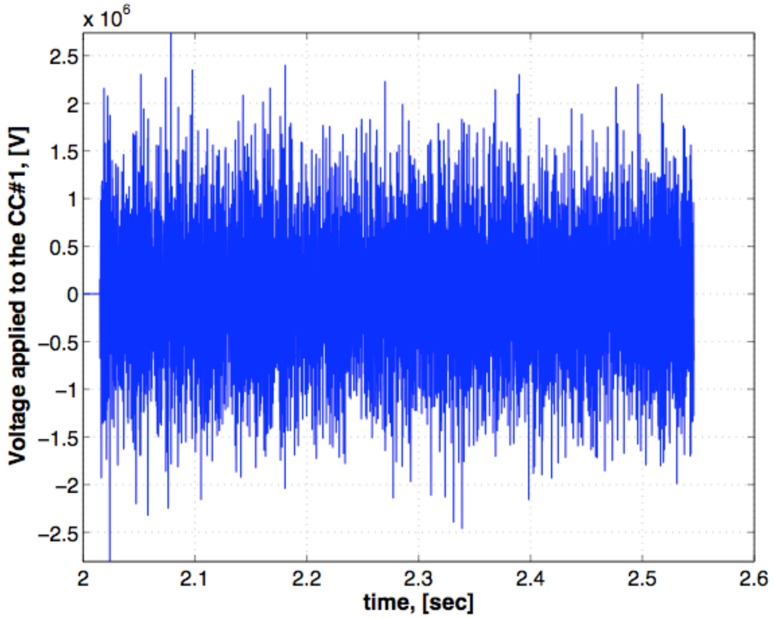
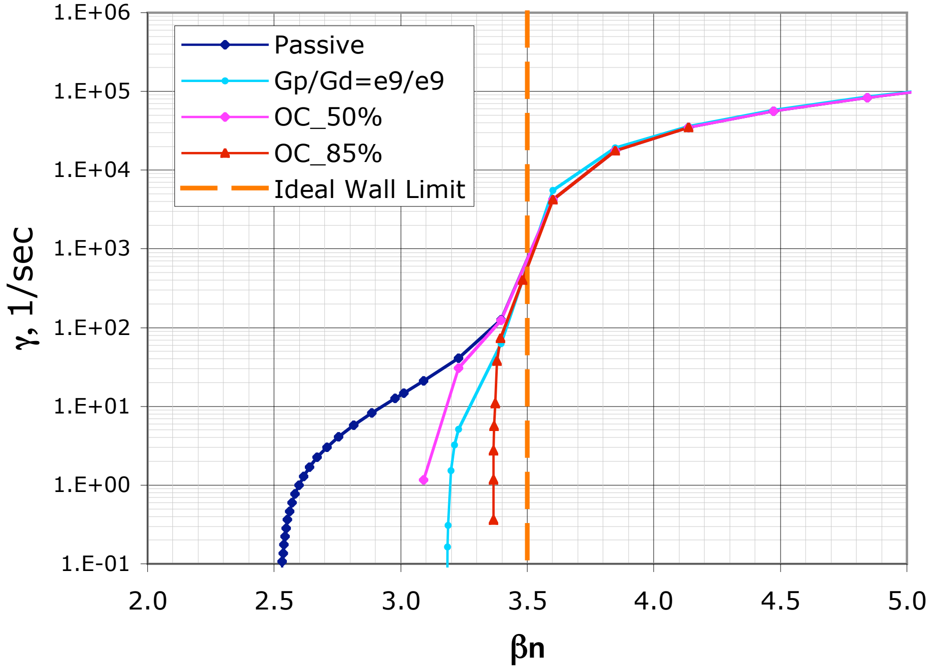
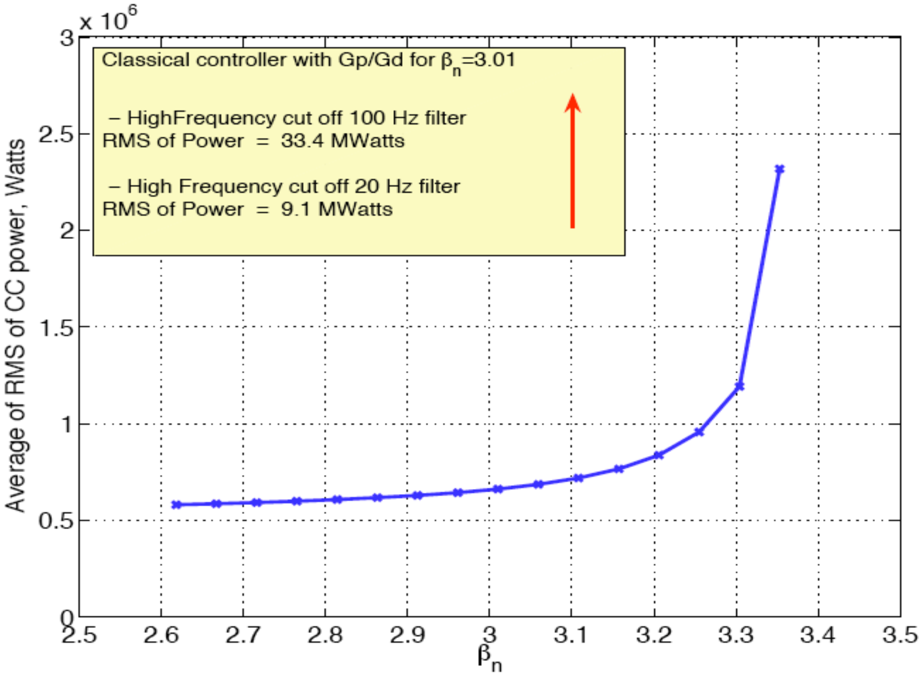


Figure 4: ITER transient run with noise, voltage applied to the control coils

Voltage Levels Reach ~ 1 MV: Need to Reduce

Improved Stabilization of ITER RWM with New Optimal Controller and Observer





Classical controller with Gp/Gd for β_n=3.01

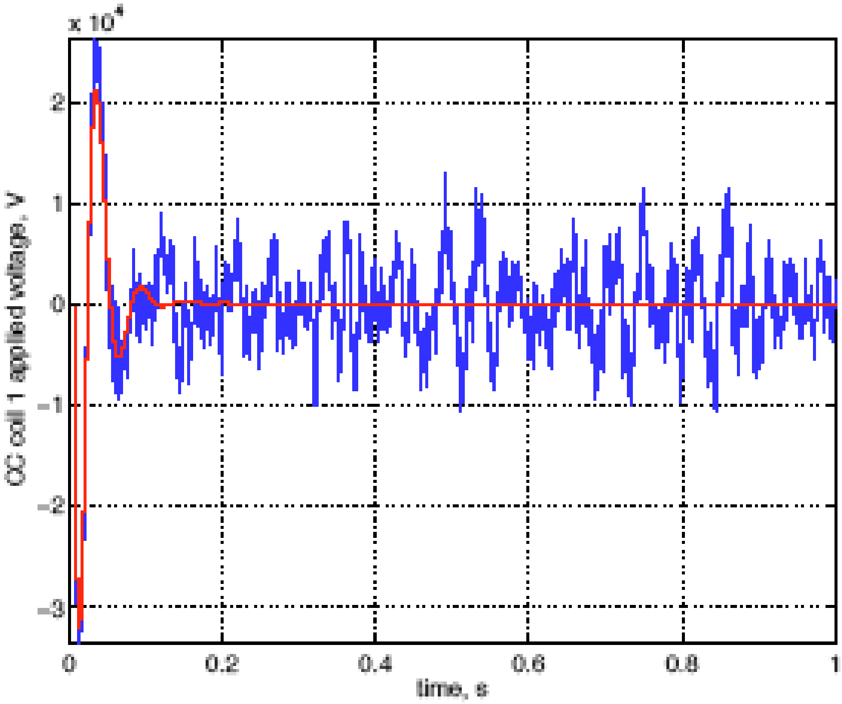
– HighFrequency cut off 100 Hz filter
RMS of Power = 33.4 MWatts

– High Frequency cut off 20 Hz filter
RMS of Power = 9.1 MWatts

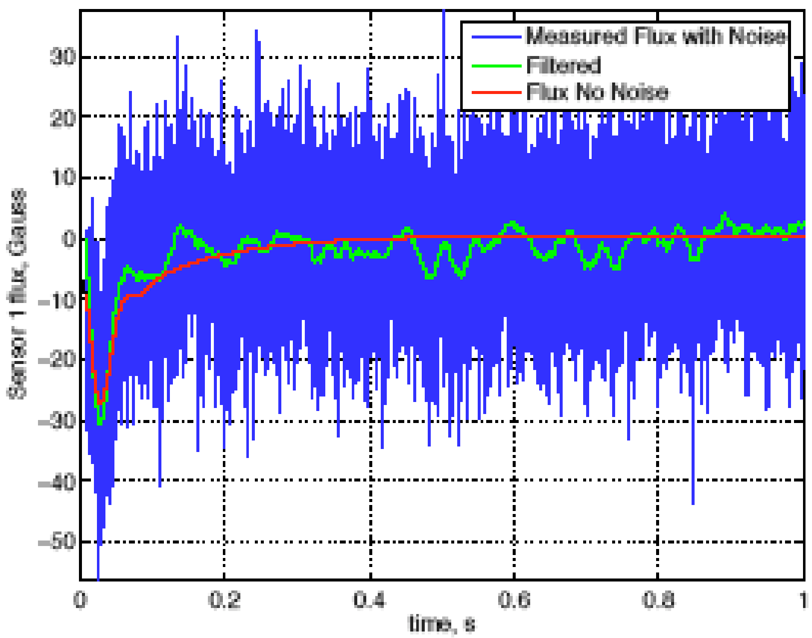
- Optimal controller and observer were designed based on reduced to 20 modes ITER VALEN model for **$C_\beta = 85\%$.** In the presence of 10 Gauss sensor noise RWM was stabilzed up to **$C_\beta = 86\%$**, as compared to $C_\beta = 68\%$ reached by classical controller with derivative and proportional gains.
- **No derivative Gain** is needed with Optimal Controller.
- **Significantly reduction in power requirements** for Optimal Controller.

ITER Optimal Controller Transient Analysis

Control Coil Voltage



Measured Sensor Flux



- Modest Overshoot at $C_\beta \sim 80\%$
- Substantial Noise Reduction!

Summary & Next Steps

- Baseline ITER External Coil Set can stabilize at $\beta_n \sim 3$ level required for basic Scenario 4 steady-state plasmas with RWM growth rates $\gamma \sim 10$/sec. Optimal Controller/Observer needed to reduce power requirements to acceptable levels and provide margin for RWM Control
- Blanket Modules in ITER extend the RWM reduced growth rate branch up to $\beta_n \sim 5$ and create an extended AT regime with important DEMO implications.
- Accessibility of DEMO AT relevant $\beta_n \geq 4$ requires installation of internal control coils to stabilize RWM growth rates $\gamma > 100$/sec.
- USBPO & ITPA exploring possible combination RMP ELM Control and RWM Control normal conductor set trading off against Baseline Superconducting Error Correction Coil Set & HV Power Supplies.