ITER RWM benchmarking VALEN modeling results

6th ITPA MHD topical group meeting

Tarragona, Spain 4 July 2005

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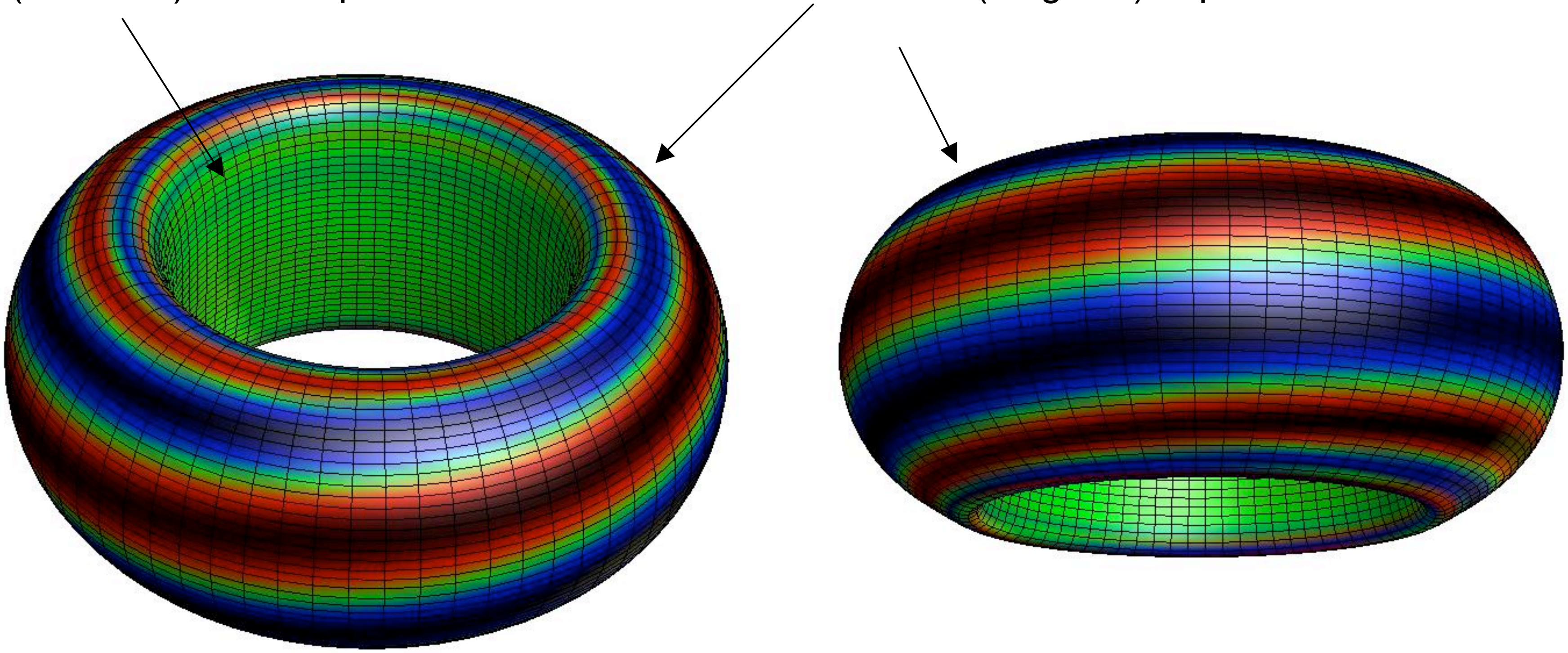
Columbia University

outline

- RWM mode from CHEASE / DCON
- Benchmarking techniques and models
  - Current control with continuous external coil system
  - Voltage control with 6 coil external coil system
  - Effect of blanket modules
- Extended analysis, interior RWM coils with blanket modules, using voltage control
- summary

CHEASE equilibria for scenario 4 used in VALEN computations,
the n=1 DCON B-normal distribution (B_n) on the plasma surface
is shown below, B_n & □W are used as VALEN input,
Color scale: from dark red, to green (approx zero) to dark blue.

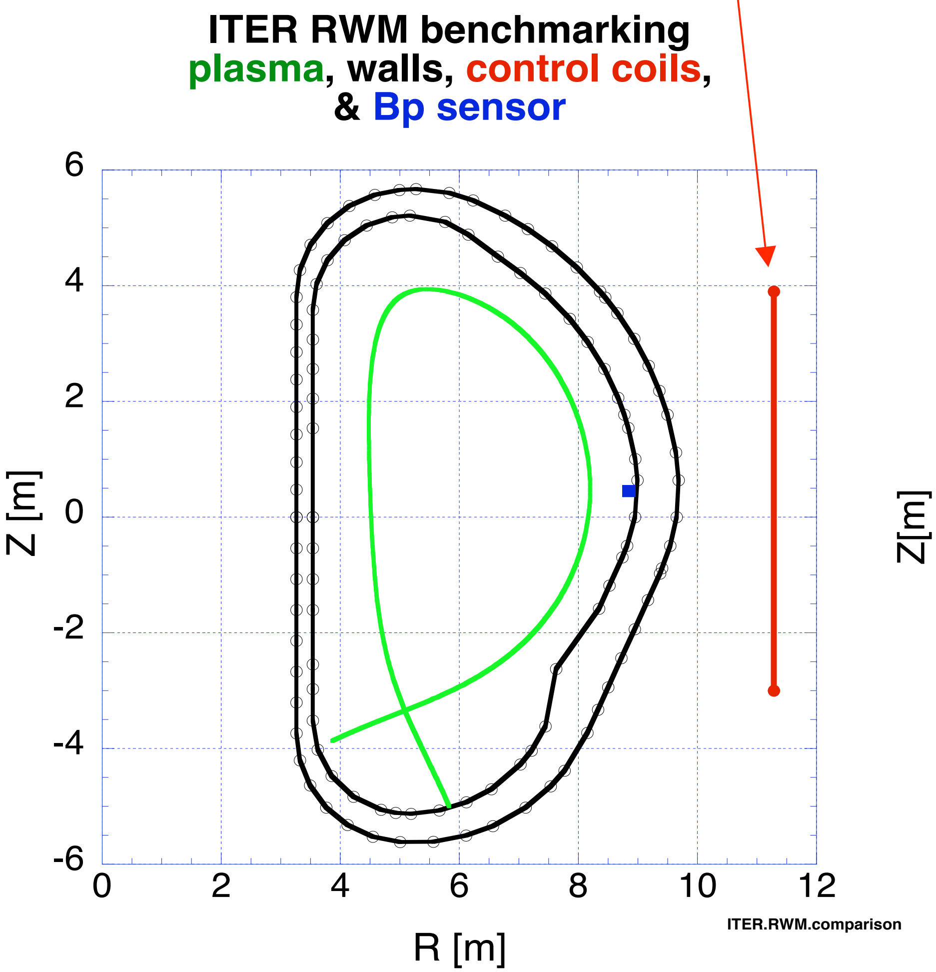


Field perturbation on inside
(small R) is not important

Dominant field perturbation
on outside (large R) of plasma

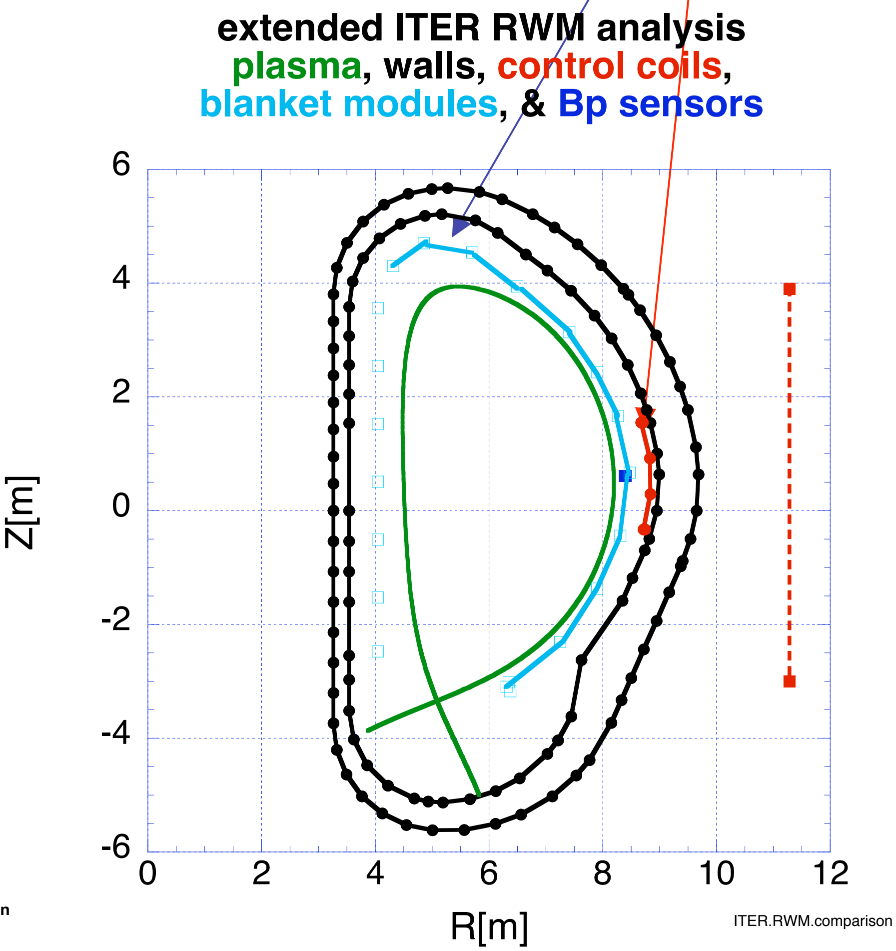
Benchmarking model

continuous external RWM coil
axisymmetric VV
no blanket modules



Extended ITER model

discrete interior RWM coils
penetrations in VV
segmented blanket modules



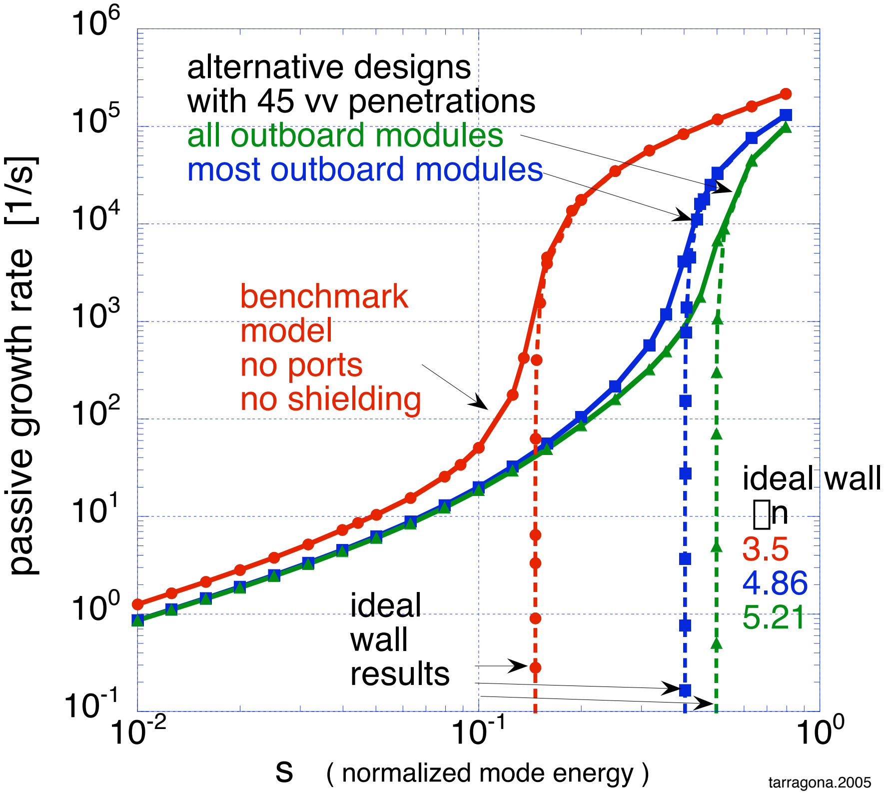
VALEN calculation of ITER passive RWM growth rates

High conductivity wall allows estimate of ideal wall □$_n$ limit

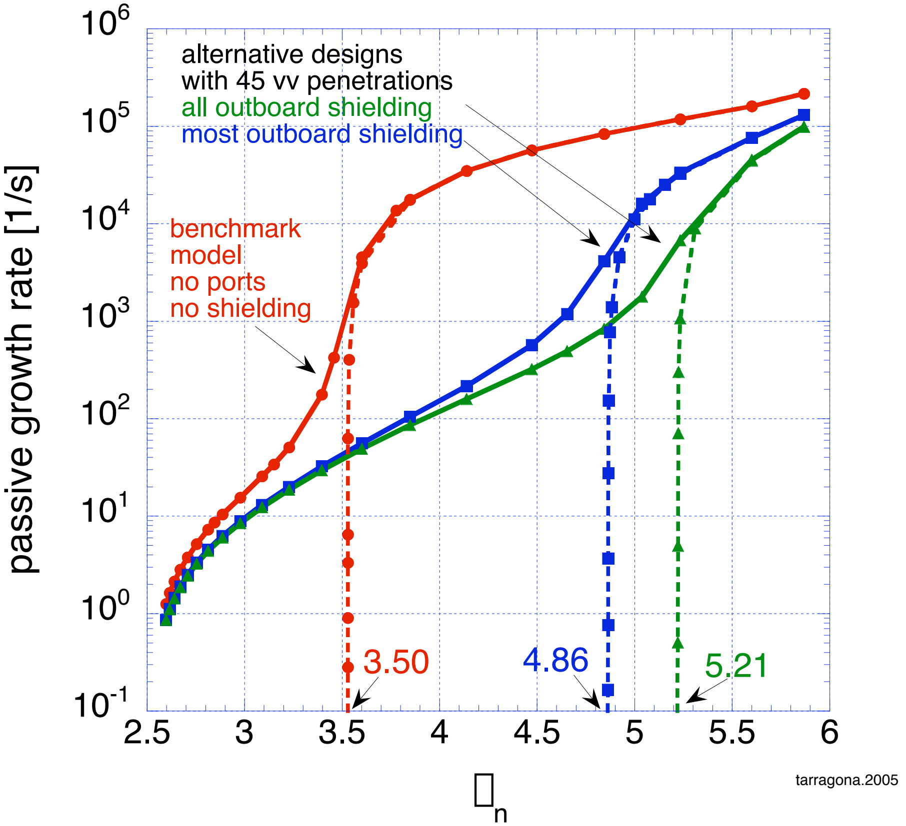
No wall and ideal wall □$_n$ limit define C$_{□}$ scale

no wall □$_n$ limit = 2.52

VALEN
passive growth rates
real & ideal walls



VALEN
passive growth rates
real & ideal walls

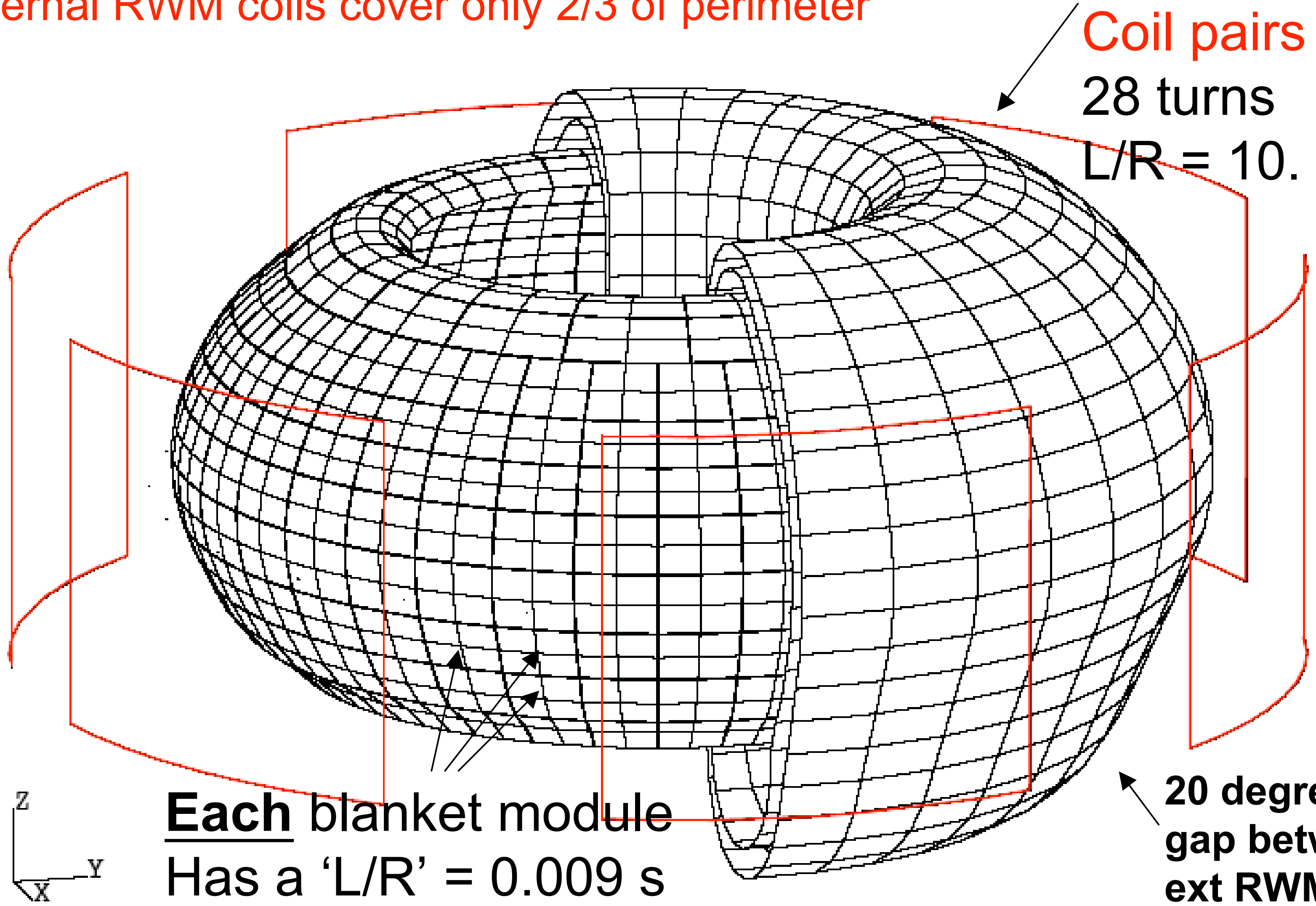


ITER baseline external RWM coils shown

Cut away view of axisymmetric vacuum vessel

VALEN blanket modules visible without VV

External RWM coils cover only 2/3 of perimeter



Coil pairs have
28 turns
L/R = 10. s !

Each blanket module
Has a ‘L/R’ = 0.009 s

20 degree
gap between
ext RWM coils

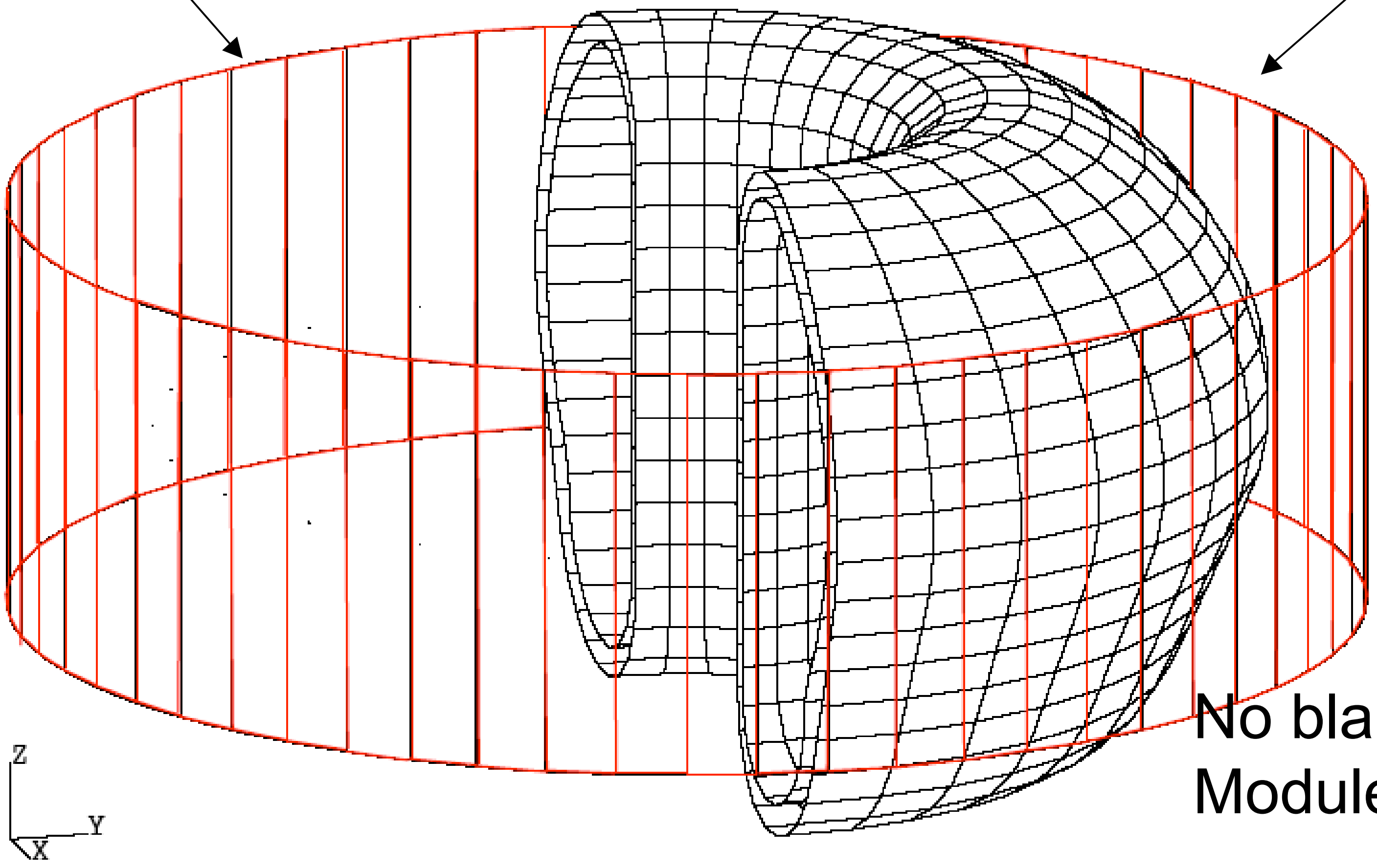
VALEN benchmark RWM coil and cut away view of axisymmetric vacuum vessel model

Continuous RWM coils system shown

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

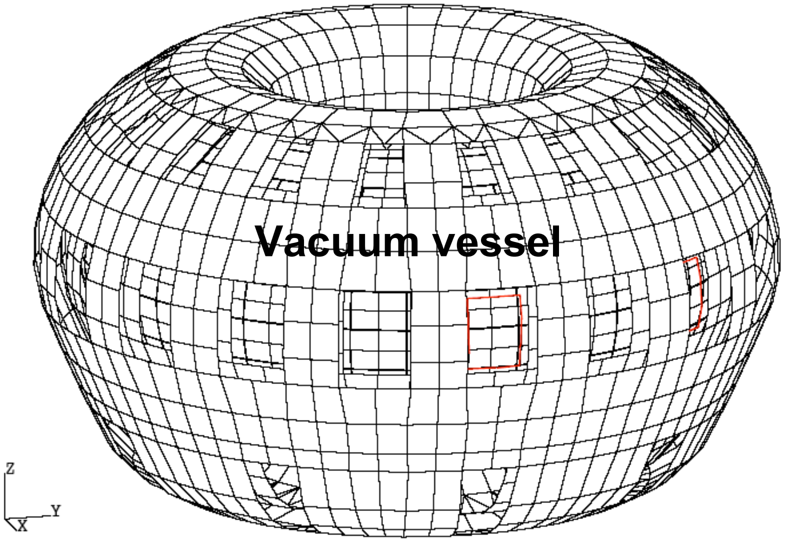
Approximate current control !

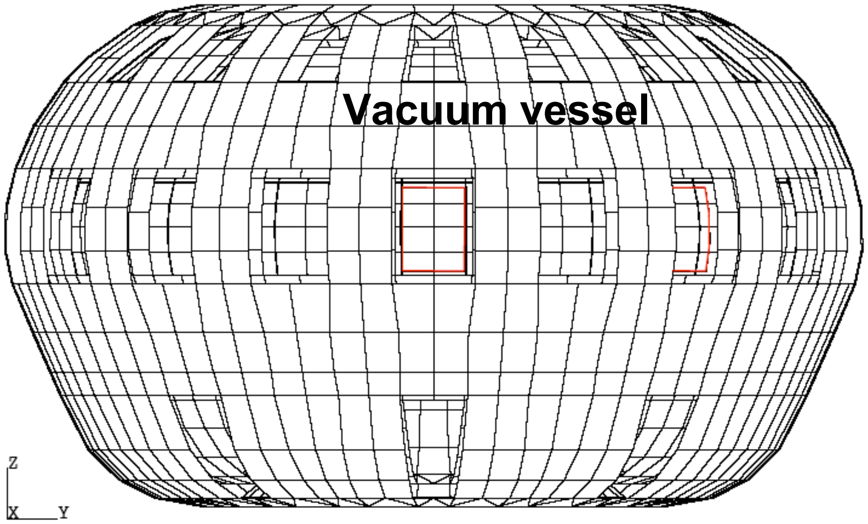
Each coil has a different current, this resultsi n a n=1 distribution of current

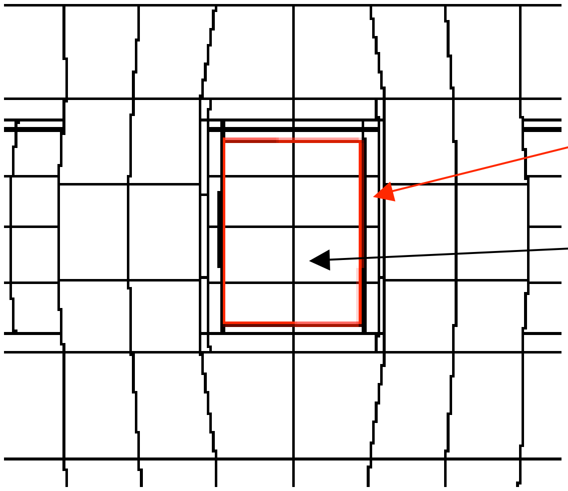


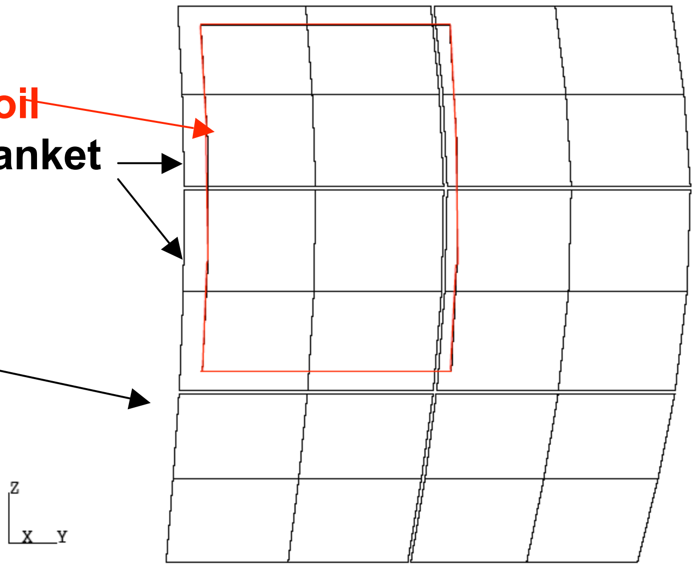
No blanket Modules !

Extended ITER models use internal coils and have penetrations in the vacuum vessel









Internal coil
behind blanket modules

Gaps between blanket modules

VALEN benchmark model approximates MARS continuous RWM control coil

-axisymmetric walls
- ignore blanket modules
-continuous external RWM coil
-approximate current control in feedback logic

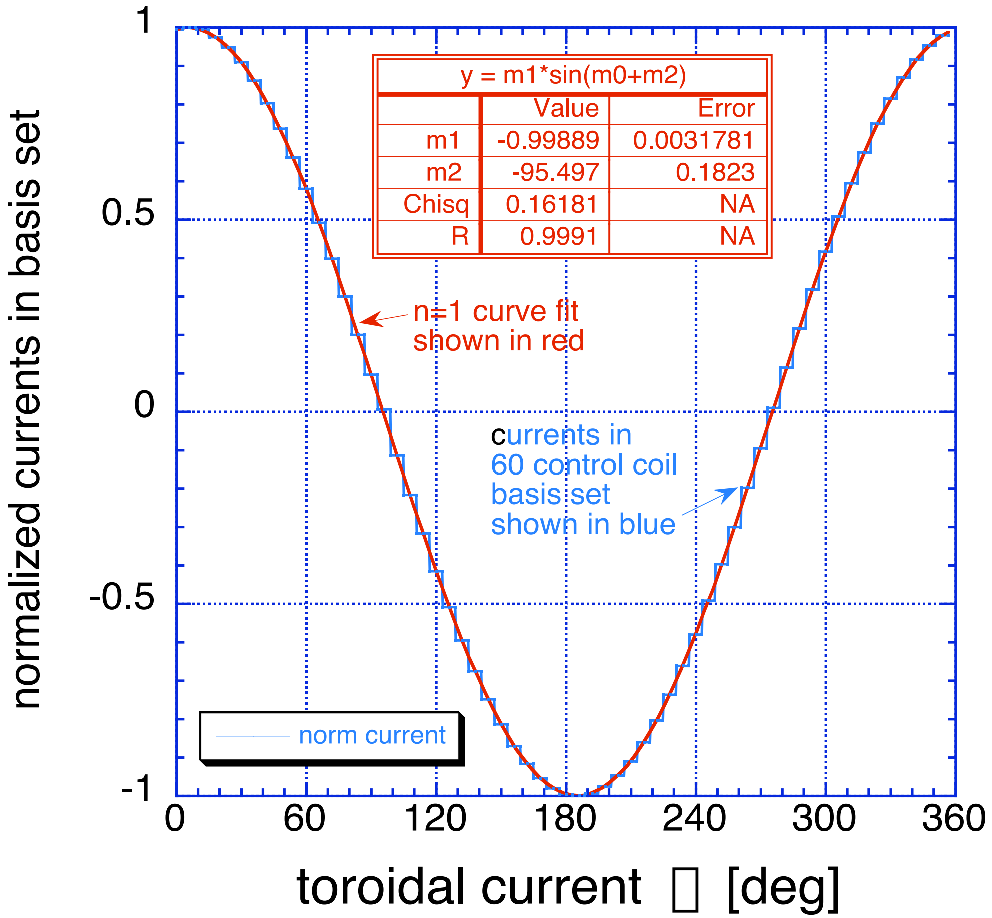
VALEN implements feedback via voltage control. Sensor signals to control logic determines the voltage applied to the RWM coils.

Technique:
RWM control coils
Model continuous RWM coil system by many small (non overlapping) 'picture frame' coils

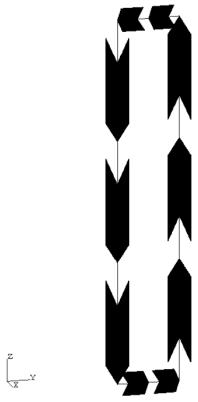
Technique:
current control
Make each sub-coil have fast (L/R) time constant so that requested coil current is obtained with minimal delay

VALEN can approximate A continuous RWM coil

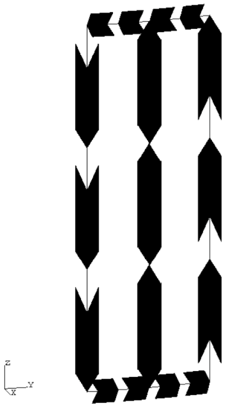
VALEN approximation
to n=1 current distribution
in 60 control coil basis set



y = m1*sin(m0+m2)		
	Value	Error
m1	-0.99889	0.0031781
m2	-95.497	0.1823
Chisq	0.16181	NA
R	0.9991	NA

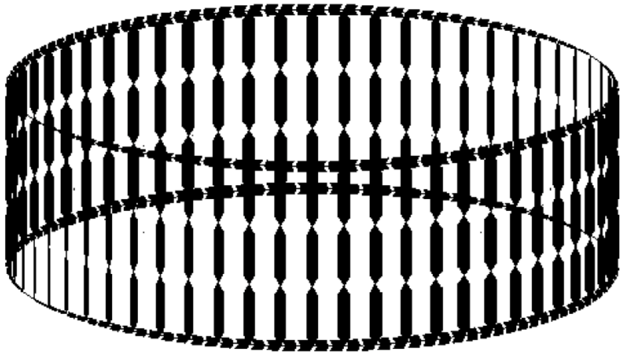


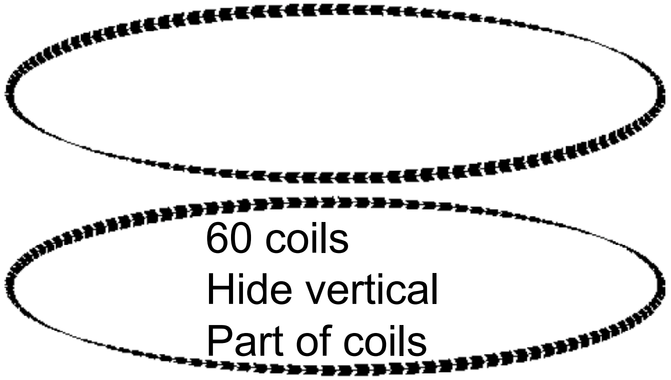
One coil



Two coils

60 coils





60 coils
Hide vertical
Part of coils

Mode control feedback in VALEN RWM model

Sensors track B_p inside VV & have area = 10^{-4} m^2

VALEN solution variables are currents in model

i.e., {I(t)} and {dI/dt} for each wall element & coil & plasma

Voltage control is used to specify feed back in VALEN:

$$\text{sensors:}\quad \{\Phi_s(t)\} = [M_{sI}]\{I(t)\} \text{ and } \{-\dot{\Phi}_s(t)\} = -[M_{sI}]\{\dot{I}(t)\}$$

$$\text{voltage feedback:}\quad V_{cc}(t) = -G_p\Phi_s(t) + -G_d\left(-\dot{\Phi}_s(t)\right)$$

To approximate ideal current control

we adjusted R_{cc} so L_{cc}/R_{cc} of coil is fast.
We keep L_{cc} fixed and increase R_{cc}.
Studied L_{cc}/R_{cc} < 1ms and < 1 μs !
Each increase in R_{cc} required an increase in gain to match performance.
We obtain requested current $=V_{cc}/R_{cc}$ in ~ L_{cc}/R_{cc} sec

We also examine voltage control with actual external coil parameters, i.e.,

$L/R|_{cc(pairs)}$ = 39.2e-3H /3.92e-3Ω
= 10. s

VALEN RWM dispersion relation For ITER benchmark model with fast L/R<1 μs [approximates current control]

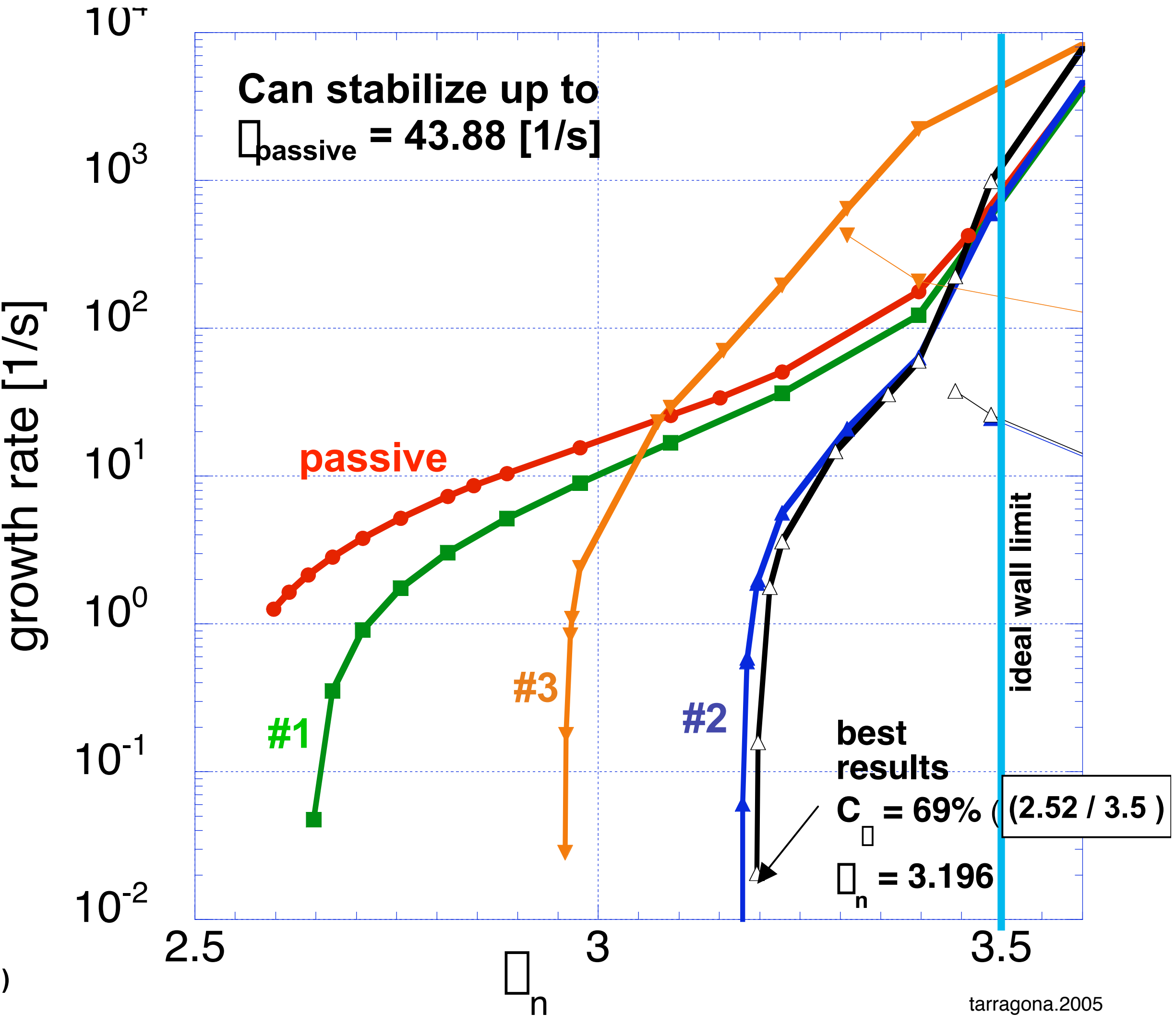
#1 $G_p=10^{12}$[v/w] (real)
@ 1 gauss
I_{cc}=0.518 KA

#2 $G_p=10^{13}$(complex c. pairs)
@ 1 gauss
I_{cc} = 5.18 KA

#3 $G_p=10^{14}$(complex c pairs)
@ 1 gauss
I_{cc} = 51.8 KA

Best results use
$G_p/G_d = 10^3$

(L/R = 16.8 μH/19.29 μΩ
= 0.87 μs for each coil)



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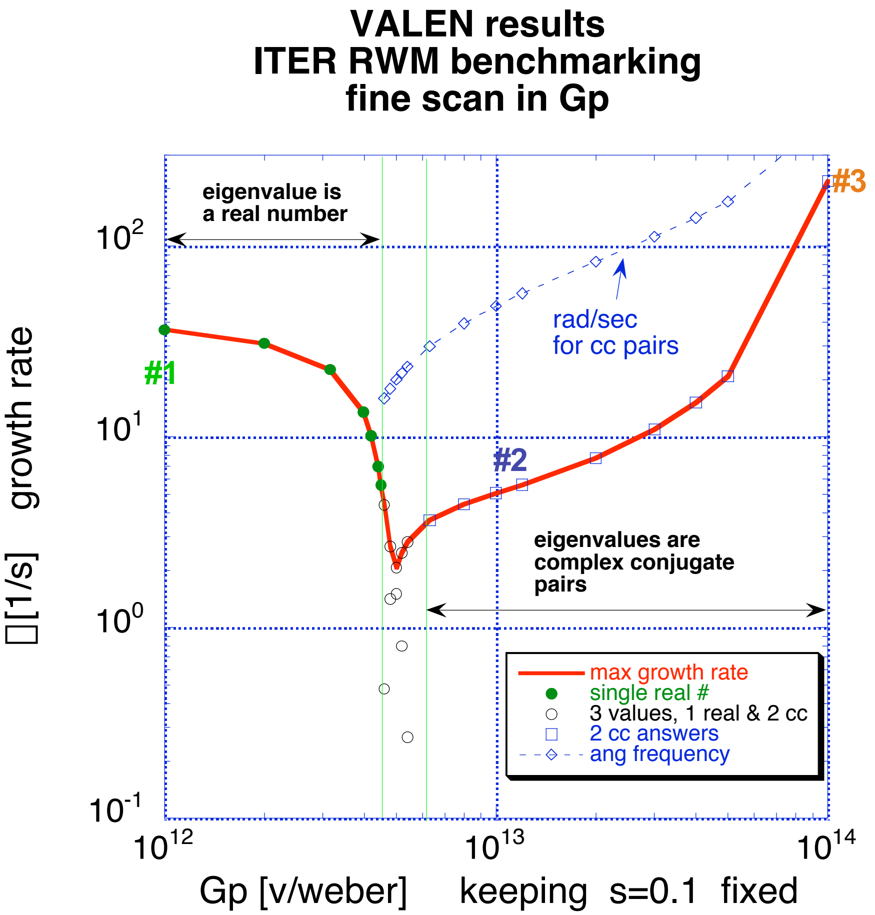
Investigate RWM feedback performance limits as gain applied to sensor flux & sensor voltage is varied

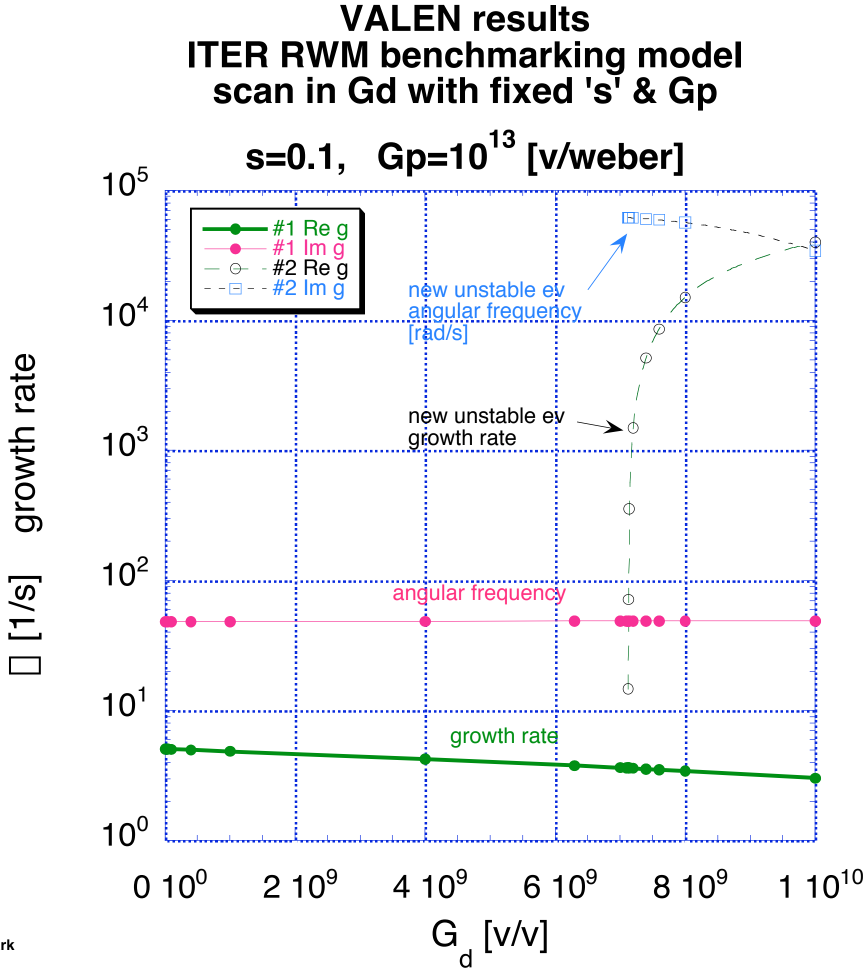
Look at β_n = 3.22, C_β = 72% (2.52 / 3.50), (or s=0.1)

Can not stabilize this growth rate ($\gamma_{passive}$ = 50.8 [1/s])



VALEN results
ITER RWM benchmarking
fine scan in Gp

ITER.s.beta.benchmark



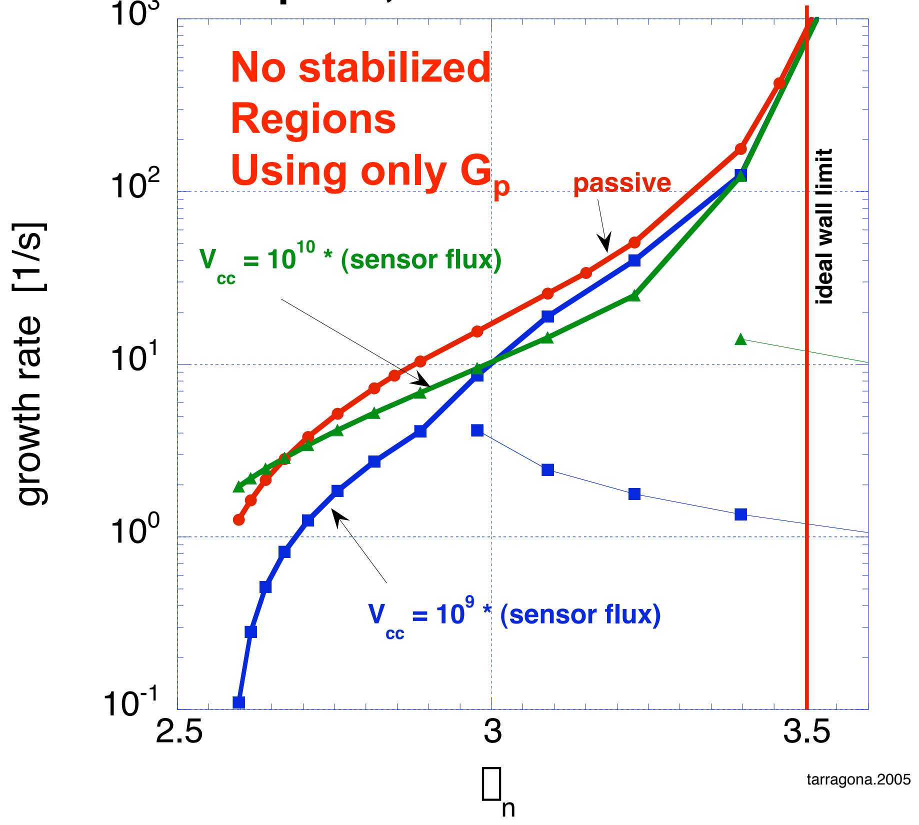
VALEN results
ITER RWM benchmarking model
scan in Gd with fixed 's' & Gp

s=0.1, Gp=10^{13} [v/weber]

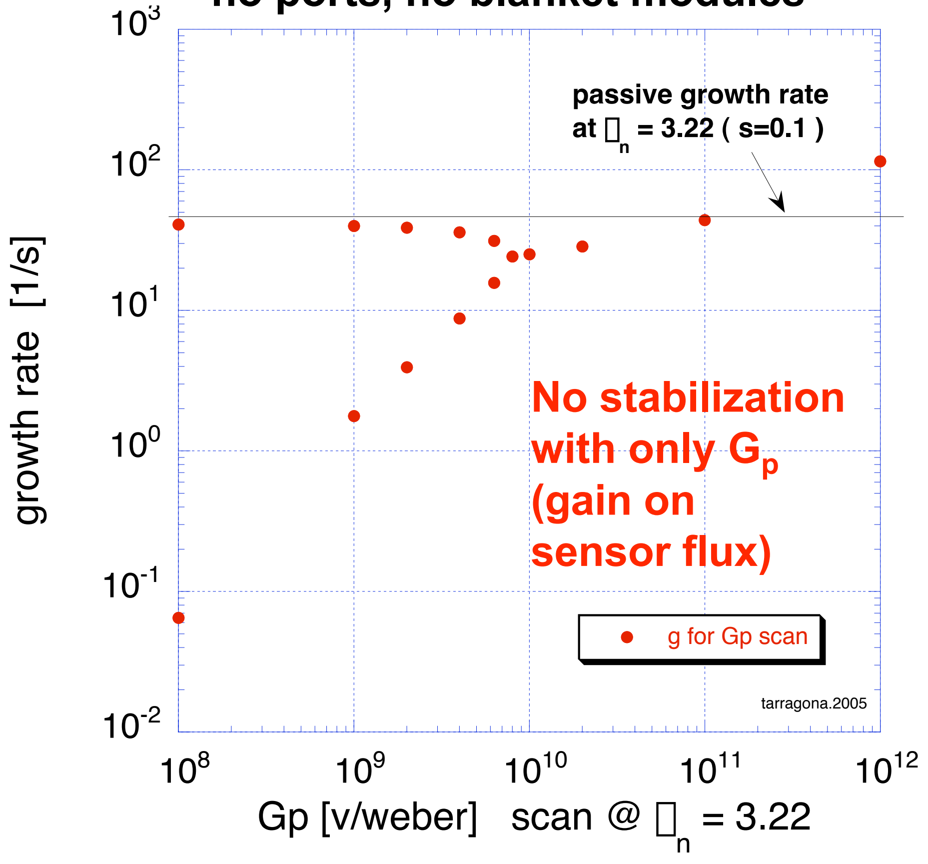
Performance with 6 external coils with **10 s time constants**
Can not stabilize RWM with only G_p[v/w] in ITER Baseline Design

V_{cc} = (gain * sensor flux)   still no blanket modules

only V_{cc} = sensor flux * gain
VALEN results voltage control
6 external coils with L/R = 10. s
no ports, no blanket modules



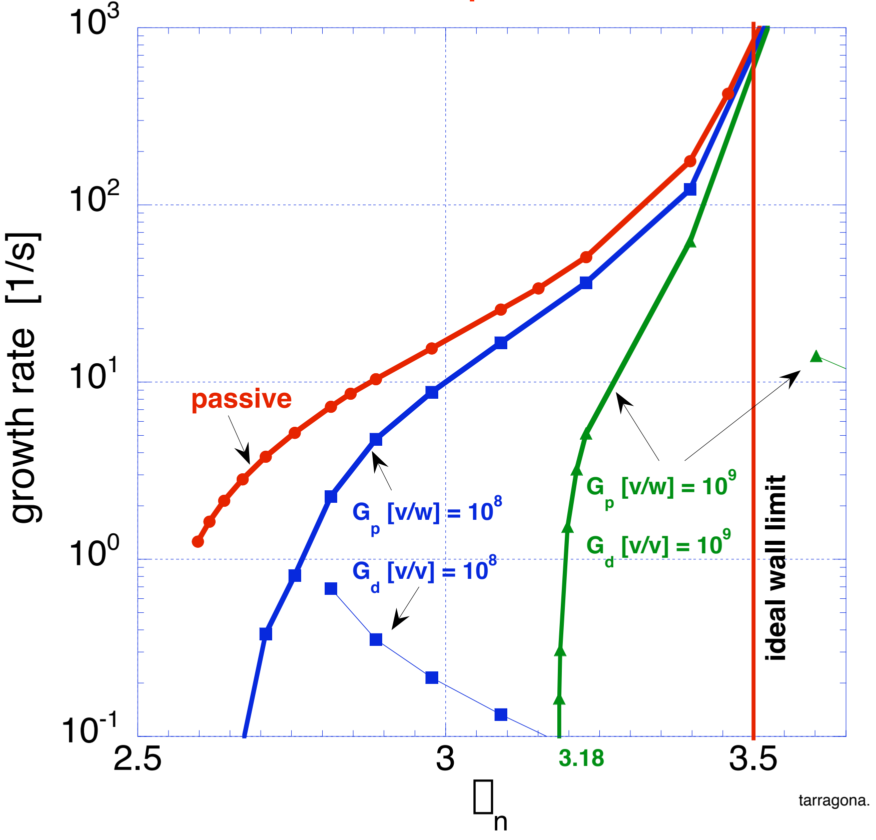
scan in G_p (proportional gain)
VALEN results voltage control
6 external coils with L/R = 10. S
no ports, no blanket modules



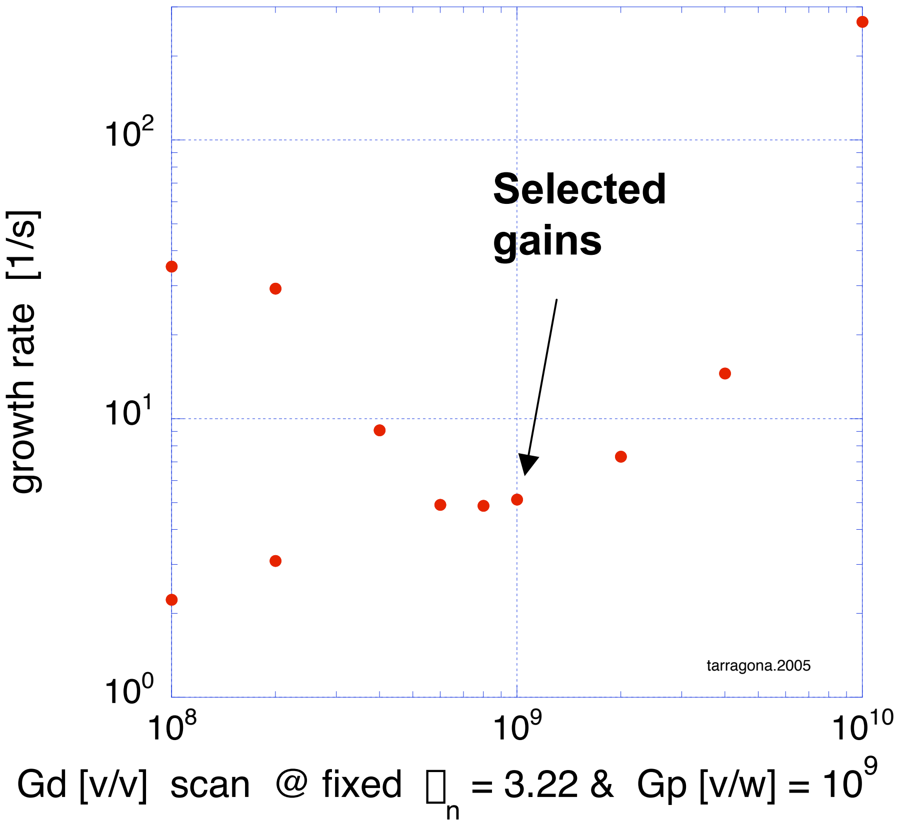
Performance with 6 external coils with 10 s time constants
Investigate combined G_p [v/w] & G_d [v/v] gain

$V_{cc} = G_p$ x(sensor flux) + G_d x(sensor voltage), still no blanket modules

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



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



Performance with 6 external coils with 10 s time constants
Same G_p & G_d, add blanket modules to model (no ports)

Recall ideal wall β_n limits

Gain settings:

$G_p = 10^9$ [v/w]

$G_d = 10^9$ [v/v]

Best $\beta_n = 3.177$

(with all blanket modules)

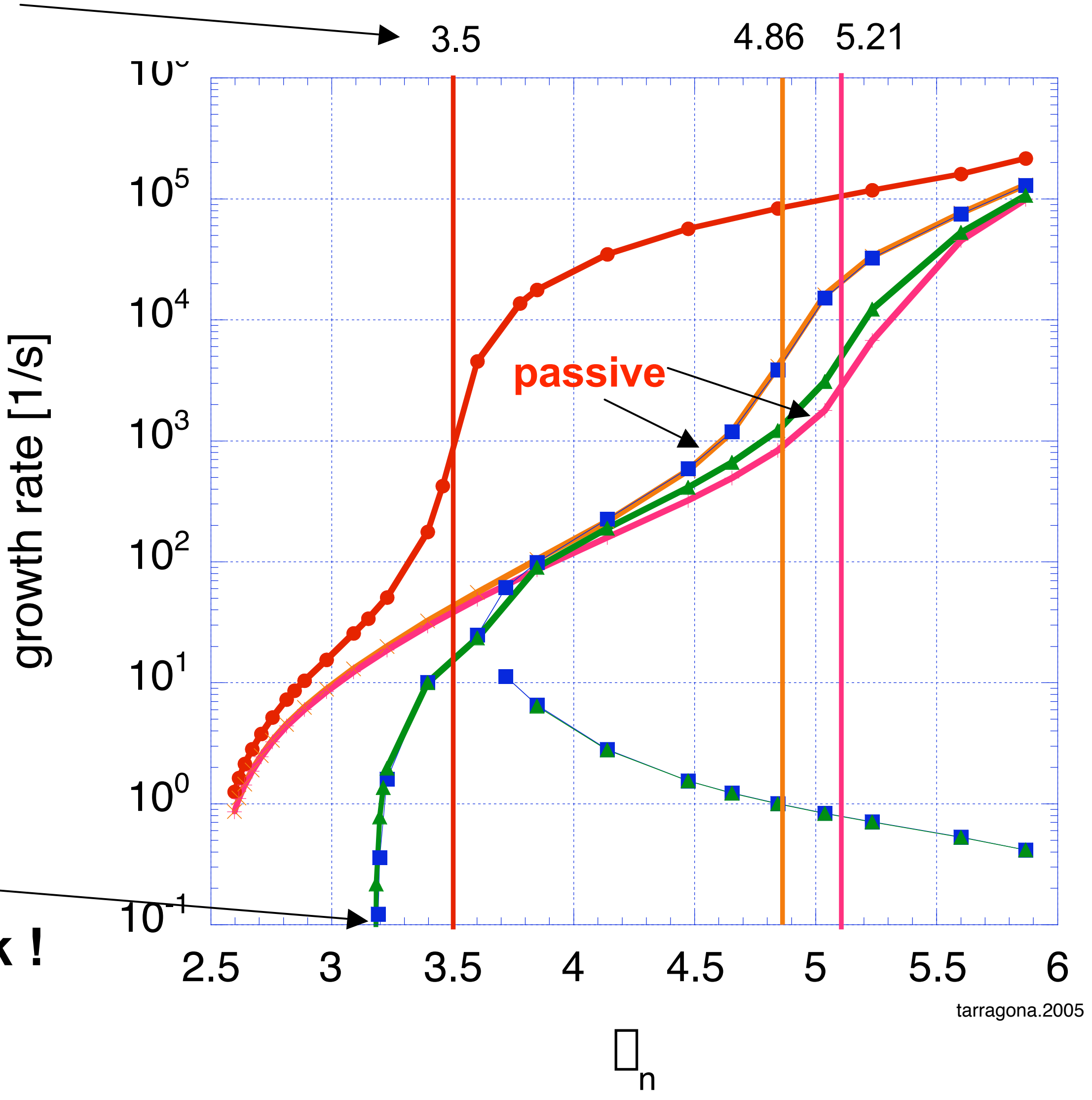
Best $\beta_n = 3.189$

(with blanket modules removed from mid plane ports)

Best

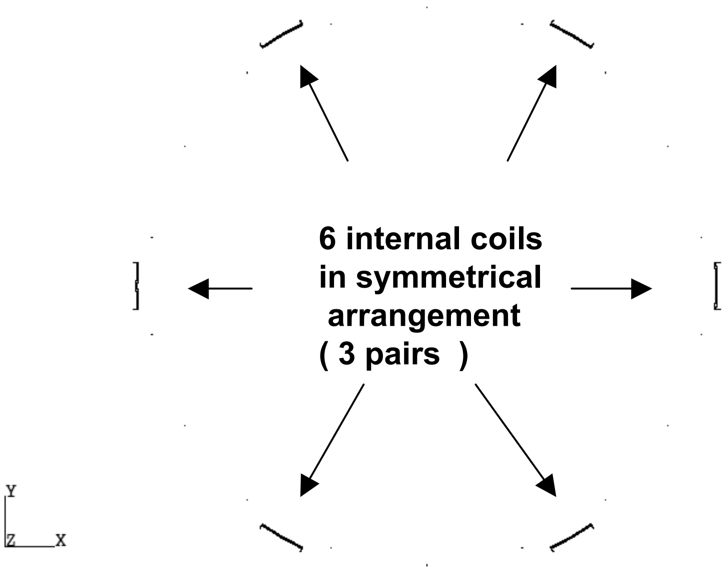
Results

About same as benchmark !

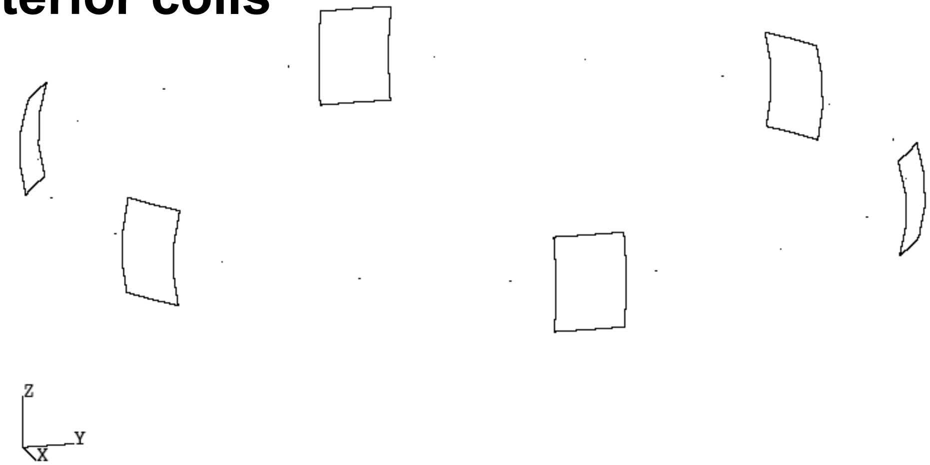


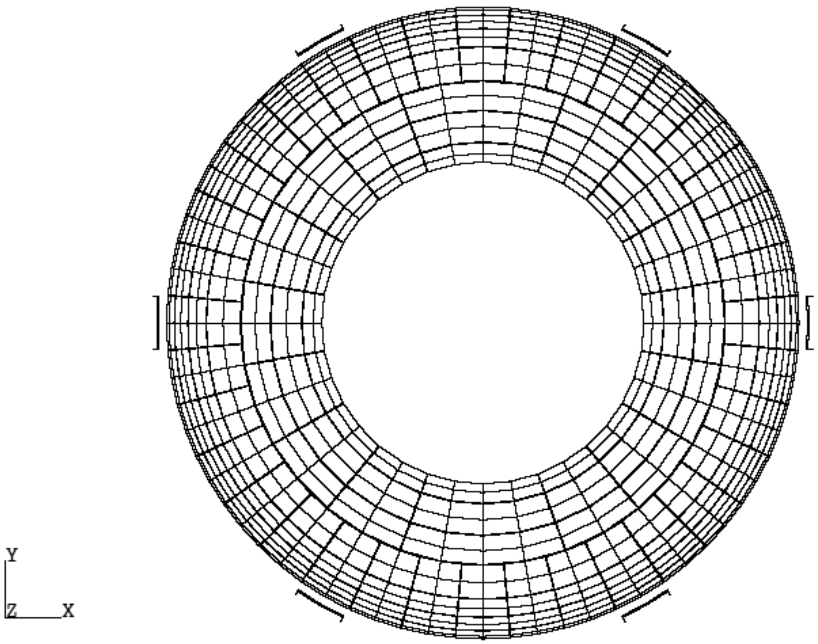
Extended ITER RWM analysis

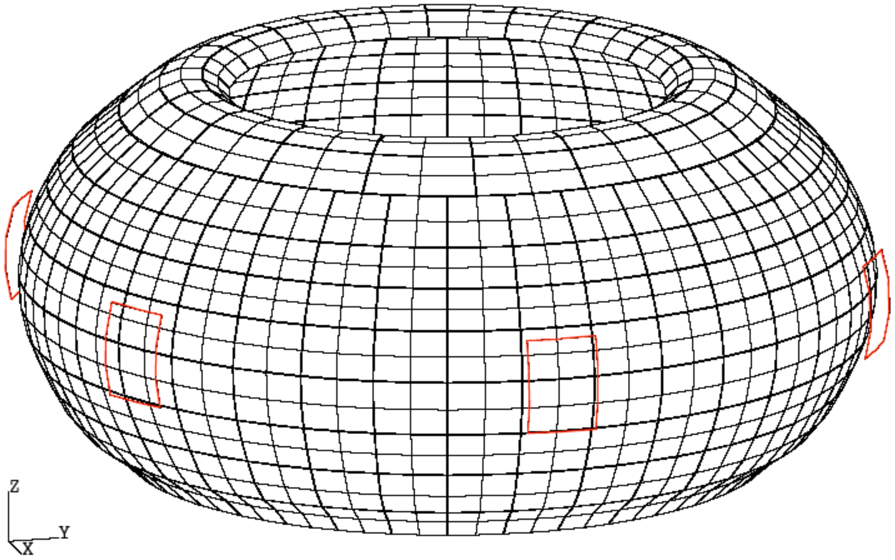
6 interior coils



6 internal coils
in symmetrical
arrangement
(3 pairs)



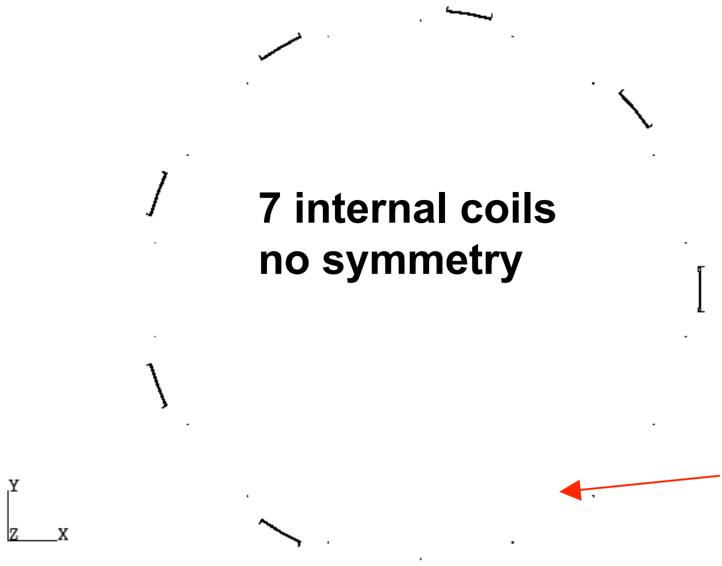




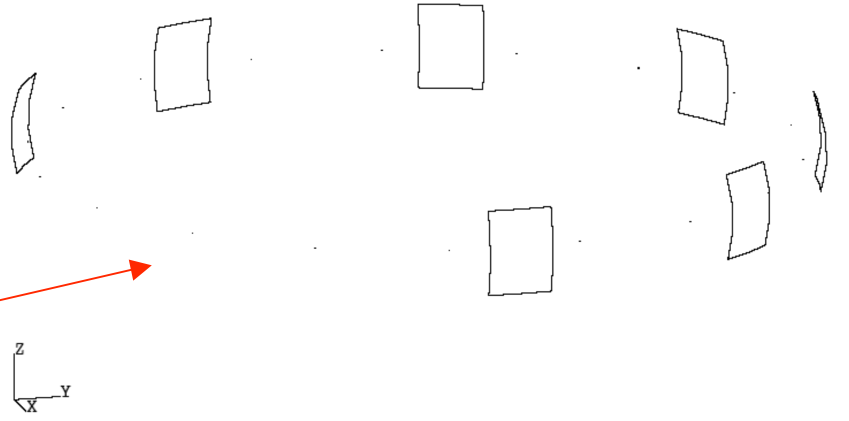
Blanket modules and
Interior RWM coils shown above

Extended ITER RWM analysis

7 internal coils

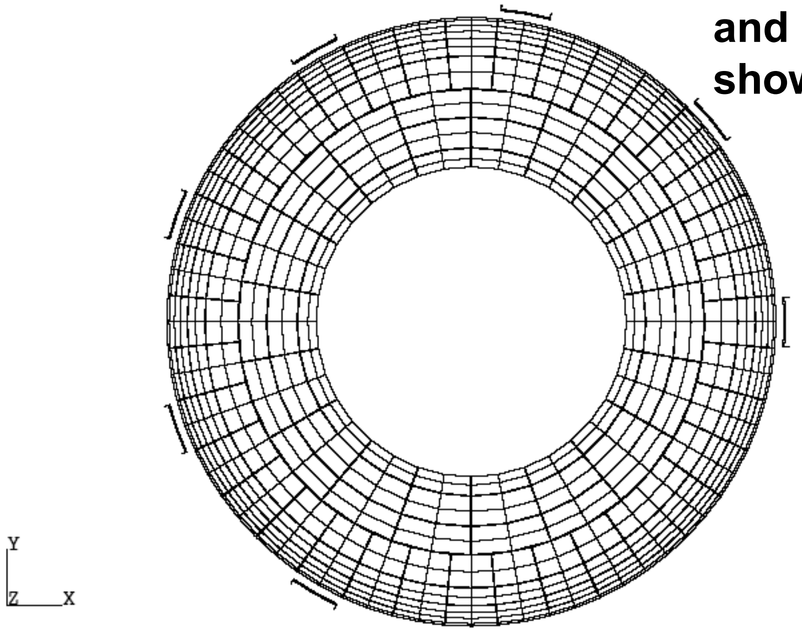


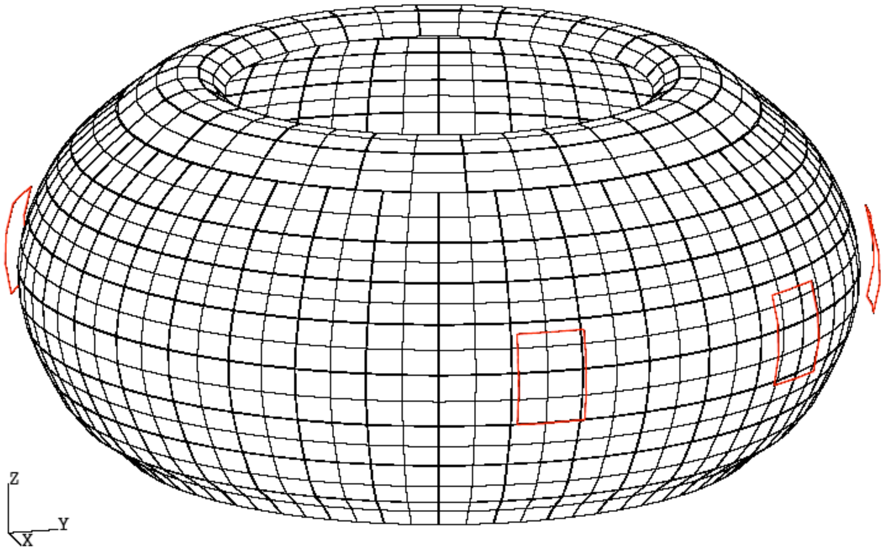
7 internal coils
no symmetry



Neutral beams here ?

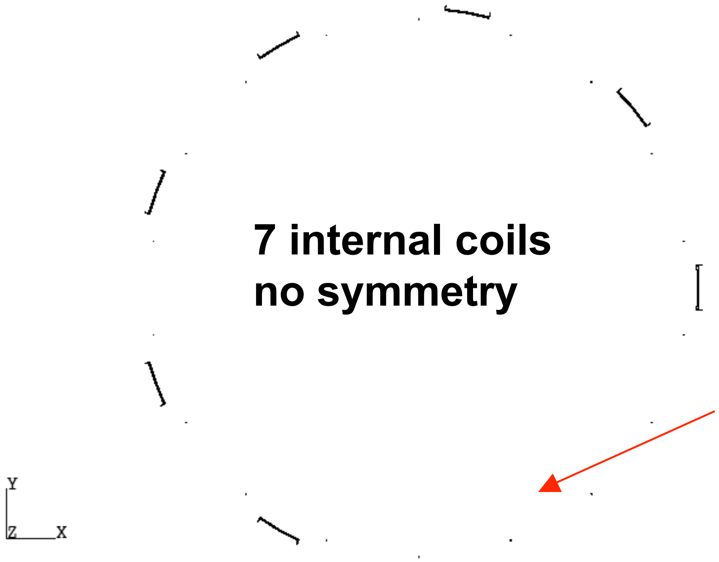
7 internal coils
and all blanket modules shown



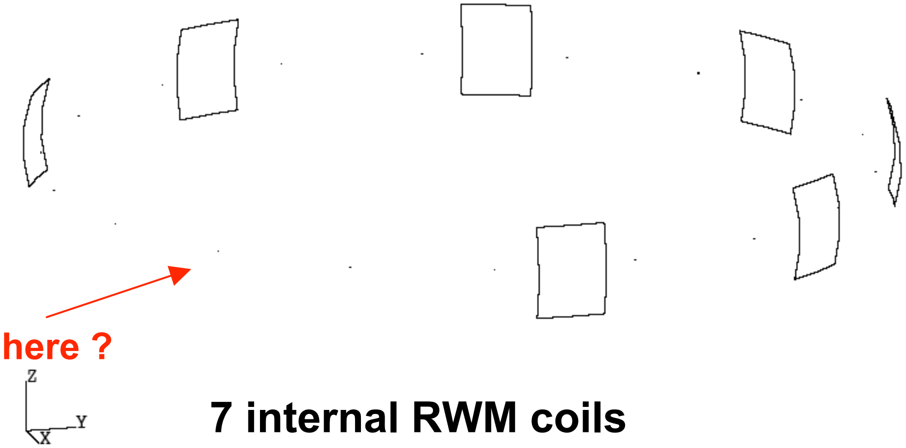


Extended ITER RWM analysis

Remove blanket modules at mid plane ports

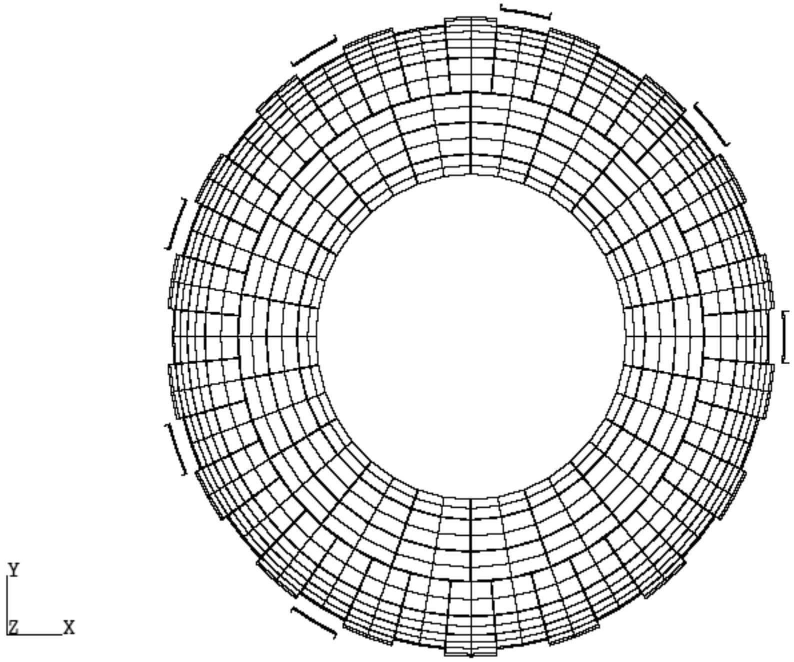


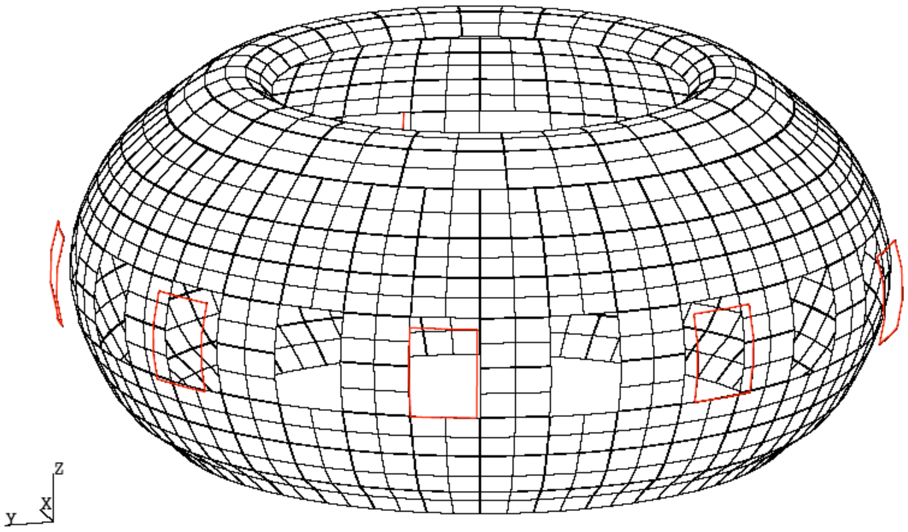
7 internal coils
no symmetry



Neutral
beams here ?

7 internal RWM coils
and blanket modules
shown, blanket modules removed
at all radial ports





Performance with 6 internal coils, **all blanket modules**
One coil in every third radial port (symmetrical)
Exceeds best performance with exterior coils

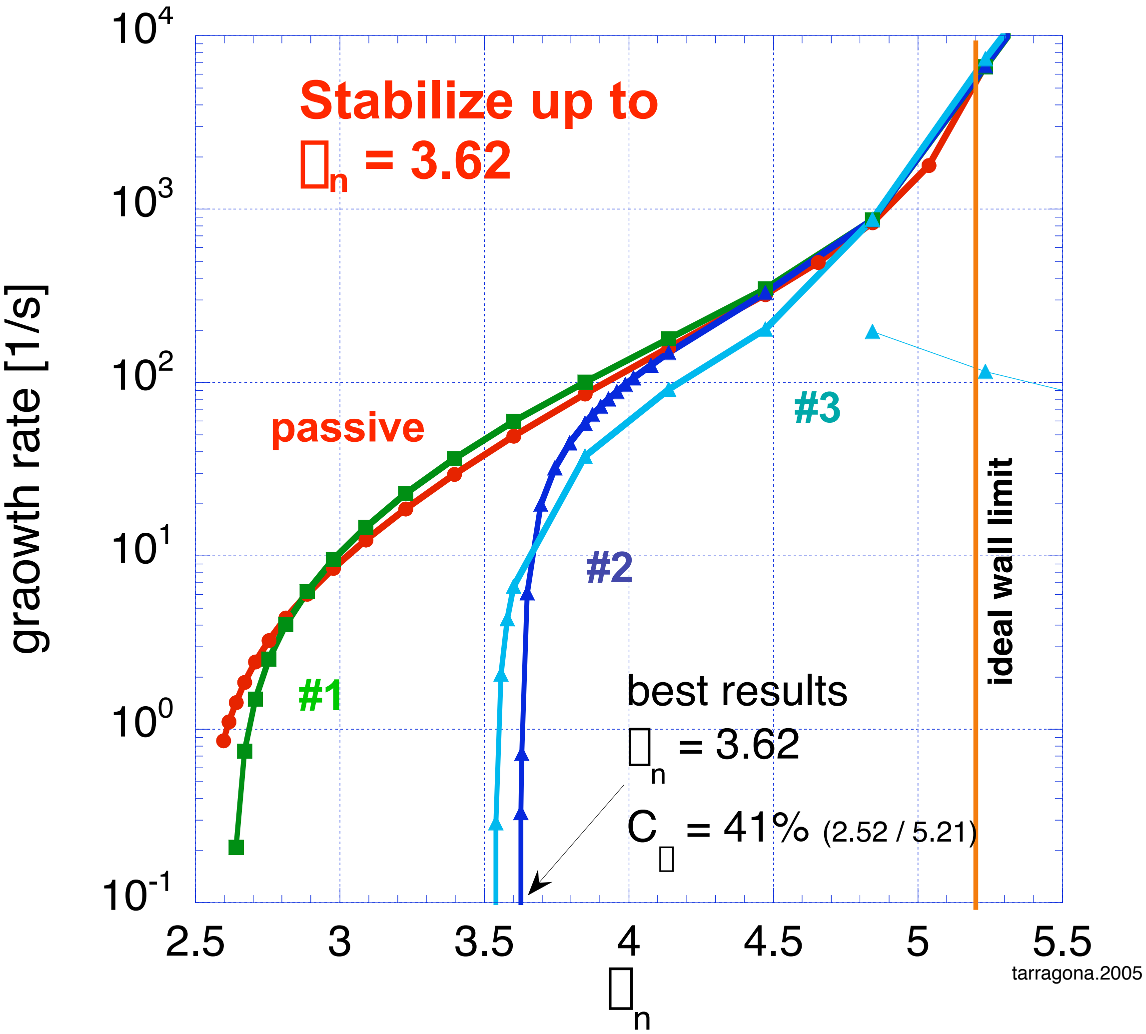
#1 $G_p=10^7$ [v/w]

#2 $G_p = 10^8$

#3 $G_p = 10^9$

6 internal coils connected Into 3 pairs Each pair has L/R = 7.2e-6 H /360.e-6 Ω = 20. ms

No optimization was done. Only G_p used !



Performance with 7 internal coils, again better than external coils, one coil every other radial port Has best performance with **all blanket modules**

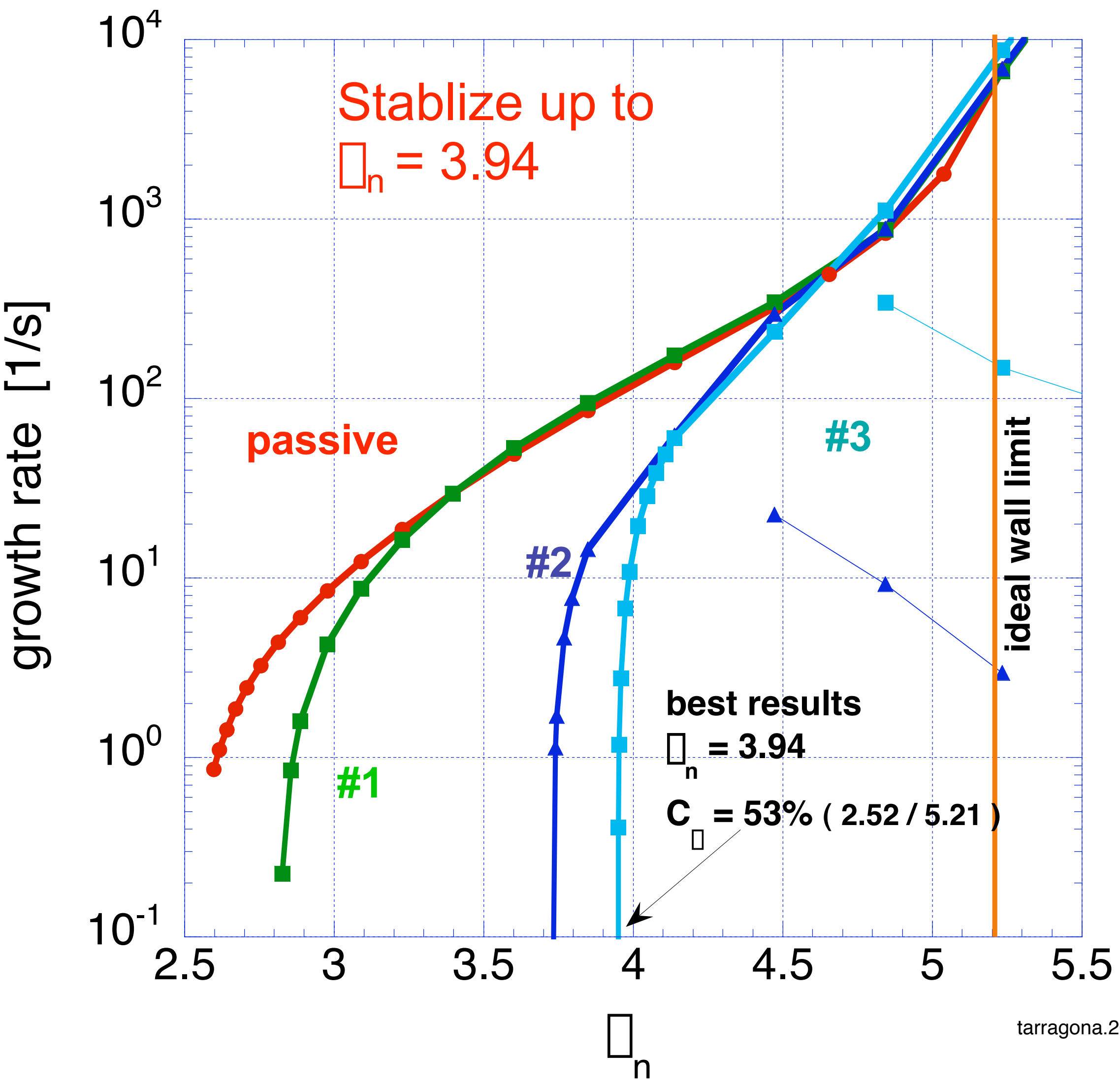
#1 $G_p=10^7$ [v/w]

#2 $G_p = 10^8$

#3 $G_p = 10^9$

7 single coils
Each coil has
L/R = 3.6e-6 H /180.e-6 Ω
= 20. ms

No optimization
was done.
Only G_p used !



Stablize up to $\beta_n = 3.94$

best results
$\beta_n = 3.94$
$C_\beta = 53\%$ (2.52 / 5.21)

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Removing blanket modules in front of internal coils Gives best of all cases $C_\beta = 98.7\%$ (2.52 / 4.86), 7 interior coils with one coil every other radial port

#1 $G_p=10^7$ [v/w]

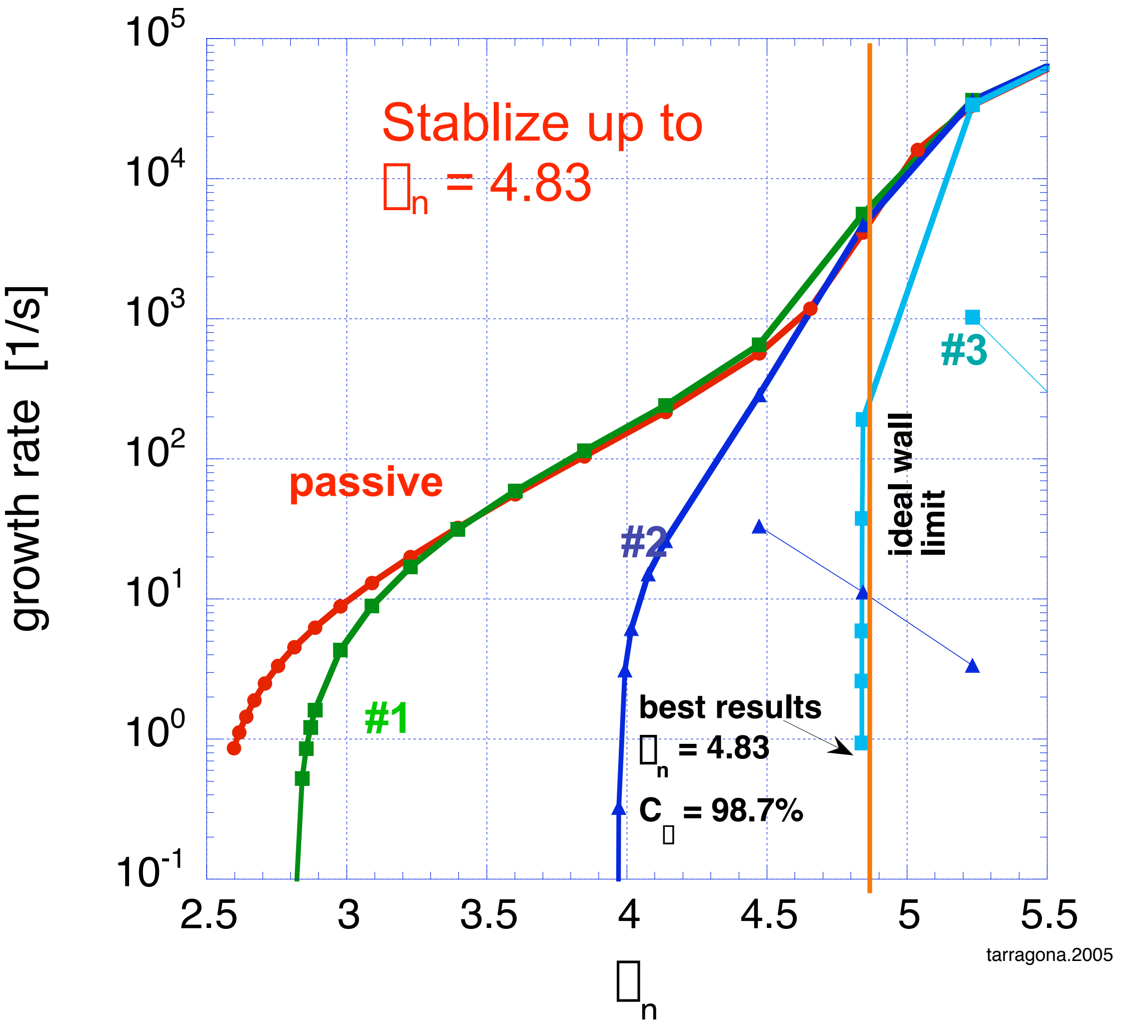
#2 $G_p = 10^8$

#3 $G_p = 10^9$

7 single coils each coil has L/R = 3.6e-6 H /180.e-6 Ω = 20. ms

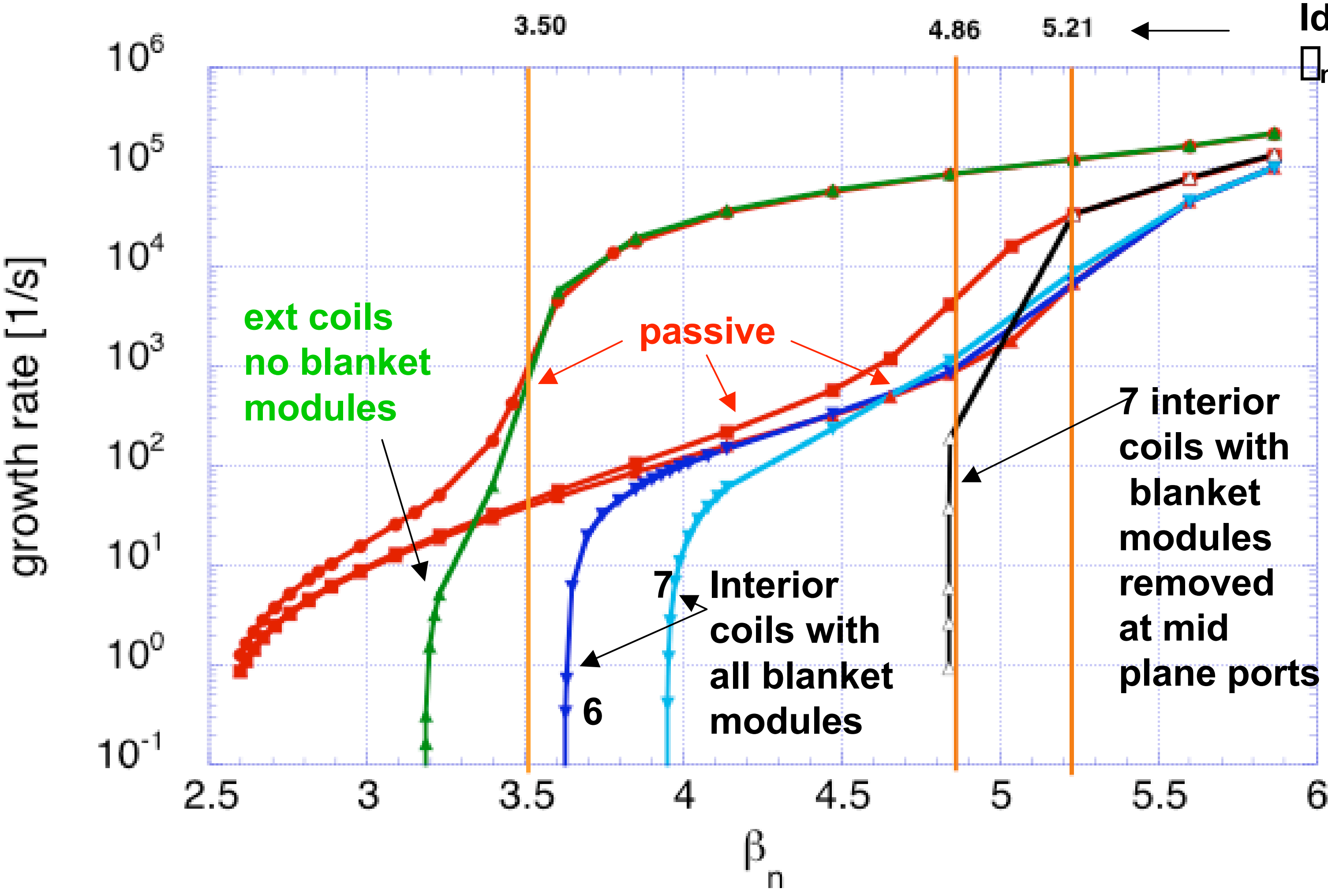
All blanket modules In front of radial ports were removed, this lowers passive performance

No optimization was done. Only G_p used !



Graphical summary VALEN RWM best results

Internal RWM coils perform significantly better than external RWM coils



Ideal wall β_n limits

ext coils no blanket modules

passive

7 interior coils with blanket modules removed at mid plane ports

Interior coils with all blanket modules

VALEN RWM active control performance limits in ITER

ports	blankets	RWM coils	$\square_n$	$C_\square$	$\square$[1/s] (passive)
no	no	continuous (benchmark)	3.196	69% (2.52 / 3.50)	43.9
no	no	6 ext. coils	3.18	67.6% (2.52 / 3.50)	40.9
no	9.ms	6 ext coils	3.177	24.4 % (2.52 / 5.21)	16.38
yes	9.ms	6 int. coils	3.62	41% (2.52 / 5.21)	52.5
yes	9.ms	7 int. coils	3.94	53% (2.52 / 5.21)	110.8
yes	9.ms*	7 int. coils	4.83	98.7% (2.52 / 4.86)	4061.

*(except at ports)

Conclusions VALEN benchmarking

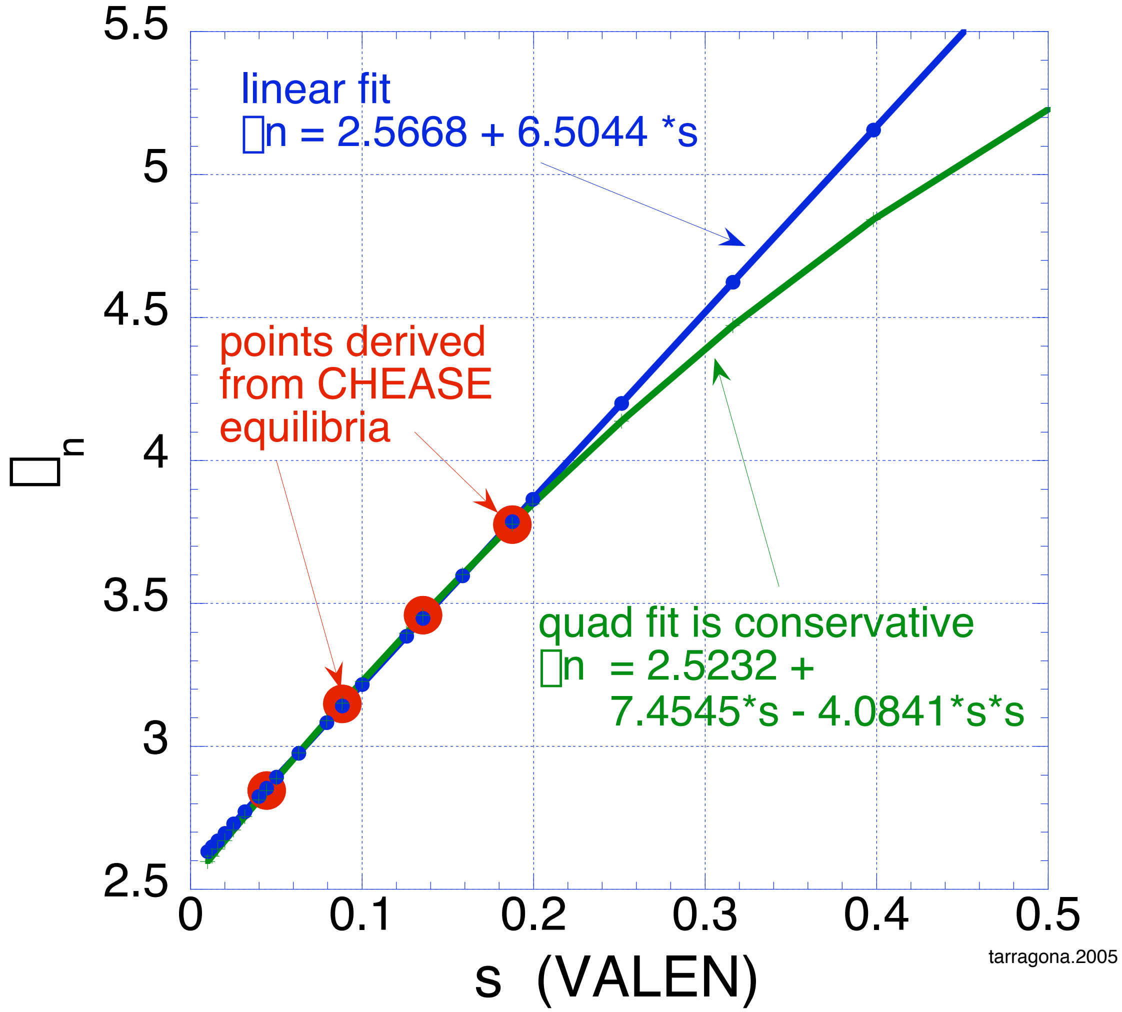
- VALEN RWM continuous coil benchmark model reaches $\beta_n = 3.196$ or $C_\beta = 69\%$ (2.52 / 3.50) [only the double wall vacuum vessel in this model].
- Presence of all blanket modules (9 ms each) extend the ideal β_n limit from 3.50 to 5.21
- ITER baseline design (no blankets, 6 ext coils with L/R =10. s & voltage control) requires both G_p & G_d (sensor flux and sensor voltage) gain, this model has about same performance as continuous coil benchmark model
- Extended ITER models with internal RWM coils performs significantly better than baseline ITER design: $\beta_n = 3.94$ with all blanket modules and $\beta_n = 4.83$ with blanket modules removed on mid plane radial ports

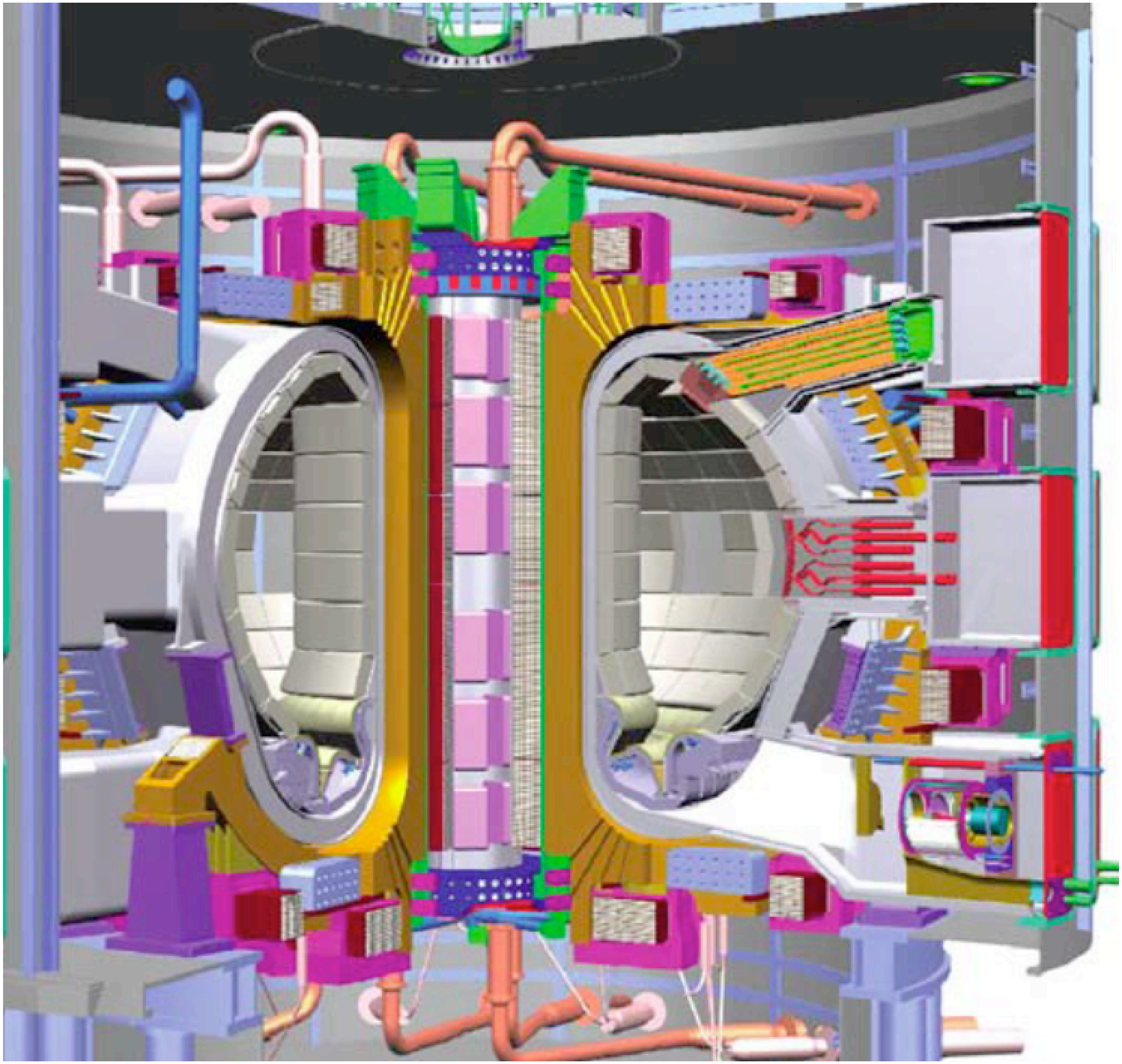
Mapping from s to β_n

VALEN parameter $s = -\Delta W / (LI^2/2)$

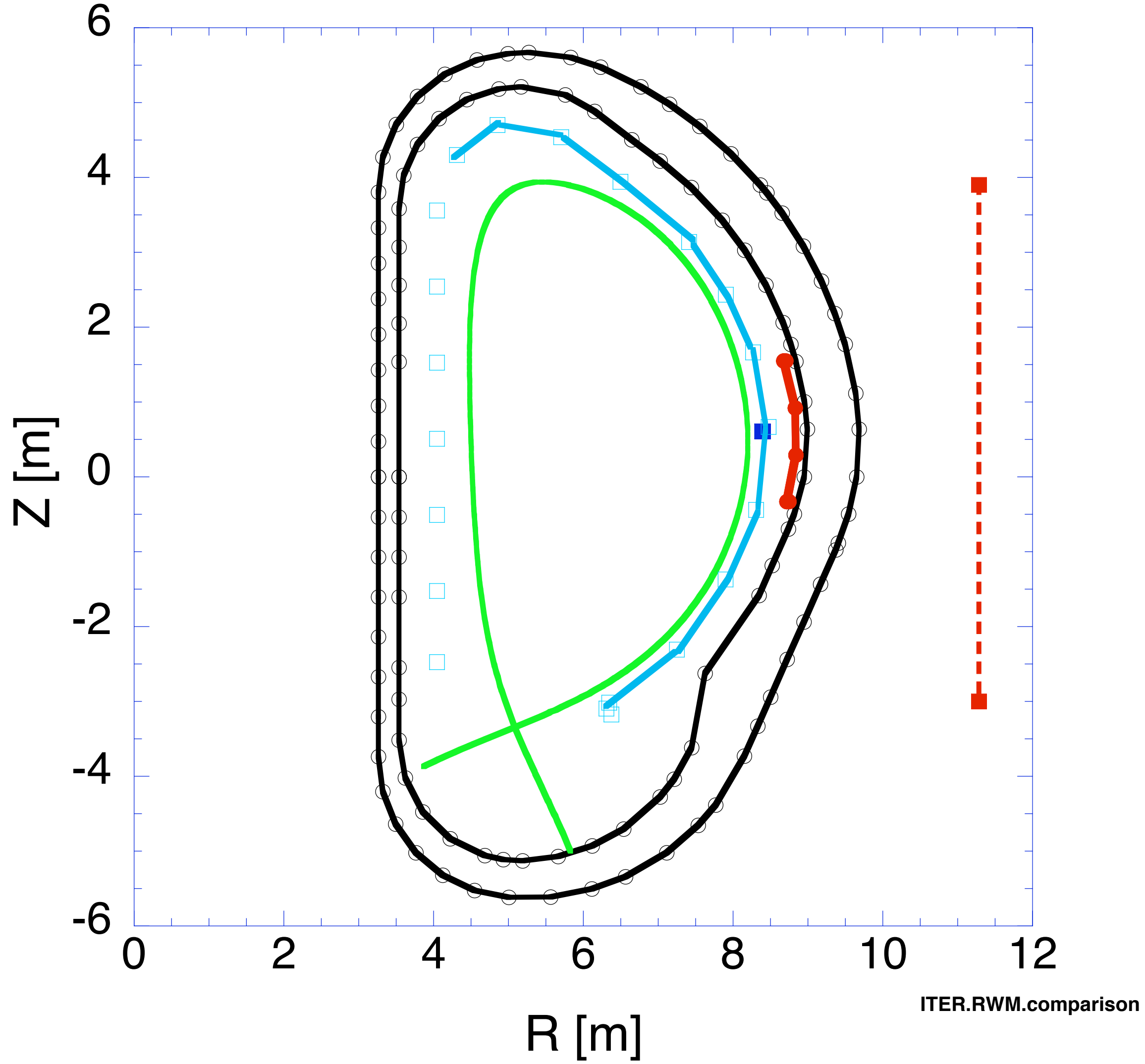
no wall β_n limit = 2.52 from conservative fit

Here $LI^2/2$ is
the energy
of the current
distribution that
produces B_n

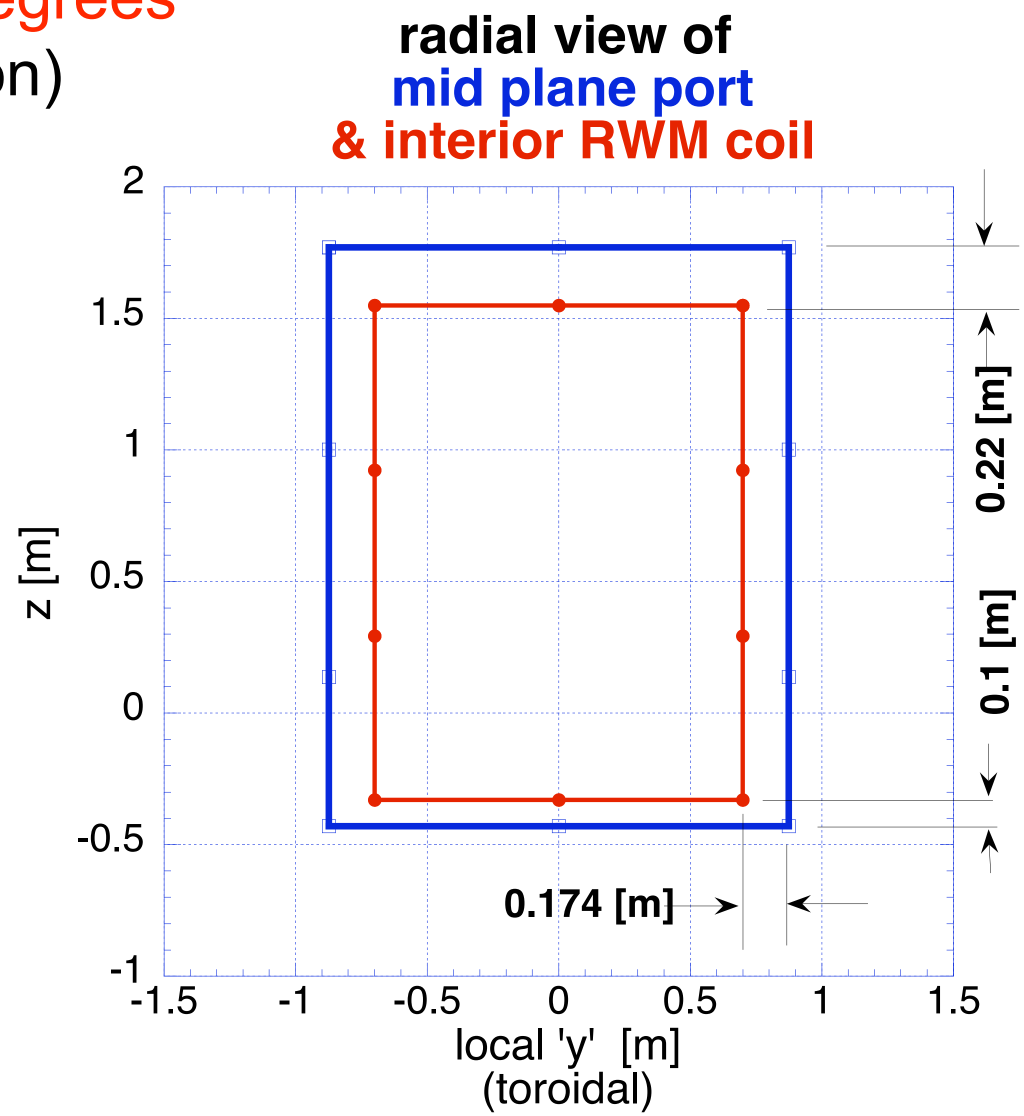


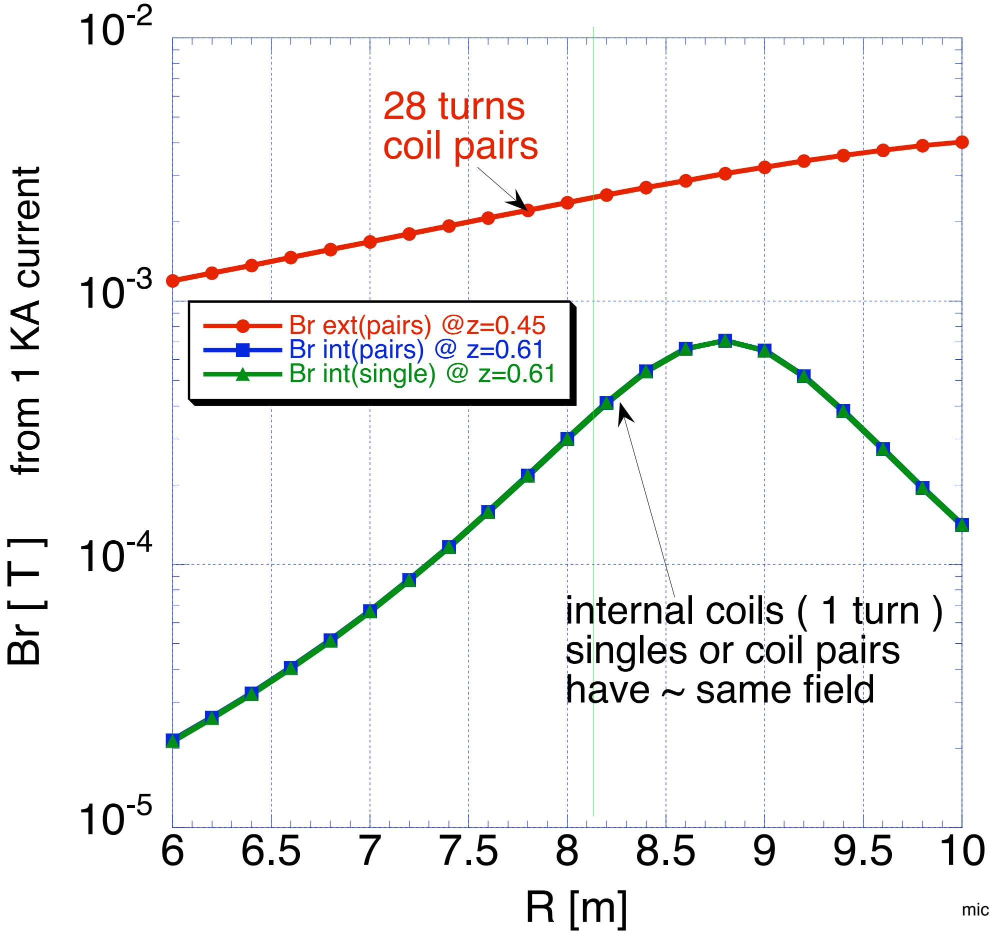


ITER RWM benchmarking
plasma, walls, control coils, blanket modules, & Bp sensors



each internal RWM coil covers 9.05 degrees (in toroidal direction)





28 turns
coil pairs

internal coils (1 turn)
singles or coil pairs
have ~ same field

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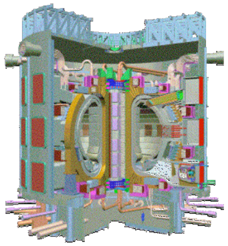
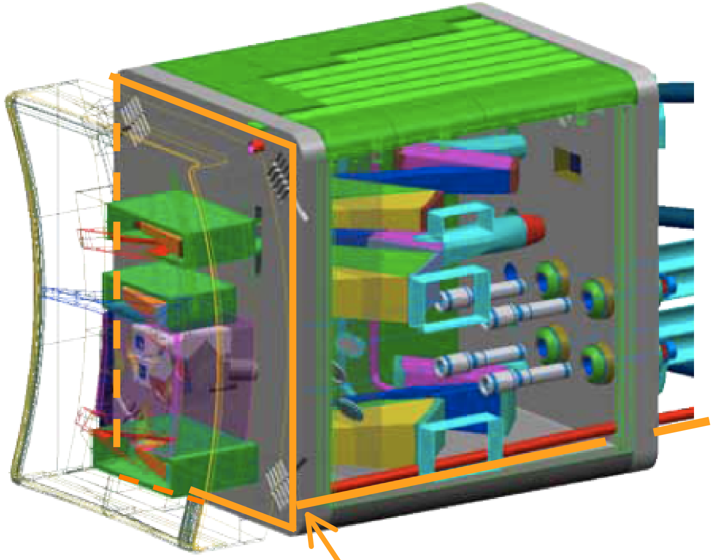
Applying FIRE-Like RWM Feedback Coils to ITER Increases β limit for n = 1 from β_N = 2.5 to ~4

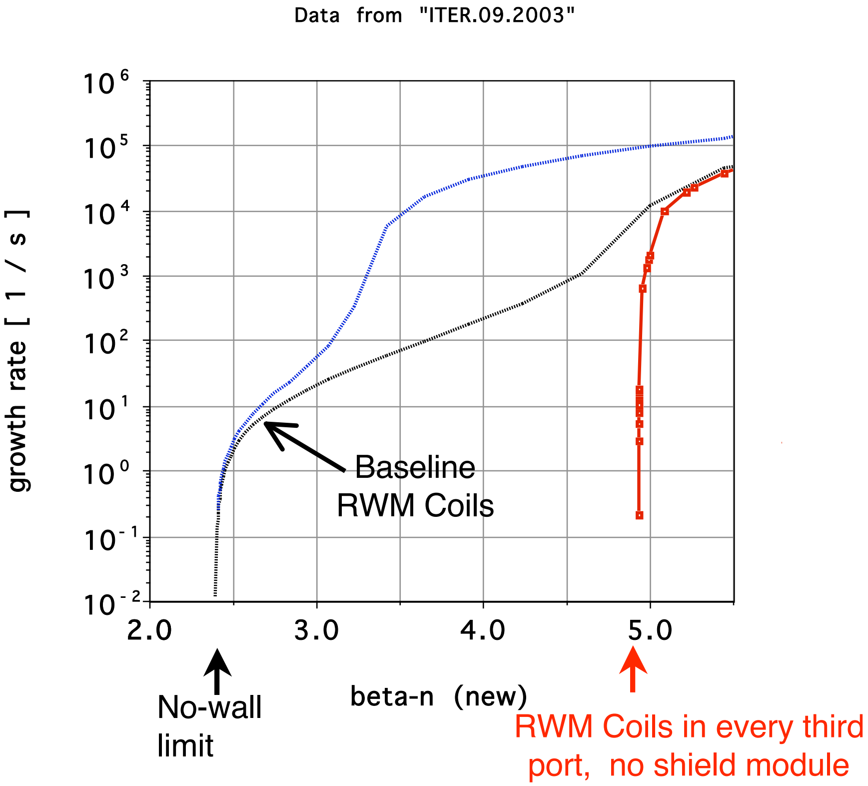


G. Navratil, J. Bialek Columbia University

VALEN Analysis Columbia University

RWM Coil Concept for ITER





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

FIRE-like RWM coils would have large stabilizing effect on n=1

- Integration and Engineering feasibility of internal RWM coils is under study.

FIRE and ITER First Wall Design Concepts are Similar

Outboard First Wall for FIRE

Prad = 0.5 MW/m^2

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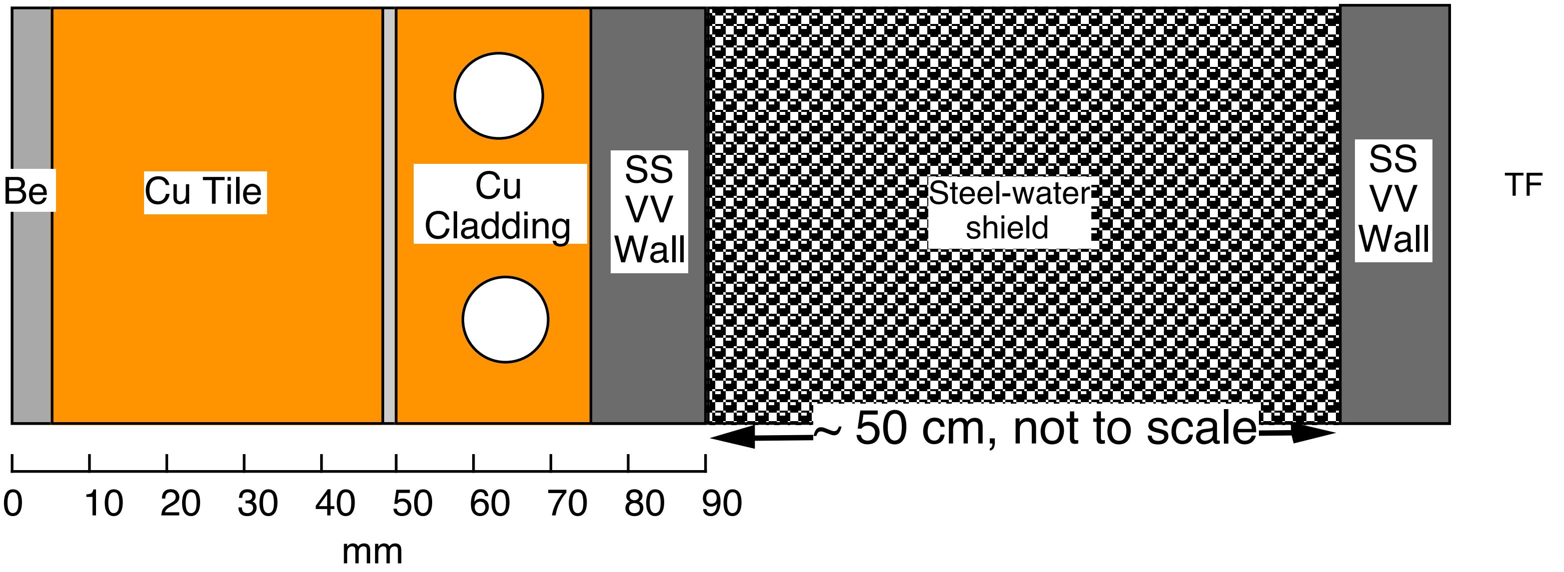
Γn = 2.2 MW/m^2

60 s

inertial

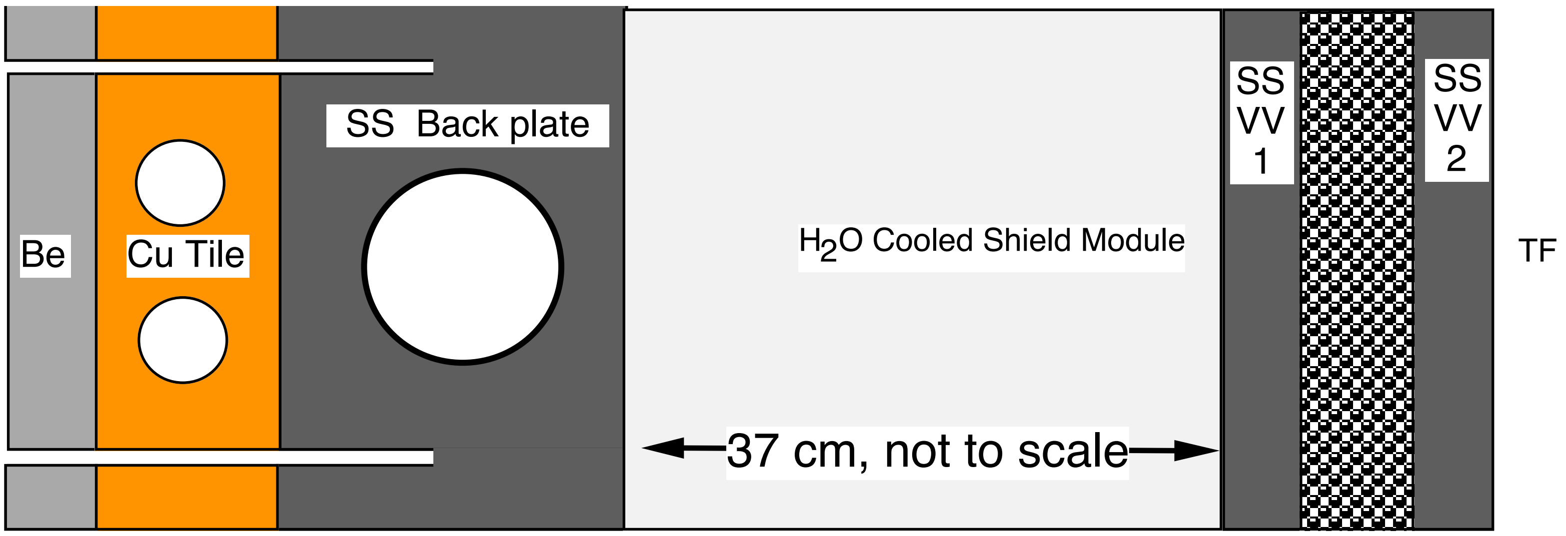


Prad = 0.5 MW/m^2

\+

Γn = 0.5 MW/m^2

steady-state



ITER First Wall Panel