NSTX

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Results and Advances in VALEN Resistive Wall Mode Modeling

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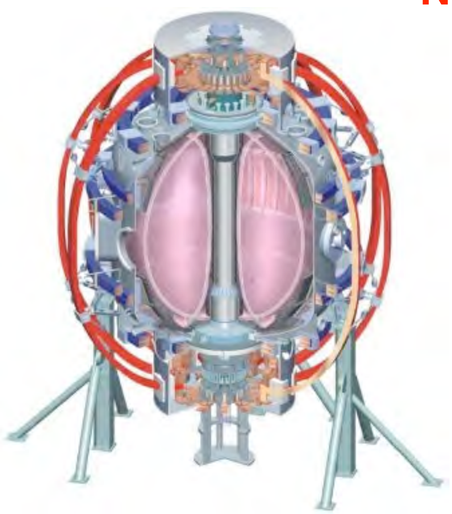

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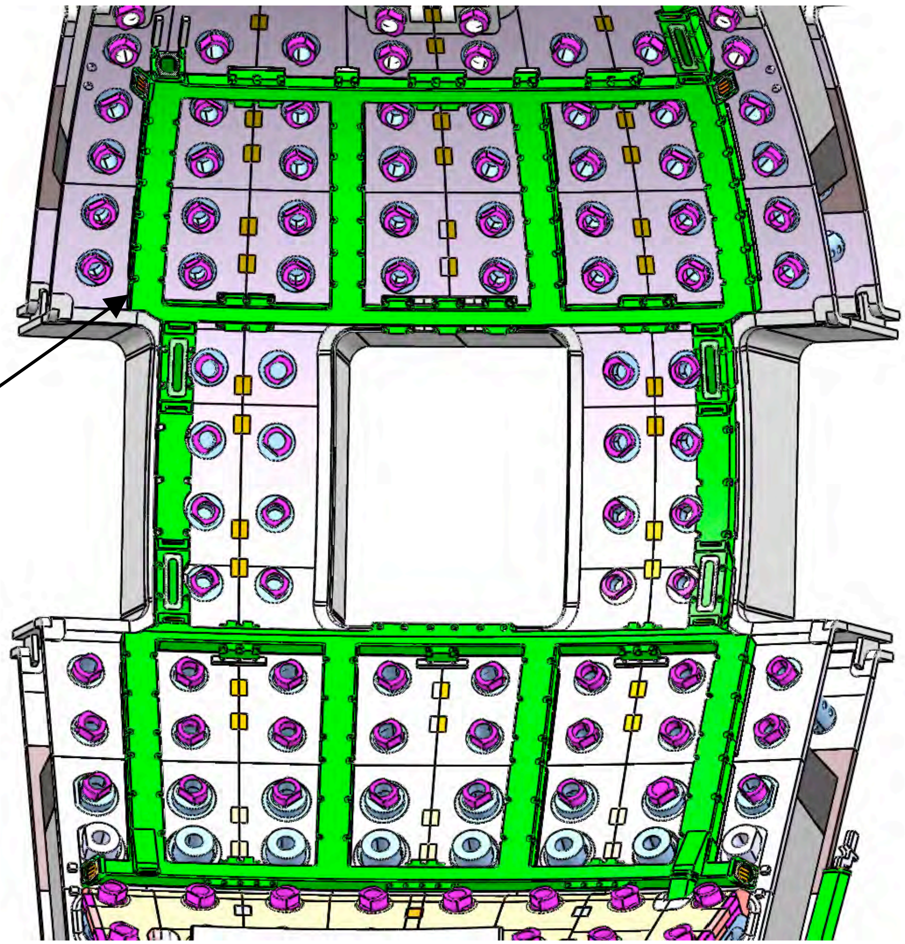
Abstract

- RWM code VALEN now has two versions: a single unstable mode and a new multi-mode version. Results are presented from the single-mode version for the ITER 'VAC-02' internal coil design. It was found that ITER scenario 4 may be stabilized up to β_n of 3.8, well above the no wall beta limit of 2.5 with modest power and current requirements. The single mode version of VALEN was also used to analyze upgrades to the RWM control system in NSTX. The new multi-mode version of VALEN allows the inclusion of multiple plasma modes, both stable and unstable for multiple values of toroidal mode number. We present the multi-mode formulation and results from the multi-mode VALEN code for HBT-EP and NSTX.

Description of Internal coils added to ITER design for ELM suppression and RWM control

- *ITER VAC02 design consists of <u>27 internal coils</u>. Connections among coils provide two complete poloidal coils for vertical control*
- *ITER VAC02 design has all coils inside metal jackets, coils are located between blanket modules and vacuum vessel inner wall*

ITER VAC02 design (40^o sector)

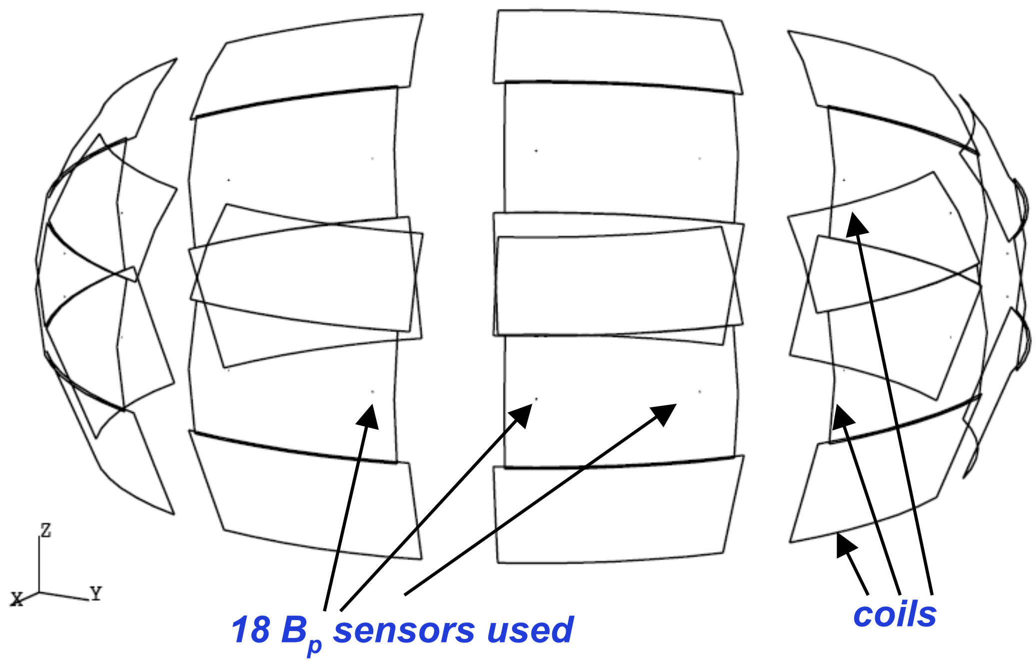


- *3 coils shown, 9 repetitions*

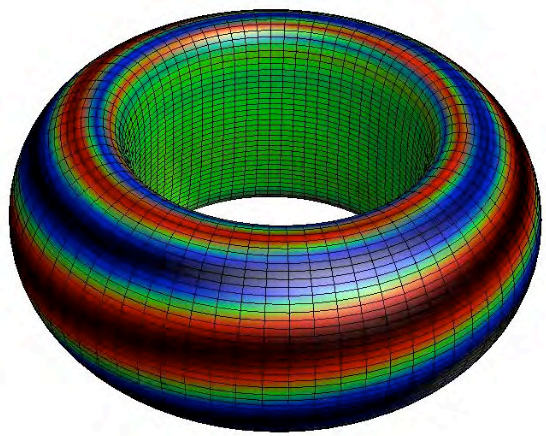
Model of ITER VAC-02 includes coils, outboard blanket modules, double wall vacuum vessel

- *ITER VAC02 design (40º sector)*

- *VALEN model of all VAC02 coils*
- *Metal jackets not yet modeled*
- *Magnetic sensors*

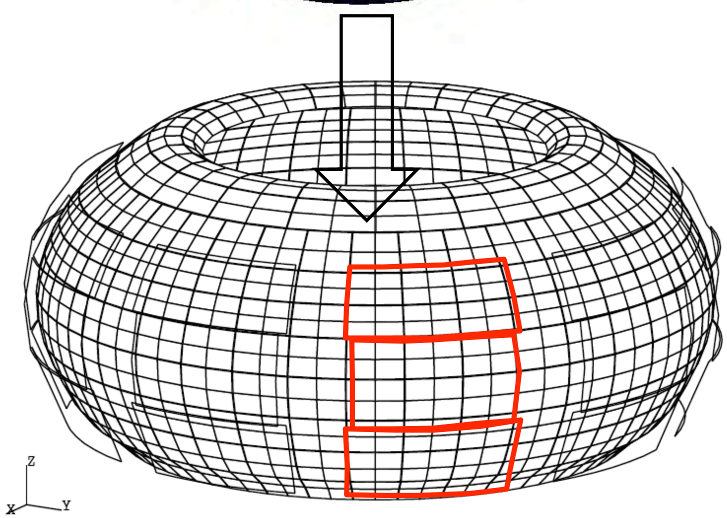


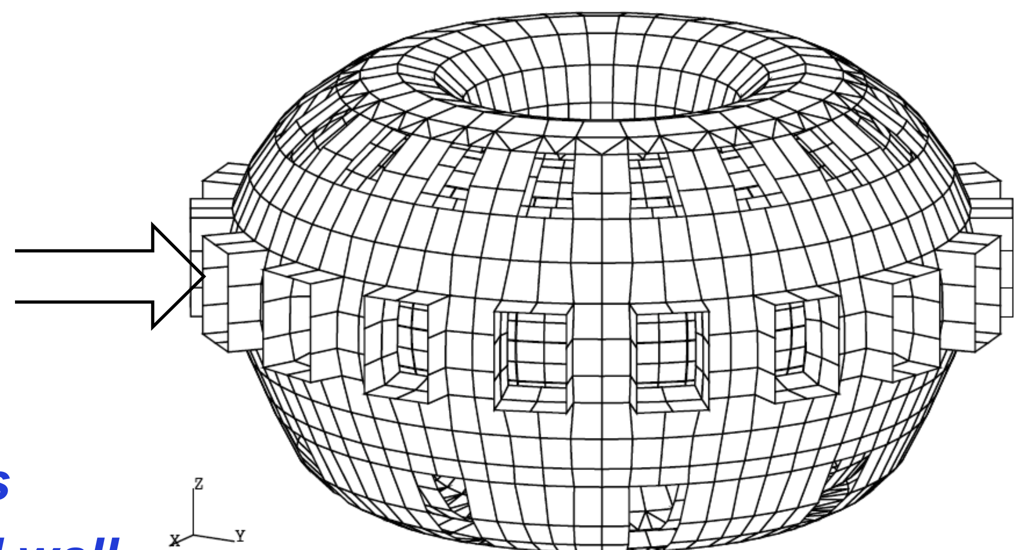
Complete VALEN 3-D model of ITER VAC-02



VALEN models unstable n=1 ITER Scenario 4 mode (from DCON) as a lumped circuit

VALEN complete model combines plasma mode, passive structure, coils and sensors





model of coils and blankets

coils between blankets and wall

each blanket module has 9 ms τ

model of double wall VV

Simple voltage feedback scheme used on n=1 RWM for ITER VAC-02 configuration

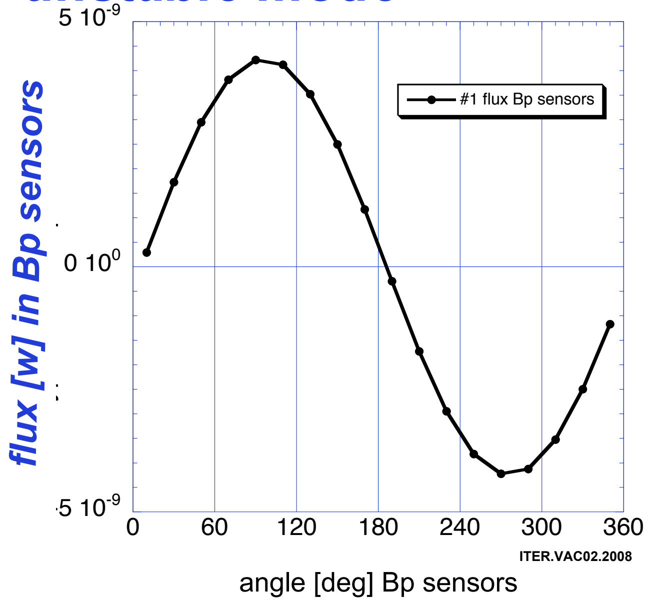
$$V_{coil} = G * phase * \Phi_{sensors}$$

Voltage applied to coil is gain * (sensor flux)

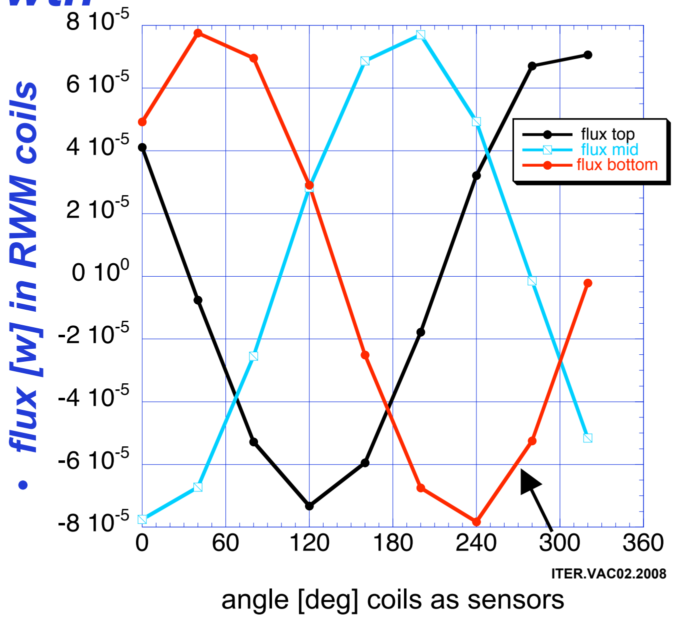
Units of gain = [V/weber]

Unit of flux = [weber]=[v*s]

typical signals in Bp sensors during passive growth of unstable mode



phasing of feedback coil currents determined by flux during passive growth



VALEN ITER VAC-02 results, simple feedback system can stabilize to β_n=3.827, C_β = 48%

best performance with feedback ***was found by considering different coil combinations and a scan in the value of feedback gain.***

best results found with a combination of top and bottom coils (18 / 27 total), ***middle coil system not used for best results***

Ideal wall limit = 5.22 with blankets

Gp=0.8*10^8 [v/w] found to be best gain setting,

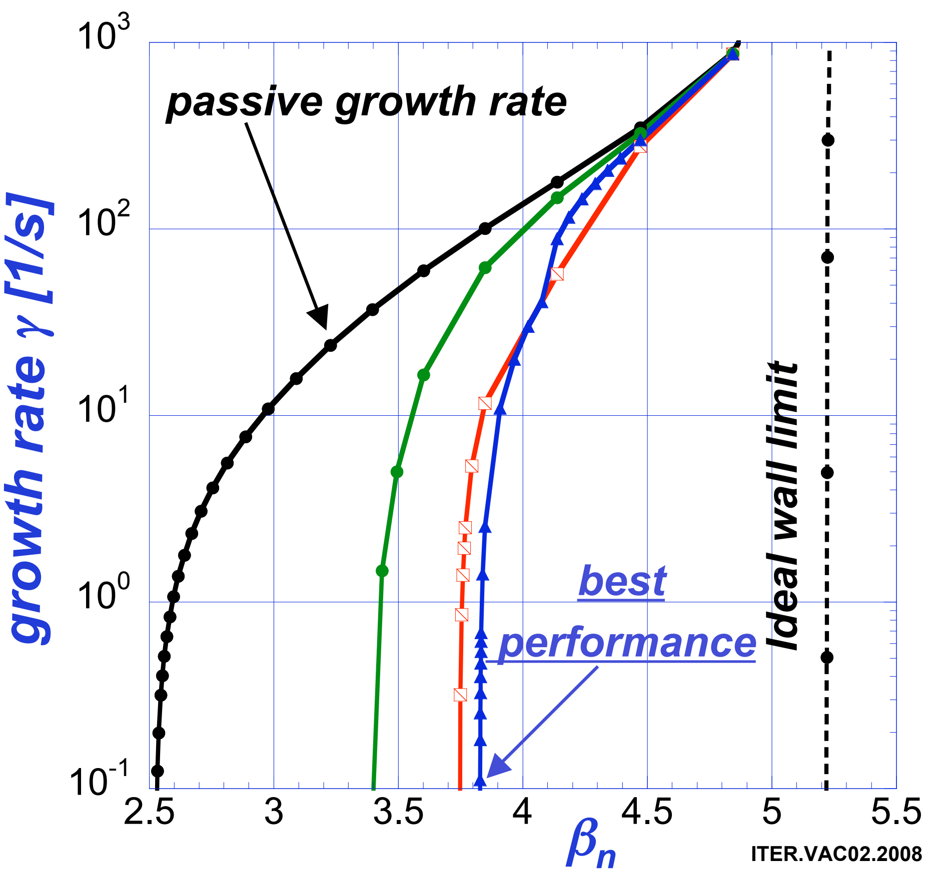
(sensors were 10^{-4} [m^2] in area, I.e., read a gauss, apply a maximum of 0.8 v to any RWM coil)

best performance with feedback

all 27 coils, β_n=3.74, C_β = 45%

only middle coils, β_n=3.39, C_β=32%

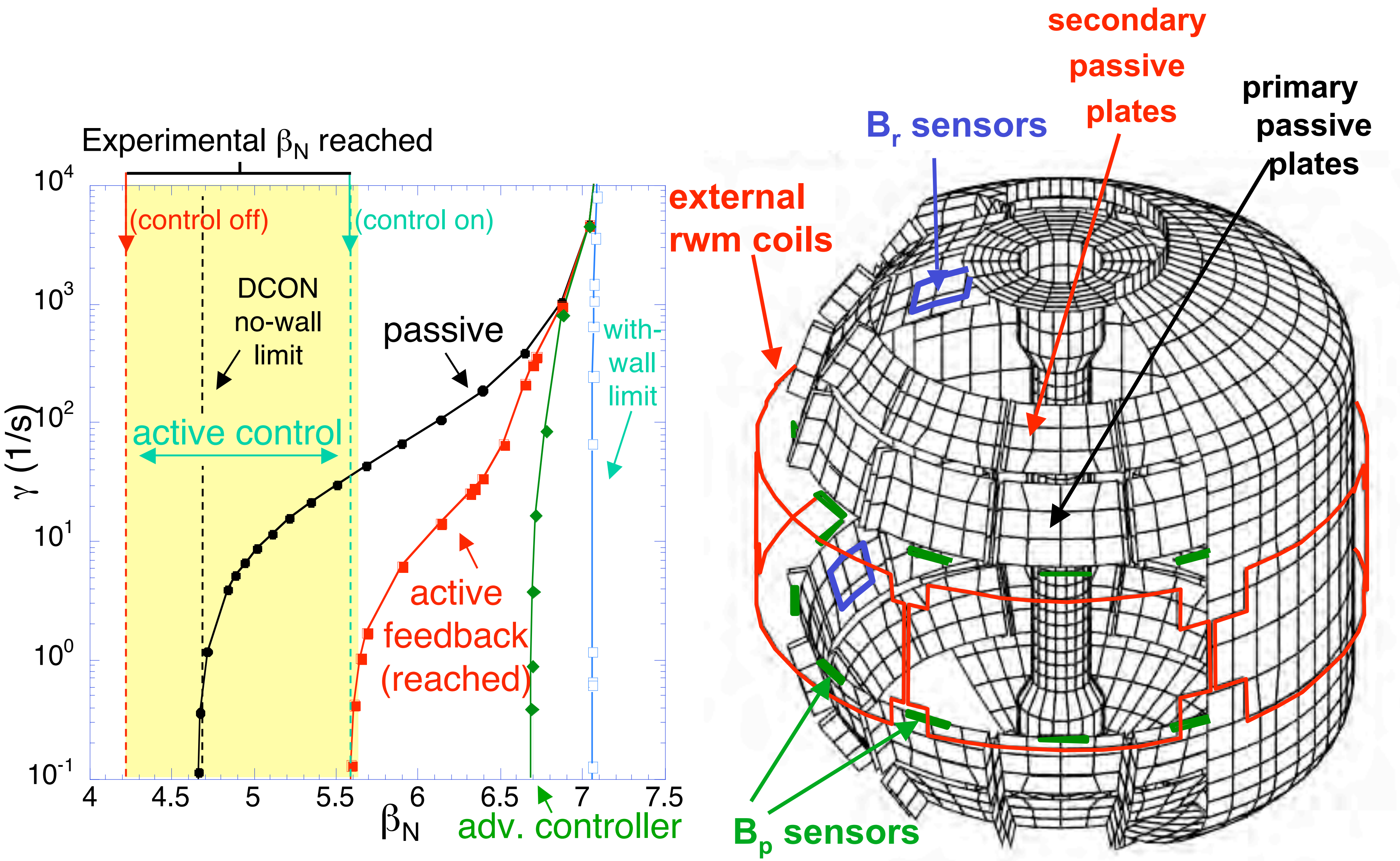
top& bottom coils, β_n=3.827, C_β=48%



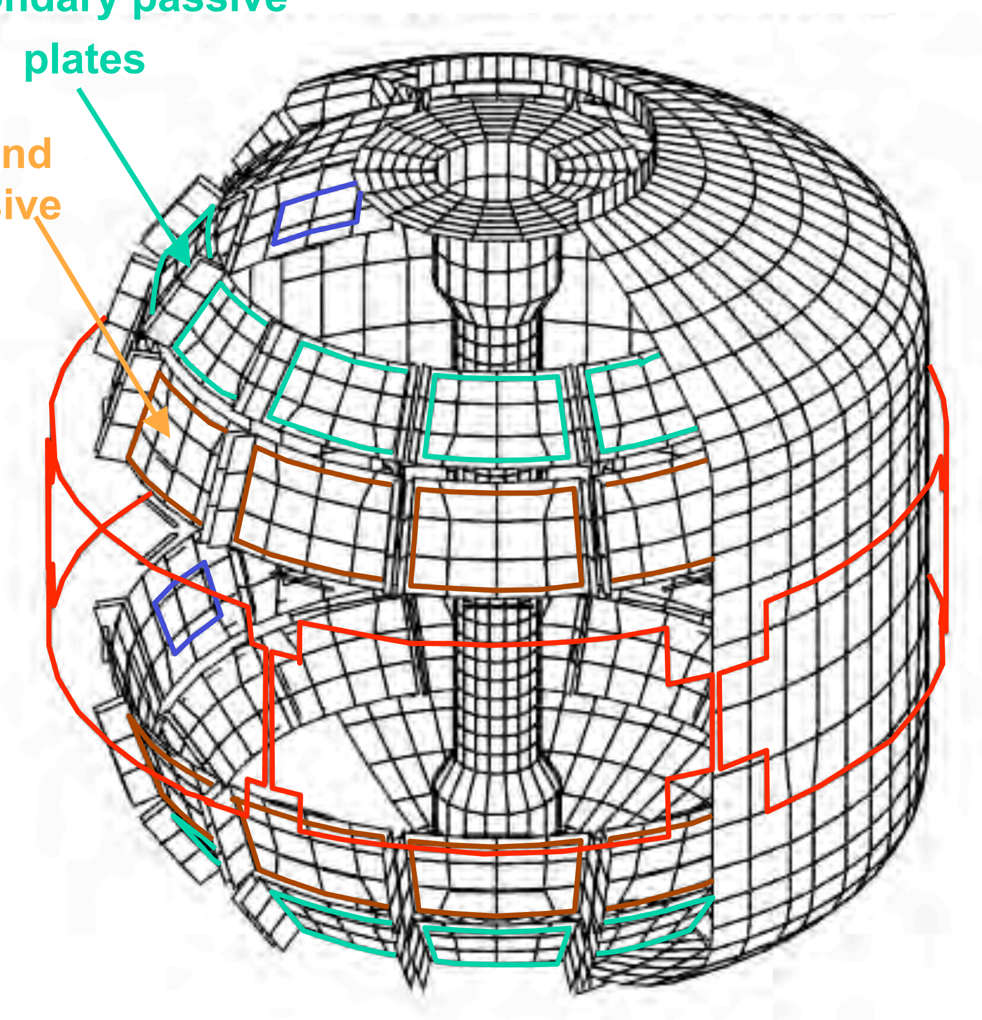
Steady state power estimates for VAC-02 coil system are extremely small

- Steady state power required was calculated in a transient simulation.
- Used all 27 coils, β_n=3.7, Used best gain setting, G_p=0.8*10^8 [v/w], and 10 g white noise. Feedback was always on. System is responding to noise in sensor system. The RWM mode is suppressed from birth.
- RMS values of current, voltage, and power calculated:
  - Average coil current = 91.1 amp, average coil voltage=4.968 v
  - Max coil current = 147.6 amp, max coil voltage = 7.96 v
  - Average <current*voltage>=0.581 KVA
  - Max <current*voltage> = 1.169 KVA
  - Sum over 27 coils of <current*voltage> = 15.71 KVA

VALEN accurately predicts present performance of NSTX with external RWM control coils



Proposed NSTX upgrade, new coils behind passive plates

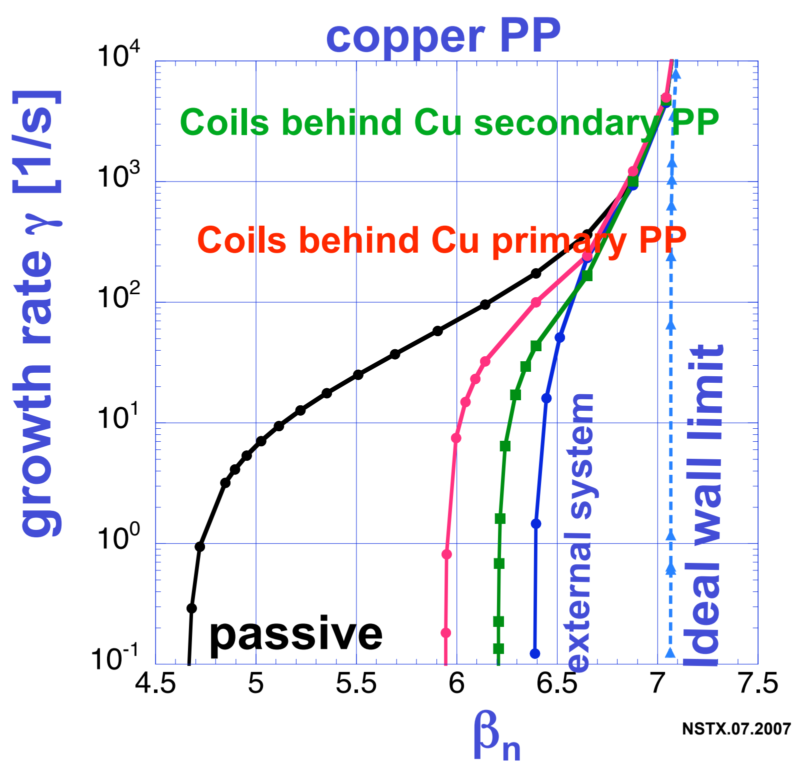


Possible upgrades

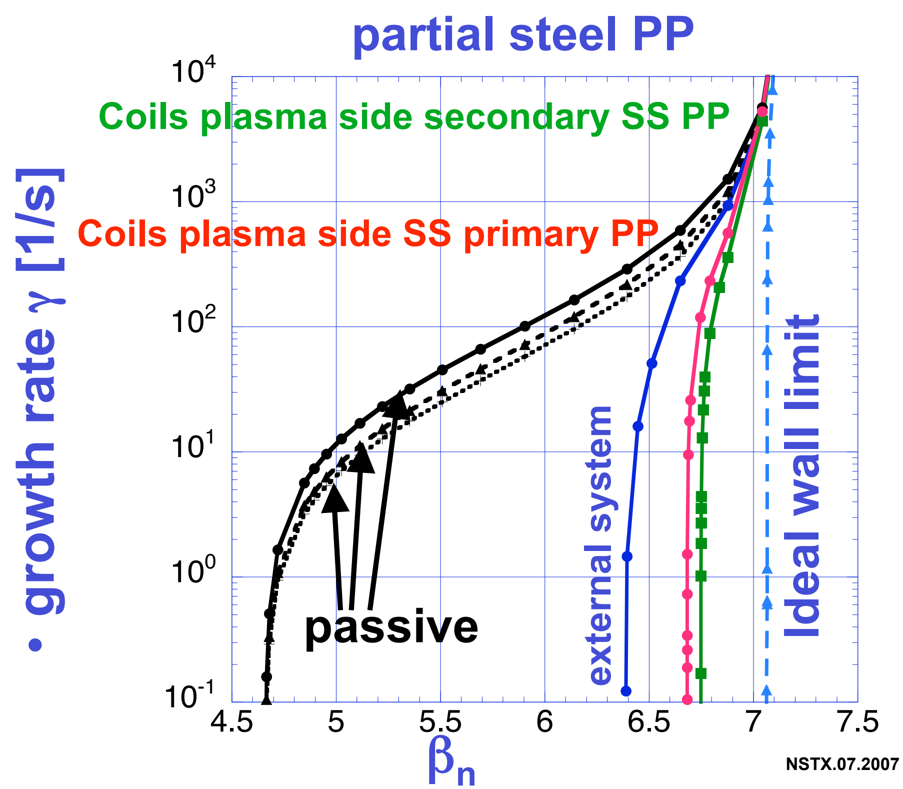
- Coils behind copper passive plates
- Change copper passive plates to SS (either primary or secondary, not both)

- We examine one such coil system at a time

VALEN RWM predictions for new control coils behind passive plates (PP)

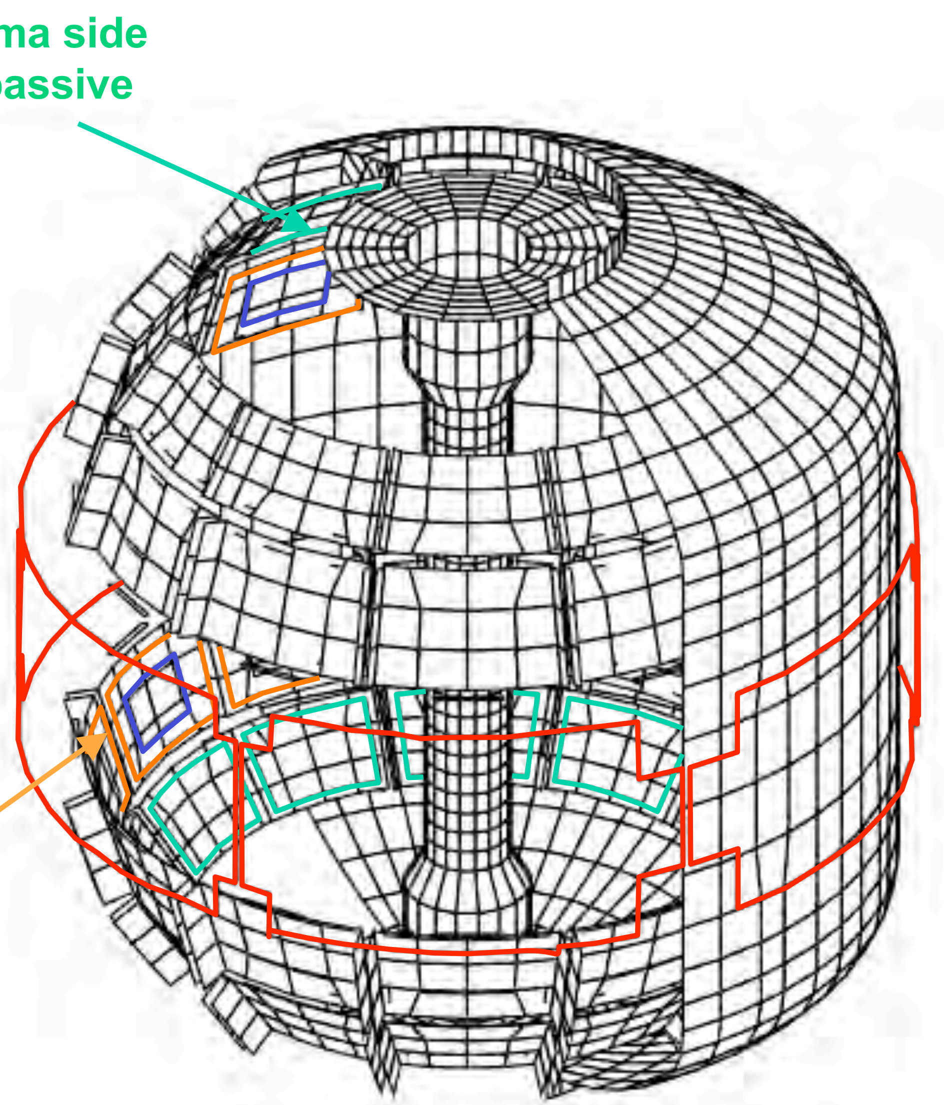


coils behind copper passive plates perform worse than existing external RWM



change copper passive plates to SS RWM performs better than existing external RWM

Proposed NSTX upgrade, coils on plasma side of passive plates



Possible upgrades:

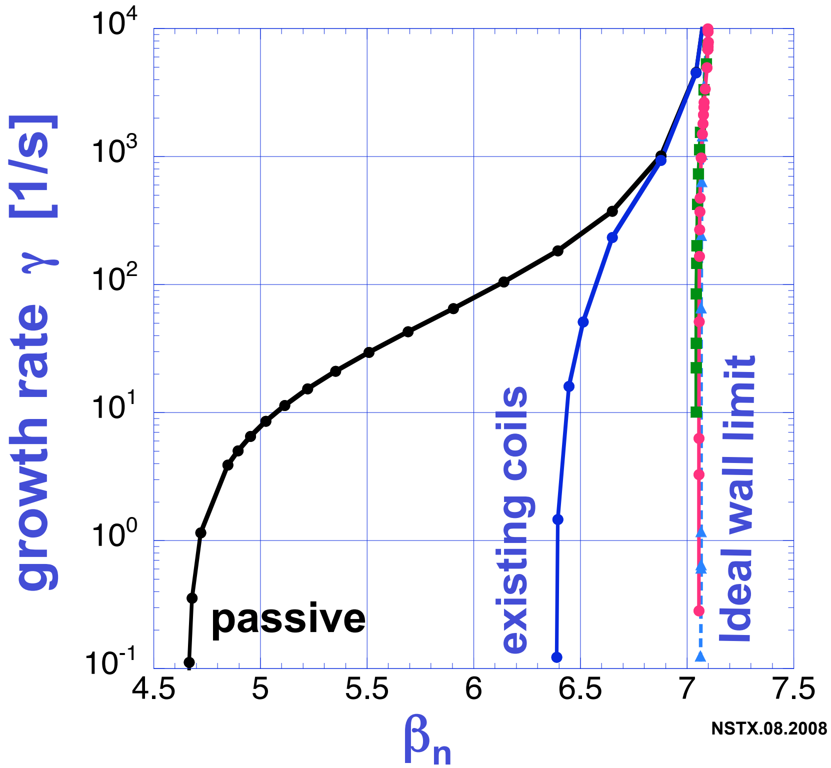
- coils on plasma side of passive plates
- we examine only one such coil system at a time
- **we approach the ideal wall limit with either coil system**

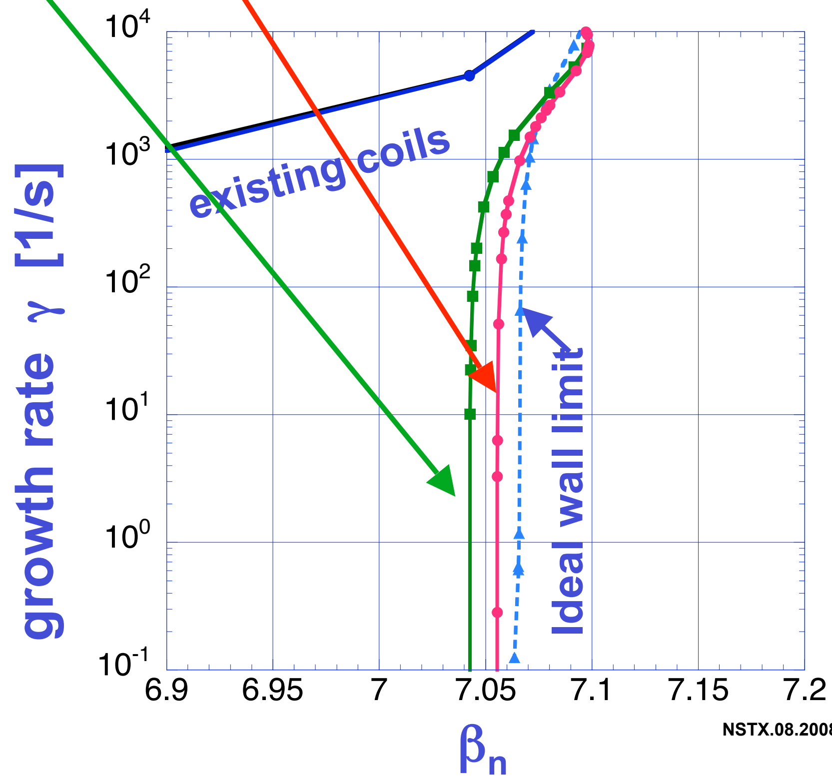
New control coils on plasma side of NSTX copper passive plates (PP) stabilize to C_β>99%

coils on plasma side Cu secondary PP stabilize to β_n = 7.04

coils on plasma side Cu primary PP stabilize to β_n = 7.05

Ideal wall limit β_n = 7.06





Multi-mode VALEN formulation allows multiple modes from multiple toroidal mode numbers

- VALEN formulation models RWM problem as L-R circuit, we include plasma response, wall currents, control coils and magnetic sensors
- Plasma magnetic response to external magnetic field found in 'Plasma Permeability matrix' [P]
  - **{total flux on plasma surface} = [P]*{flux from external world}**
    - Suggested reference: 'Resistive wall modes and error field amplification' A. Boozer, Physics of Plasmas, Vol 10, No. 5, May 2003, pg 1458
- Permeability matrix is singular at marginal stability, this dominates the physics. Smallest |dW| dominates error field amplification

VALEN formulation- plasma permeability [P]

- Plasma permeability relates total magnetic flux on plasma surface (sum of flux from plasma response and external sources) to external sources of magnetic flux.
- We express magnetic flux on the plasma surface in terms of wall currents $\{I_w\}$, plasma mode currents $\{I_p\}$, and plasma mode dissipative currents $\{I_d\}$, (replaces K.E. in standard formulation)

$$\left\{\Phi_w^{wall}\right\} = \left[L_{ww}^{wall}\right]\left\{I_w^{wall}\right\} + \left[L_{wp}^{wall-plasma}\right]\left\{I_d^{diss}\right\} + \left[L_{wp}^{wall-plasma}\right]\left\{I_p^{plasma}\right\}$$

$$\left\{\Phi_p^{plasma-TOTAL}\right\} = \left[L_{pw}^{plasma-wall}\right]\left\{I_w^{wall}\right\} + \left[L_{pp}^{plasma}\right]\left\{I_d^{diss}\right\} + \left[L_{pp}^{plasma}\right]\left\{I_p^{plasma}\right\}$$

$$\left\{\Phi_p^{plasma-EXTERNAL}\right\} = \left[L_{pw}^{plasma-wall}\right]\left\{I_w^{wall}\right\} + \left[L_{pp}^{plasma}\right]\left\{I_d^{diss}\right\}$$

$$\left\{\Phi_p^{plasma-TOTAL}\right\} = \left[P\right]\left\{\Phi_p^{plasma-EXTERNAL}\right\}$$

VALEN single mode compared to multi-mode formulation

single mode formulation

find current $g_u(\theta,\phi)$ that gives $b_u^{normal}(\theta,\phi)$

$$[P] = \left(\frac{-1}{s}\right), \quad s = \frac{-\delta W_u}{(1/2)LI^2}$$

$$\left\{\Phi_p^{pl-TOTAL}\right\} = \left(\frac{-1}{s}\right)\left\{\Phi_p^{pl-EXT}\right\}$$

$$\left[L_{PP}^{plasma}\right]\left\{I_p^{plasma}\right\} = \left(\frac{-1}{s} - 1\right)\left\{\Phi_p^{pl-EXT}\right\}$$

$$\left[L_{PP}^{plasma}\right]\left\{I_p^{plasma}\right\} = (1+s)\left\{\Phi_p^{pl-TOTAL}\right\}$$

multi- mode formulation

given basis set : $\{\mathrm{f_i}(\theta,\phi)\} = S[G]\{\mathrm{b_i^{normal}}(\theta,\phi)\}$

currents : $\{g_i(\theta,\phi)\} = \delta(r-a)\nabla\{f_i\}\times\nabla r$

$$[P] = [\Lambda]\left[L_{pp}^{plasma}\right]^{-1}, [\Lambda]^{-1} = 2[G][\varepsilon][G]^t$$

$$[\varepsilon] = diag\{\delta \mathrm{W}\ \text{from DCON}\}, [G] = \text{gram schmidt}$$

$$\left\{\Phi_p^{pl-TOTAL}\right\} = [P]\left\{\Phi_p^{pl-EXTERNAL}\right\}$$

$$\left[L_{PP}^{plasma}\right]\left\{I_p^{plasma}\right\} = ([P]-[1])\left\{\Phi_p^{pl-EXT}\right\}$$

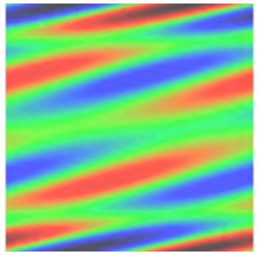
$$\left[L_{PP}^{plasma}\right]\left\{I_p^{plasma}\right\} = ([P]-[1])[P]^{-1}\left\{\Phi_p^{pl-TOTAL}\right\}$$

$$\begin{Bmatrix} \left\{\Phi_w^{wall}\right\} \\ \left\{\Phi_p^{pl-total}\right\} \end{Bmatrix} = \left[\begin{bmatrix} \left[L_{ww}^{wall}\right] & \left[L_{wp}^{wall-plasma}\right] \\ \left[L_{pw}^{plasma-wall}\right] & \left[L_{pp}^{plasma}\right] \end{bmatrix} + \begin{bmatrix} \left[L_{wp}L_{pp}^{-1}[P-1]L_{pw}\right] & \left[L_{wp}L_{pp}^{-1}[P-1]L_{pp}\right] \\ \left[L_{pp}L_{pp}^{-1}[P-1]L_{pw}\right] & \left[L_{pp}L_{pp}^{-1}[P-1]L_{pp}\right] \end{bmatrix}\right] \begin{Bmatrix} \left\{I_w^{wall}\right\} \\ \left\{I_d^{plasma}\right\} \end{Bmatrix}$$

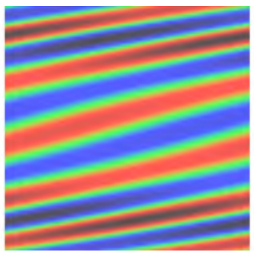
$$[L_{TOTAL}]\{\dot{I}_{TOTAL}\} + [R_{TOTAL}]\{I_{TOTAL}\} = r.h.s.$$

mmVALEN analysis of HBT used n=1 & n=2 input 38 modes for n=1, 44 modes for n=2

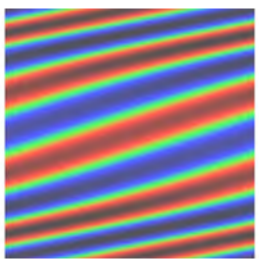
mode #4
n = 1
$\delta W = +43.5$



mode #3
n = 1
$\delta W = +41.6$

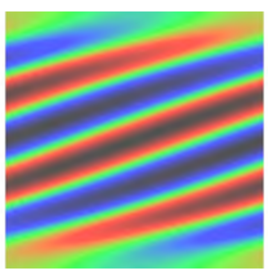


mode #2
n = 1
$\delta W = +7.93$



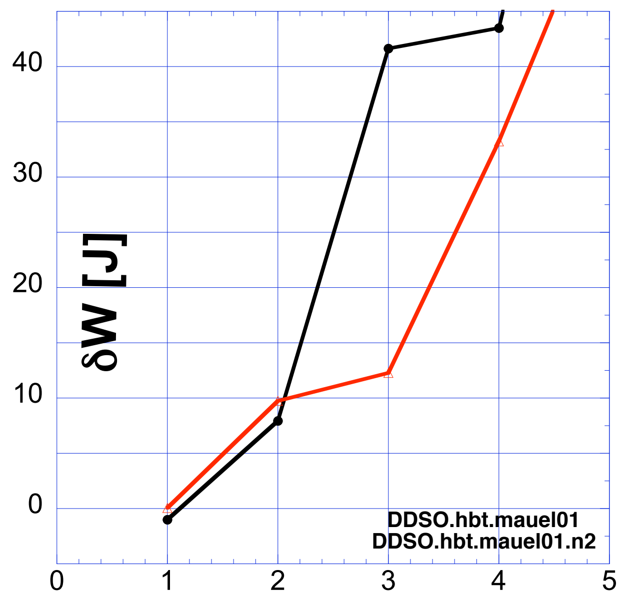
mode #1
n = 1
$\delta W = -1.005$

poloidal



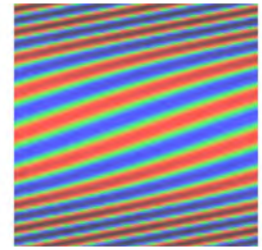
toroidal

plot of δW [J] vs. mode#
HBT plasma modes
n=1 & n=2

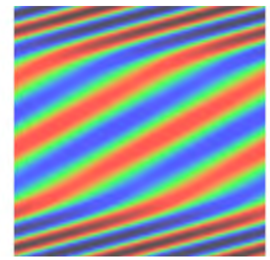


mode number

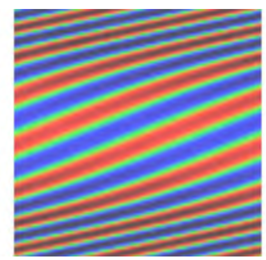
mode #4
n = 2
$\delta W = +33.2$



mode #3
n = 2
$\delta W = +12.3$

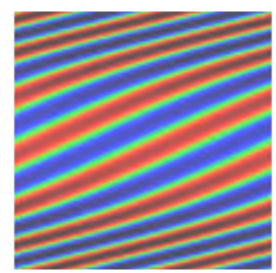


mode #2
n = 2
$\delta W = +9.74$



mode #1
n = 2
$\delta W = +0.053$

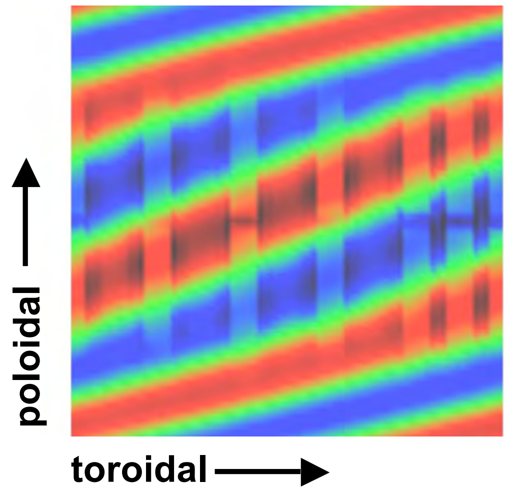
poloidal



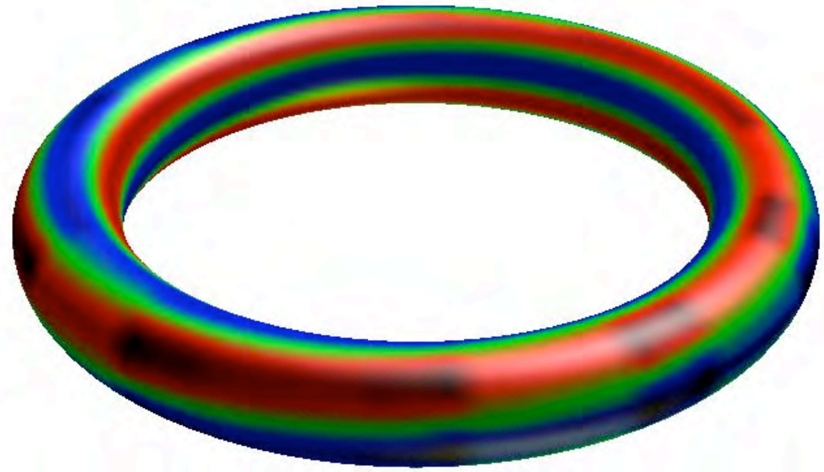
toroidal

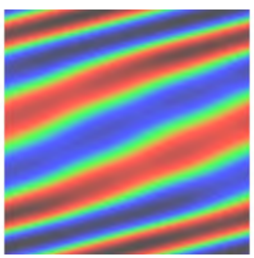
mmVALEN results for HBT, $\gamma_{passive} = 0.5*10^6$ [1/s]
B_normal on plasma surface from mmVALEN

total B_normal on plasma surface

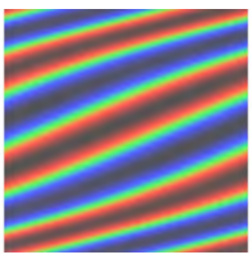


total B_normal on plasma surface

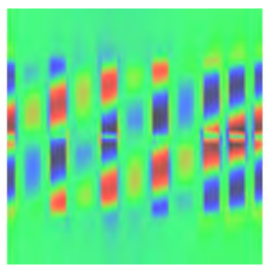




from $\{I_d\}$
~ 10^{-6}

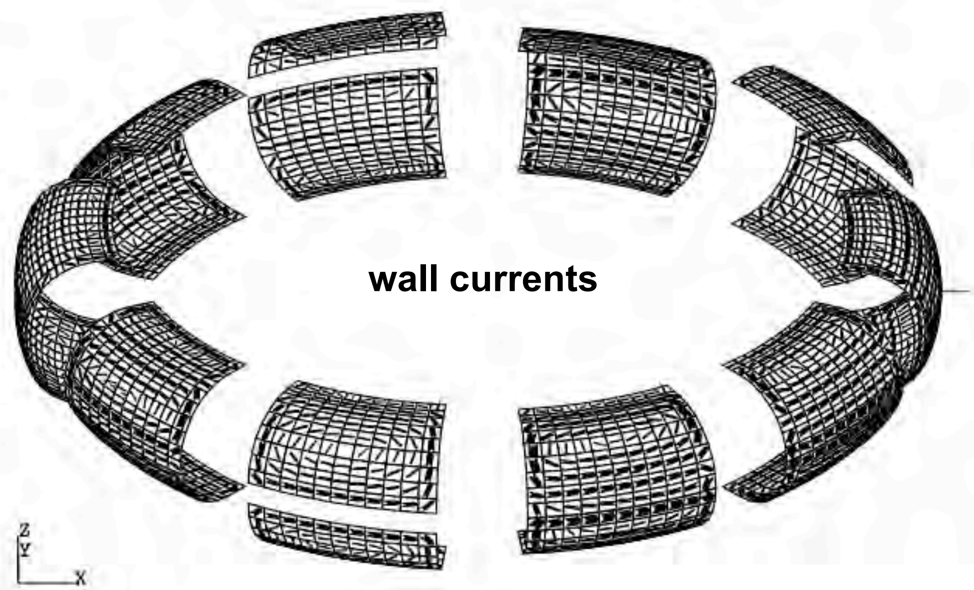


from $\{I_p\}$
~ 10^{-5}

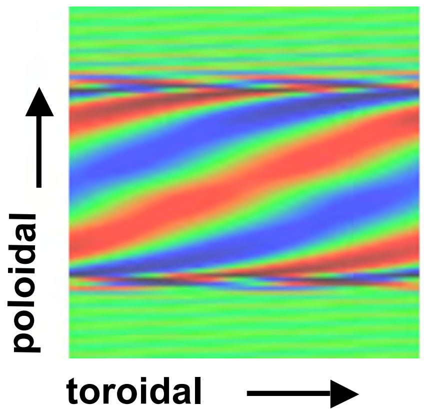


from $\{I_w\}$
~ 10^{-7}

<u>Components of B_normal on plasma surface</u>



mmVALEN analysis of NSTX used n=1, input 78 modes for n=1.



mode #1

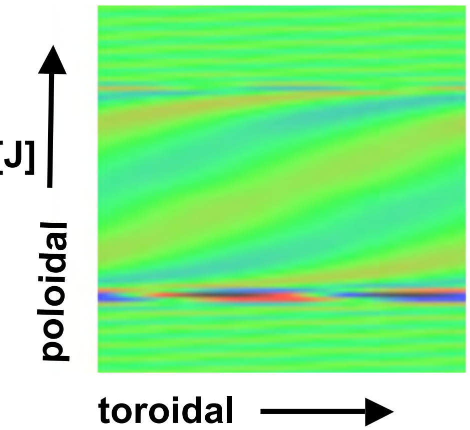
n = 1

δW = -1253. [J]

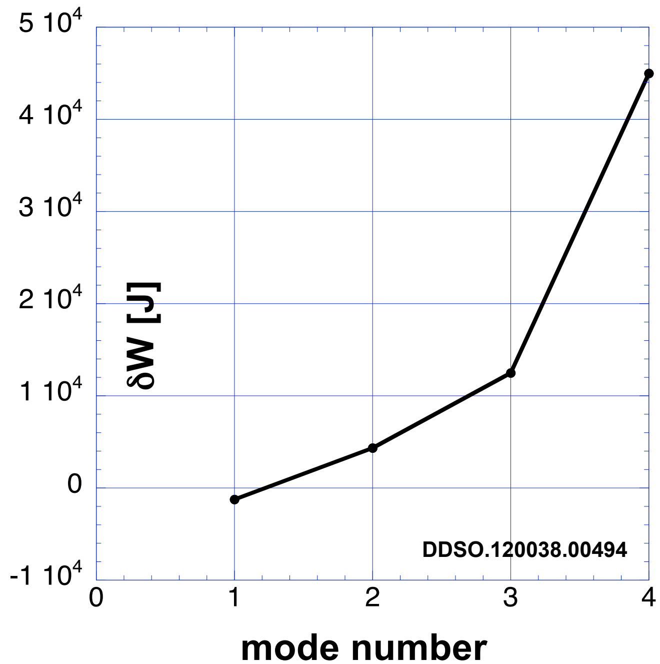
mode #2

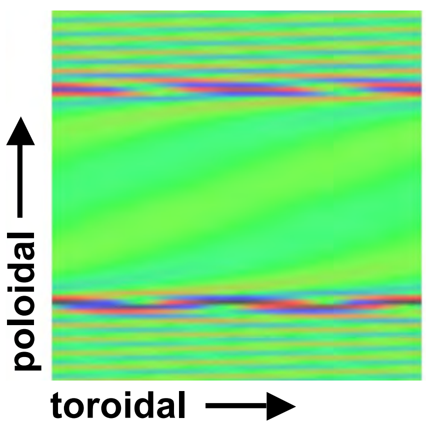
n = 1

δW = +4345. [J]



Partial mode spectrum from NSTX 120038.00494

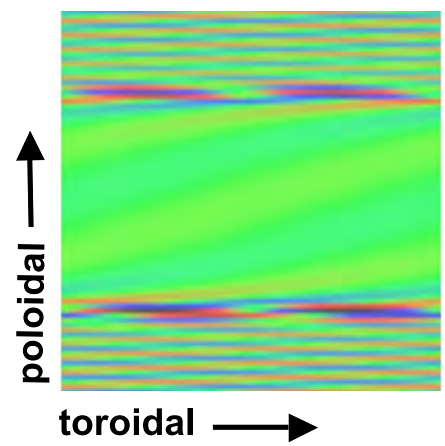




mode #3

n = 1

δW = +12497. [J]



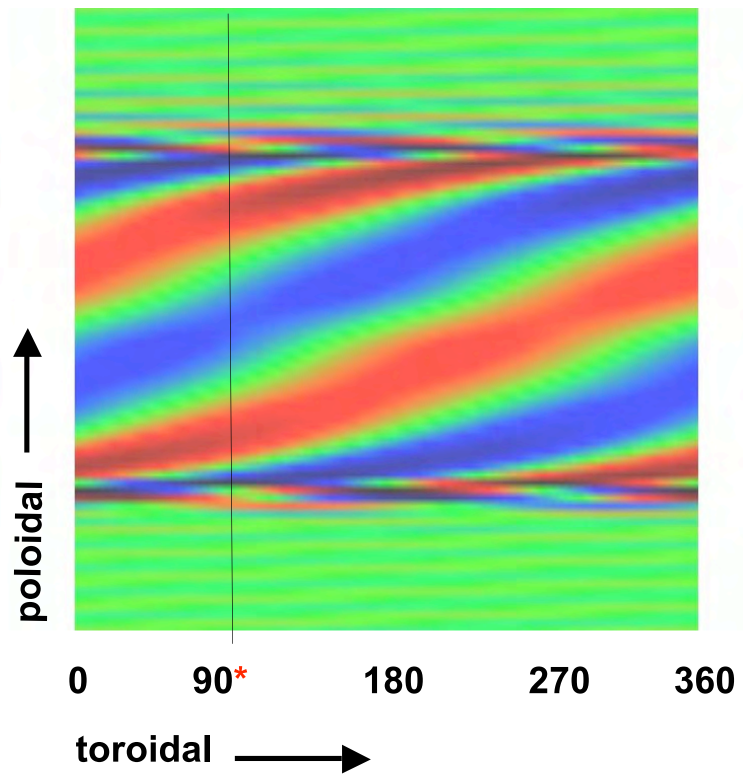
mode #4

n = 1

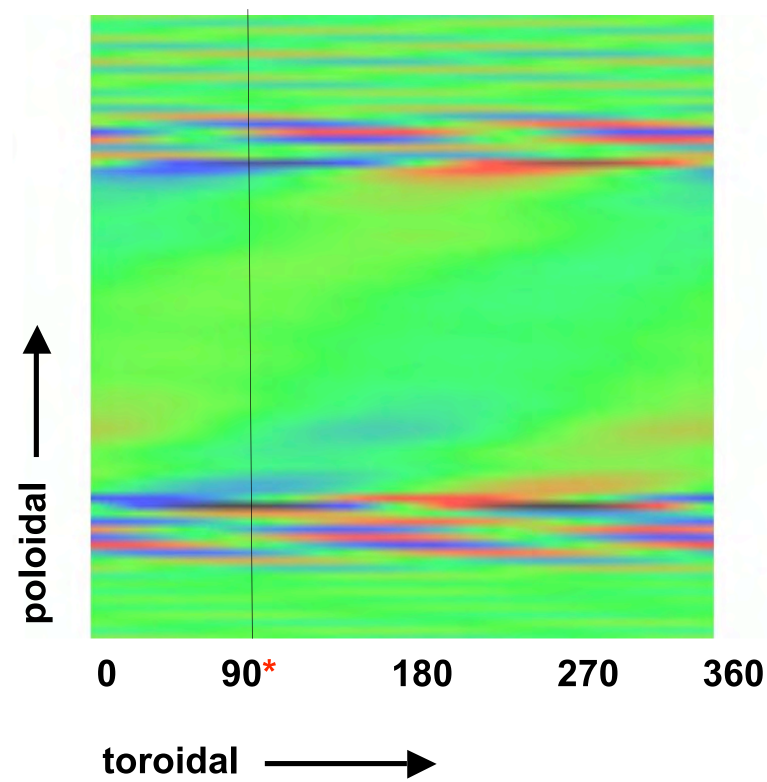
δW = +44983. [J]

NSTX plasma response from multi mode VALEN greatly different from single mode VALEN

B_normal on plasma surface from single mode VALEN

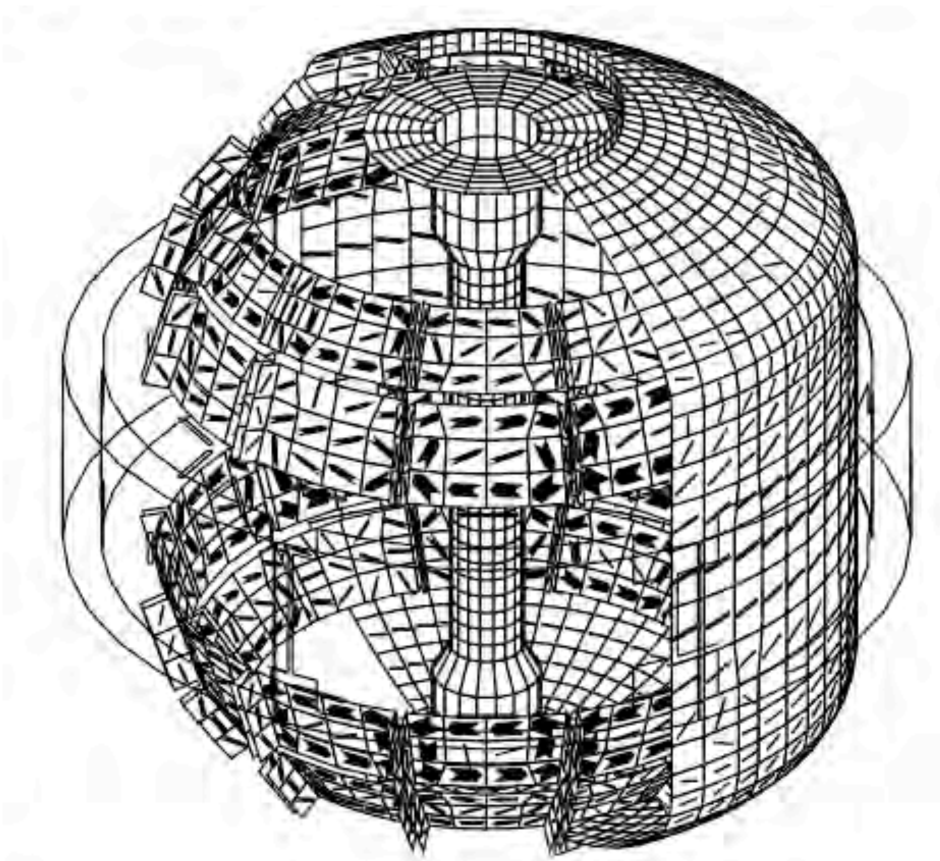


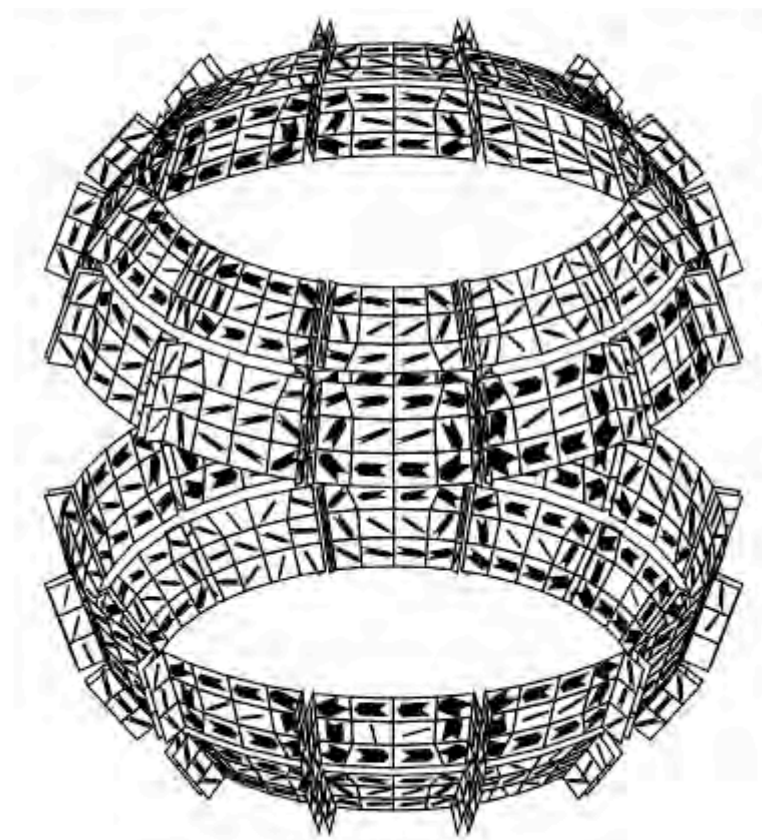
B_normal on plasma surface multi-mode mode VALEN



note* see plot page 23

Multi mode VALEN results for NSTX.120038.494, wall currents $\{I_w\}$ shown, γ=16.3 [1/s]

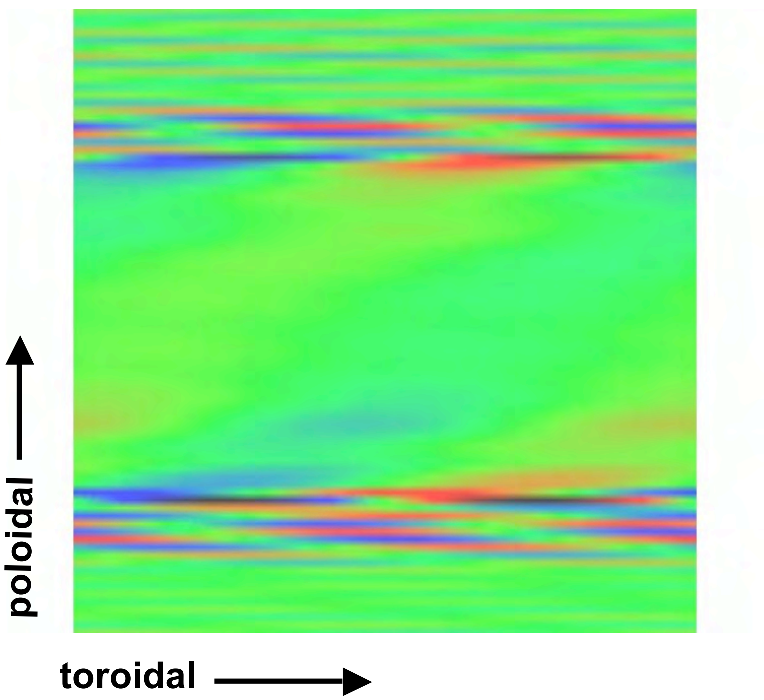




Multi mode VALEN results for NSTX.120038.494, we show B_normal on plasma surface

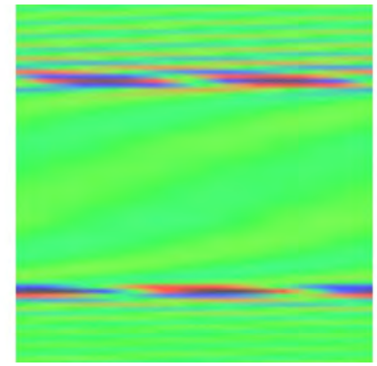
Total B_normal on NSTX plasma surface

multi-mode mode VALEN



B_normal on plasma surface from $\{I_d\}$

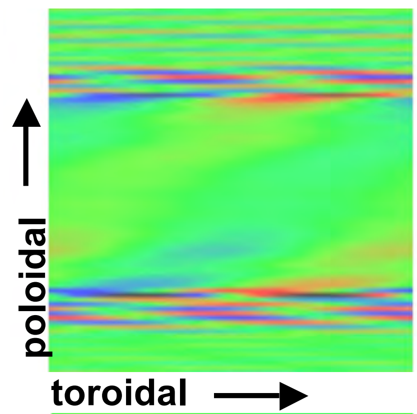
typical mag ~ 10^{-8}



B_normal on plasma surface from $\{I_p\}$

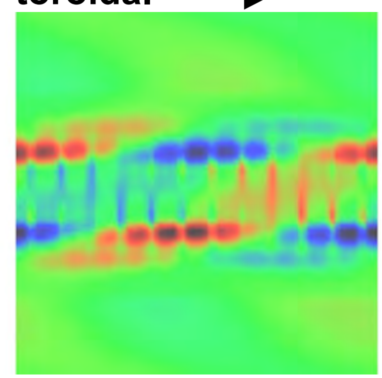
typical mag ~ 10^{-5}

dominant contribution



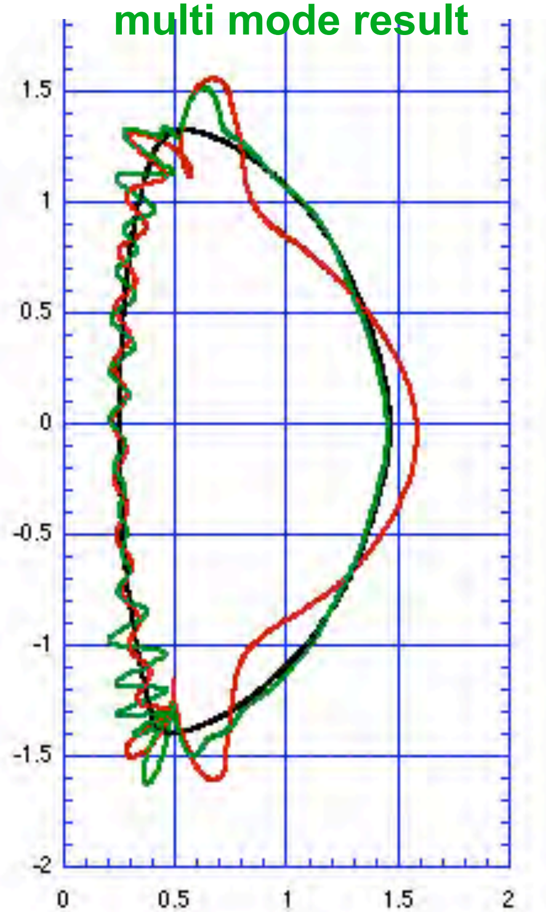
B_normal on plasma surface from $\{I_w\}$

typical mag ~ 10^{-11}



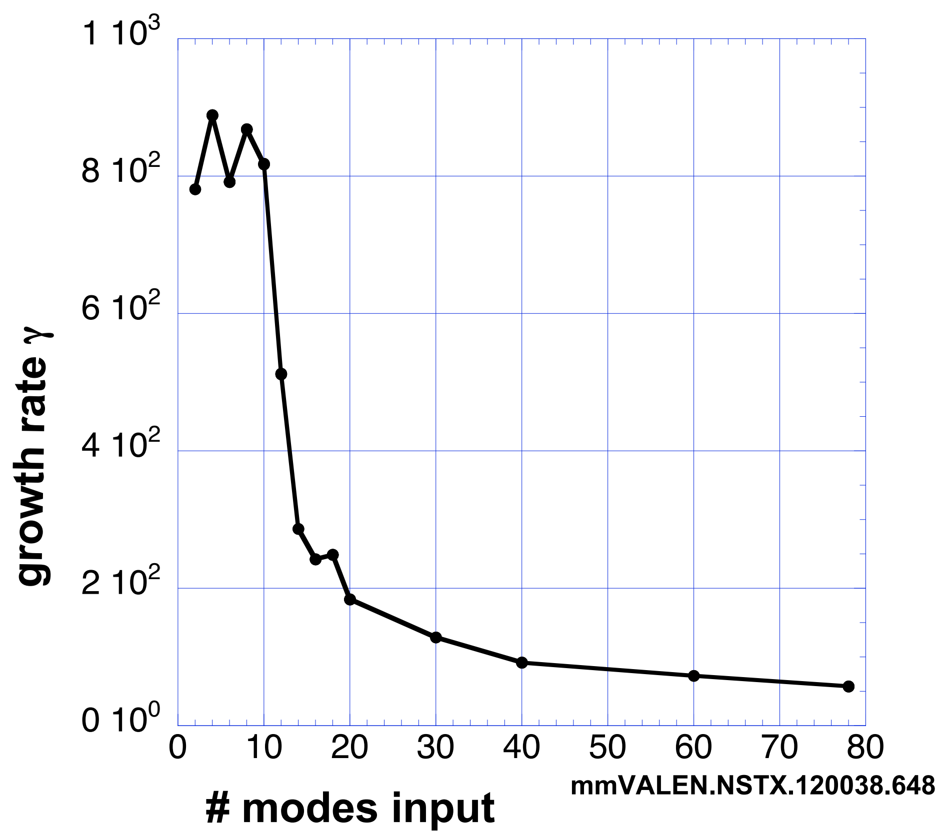
Results from multi-mode VALEN for NSTX, comparison to single mode & convergence study

B_normal on plasma surface
shown at 90 degrees toroidal
distance from surface α B_n
single mode result
multi mode result



Growth rate γ vs. # modes

we are investigating different basis functions to improve convergence



Summary
results and advances in VALEN RWM modeling

- VALEN RWM code indicates that VAC-02 coil system on ITER may reach C_β =48% in original scenario 4 with minimal power requirements

- VALEN RWM code indicates new RWM coils inside NSTX mounted on the plasma facing side of either passive plate system will allow NSTX to reach C_β > 99%

- multi-mode VALEN now running.
  - Investigations and QA in progress for eigenvalue calculations
  - Plasma response(flexibility) appears greater at small aspect ratio (NSTX)