RWM rotation modeling in ITER

workshop on MHD stability control

20 November 2007

- VALEN model with rotation includes a toroidal torque balance
- We investigate the effect of feedback with self consistent torque
- Optimal phasing for feedback determined, essentially no degradation in performance

VALEN rotation includes toroidal torque (Γ) balance*

$$\Gamma_{\text{plasma-plasma mode}} + \Gamma_{\text{plasma mode-external}} = 0$$

$$\Gamma_{\text{plasma-plasma mode}} = \text{function}\left(\varpi_{\text{plasma}} - \Omega_{\text{plasma mode}}\right)$$

‘Since the magnitude of the torque has many uncertainties, the equations will be formulated so empirical expressions for torque may be used.’

We do not predict $\Gamma_{\text{plasma-plasma mode}}$

The VALEN dimensionless parameter ‘α’ is a normalized torque. The VALEN parameters ‘s’ & ‘α’ together determine growth rate γ and rotation Ω of the plasma mode.

* See Physics of Plasmas, Vol 6, No. 8, Aug. 1999, pg.3180

$$\alpha = \frac{\Gamma_{\text{plasma mode - external}}}{\mathrm{L}_{\mathrm{B}} I_B^2 /2} \propto \varpi_{\text{plasma}} \upsilon_{diss}$$

Torque and energy have same units so α is dimensionless

If we understood the dissipation model and can calculate the torque, then we can make predictions for critical plasma rotation for a given rotation profile shape.

VALEN-ROTATION with a torque balance is more realistic

- old VALEN results used a single unstable mode with a fixed toroidal orientation, no change in toroidal orientation of the plasma mode was allowed, toroidal torque was ignored, plasma mode could change growth rate but could not change its initial toroidal orientation.

- VALEN-ROTATION uses two copies of a single unstable mode, start with $\pi/2$ difference in initial position. The application of torque determines growth rate(s), and rotation or orientation(s). (i.e., choose 'α' and possibly apply feedback)

- VALEN-ROTATION with field errors requires a time dependent calculation, we report here only eigenvalue results (without error fields).

We demonstrate VALEN-ROTATION with our most complete VALEN model of ITER,using 7 mid plane port plug control coils

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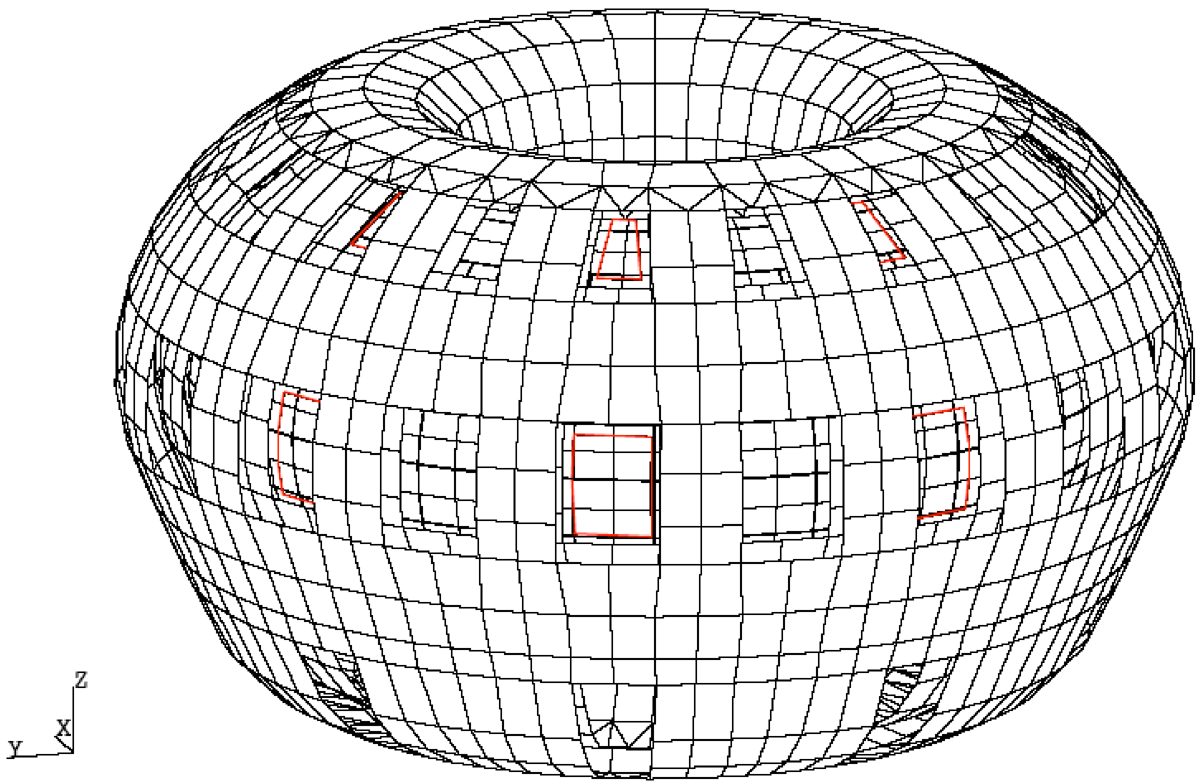
model includes double wall vacuum vessel (45 ports), blanket modules, control coils, and interior Bp sensors for mode detection

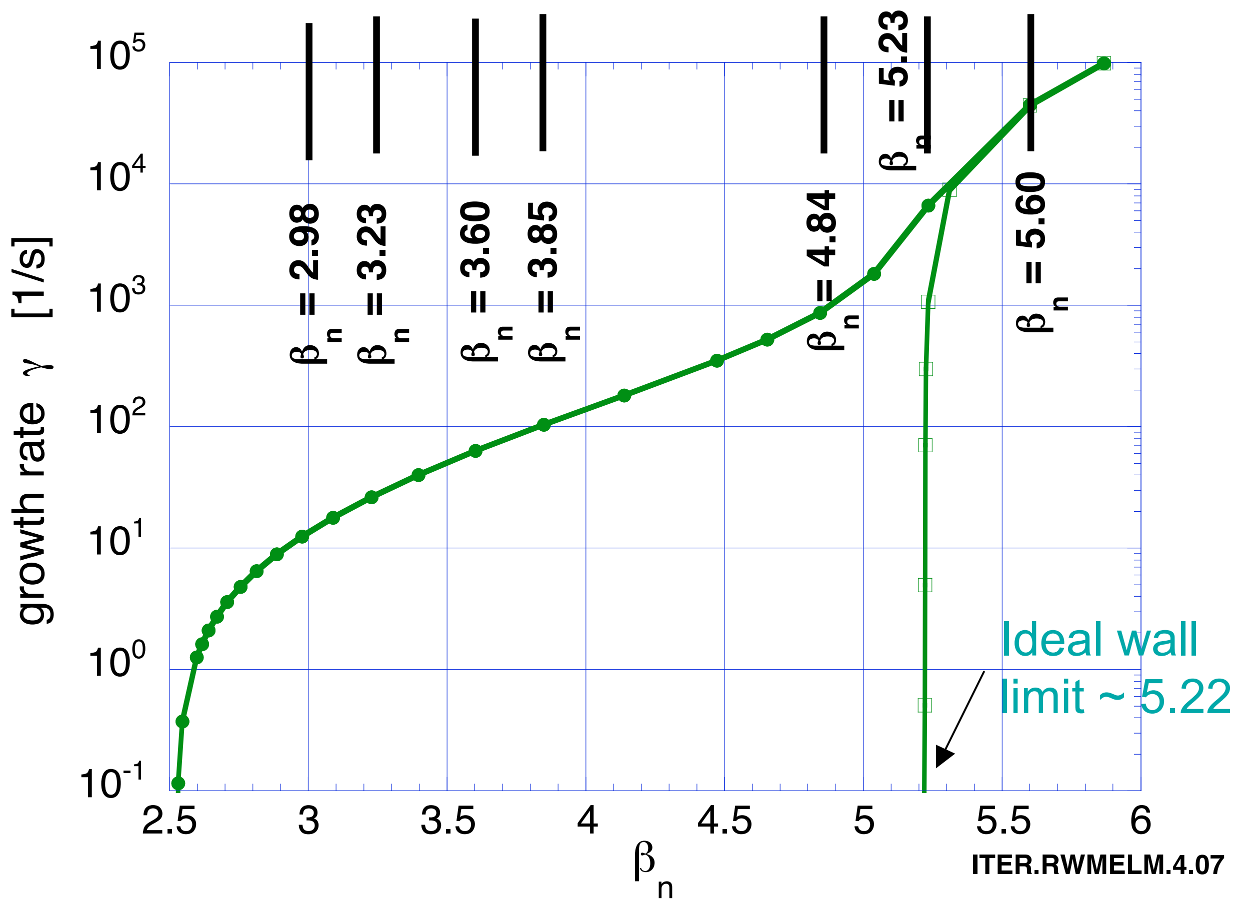


mid and top port plug coils shown in red

ITER passive growth rate with zero mode rotation (‘α’=0).

We now add rotation by doing a scan in normalized torque ‘α’

We next show growth rate altered by mode rotation near the operating point and near the ideal wall limit



VALEN prediction of growth rate and mode rotation

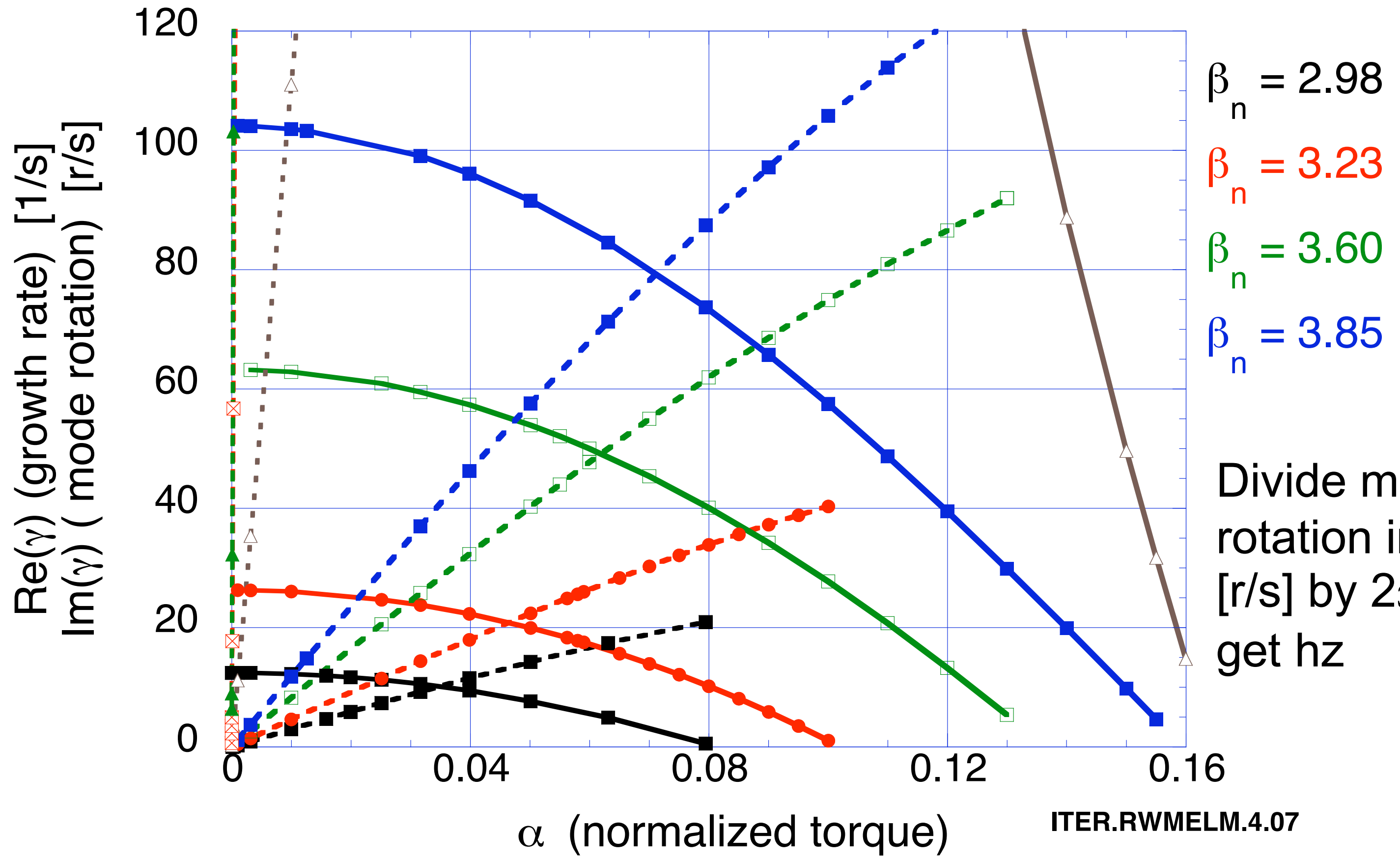
for our most complete ITER model, scenario 4 used

Re(γ) = Mode growth rate - solid lines

Im(γ) = Mode rotation - dashed lines

Growth rate at α=0 is ~ growth rate from no-rotation VALEN calculation

All cases shown may be stabilized by adequate rotation



Divide mode rotation in [r/s] by 2π to get hz

ITER.RWMELM.4.07

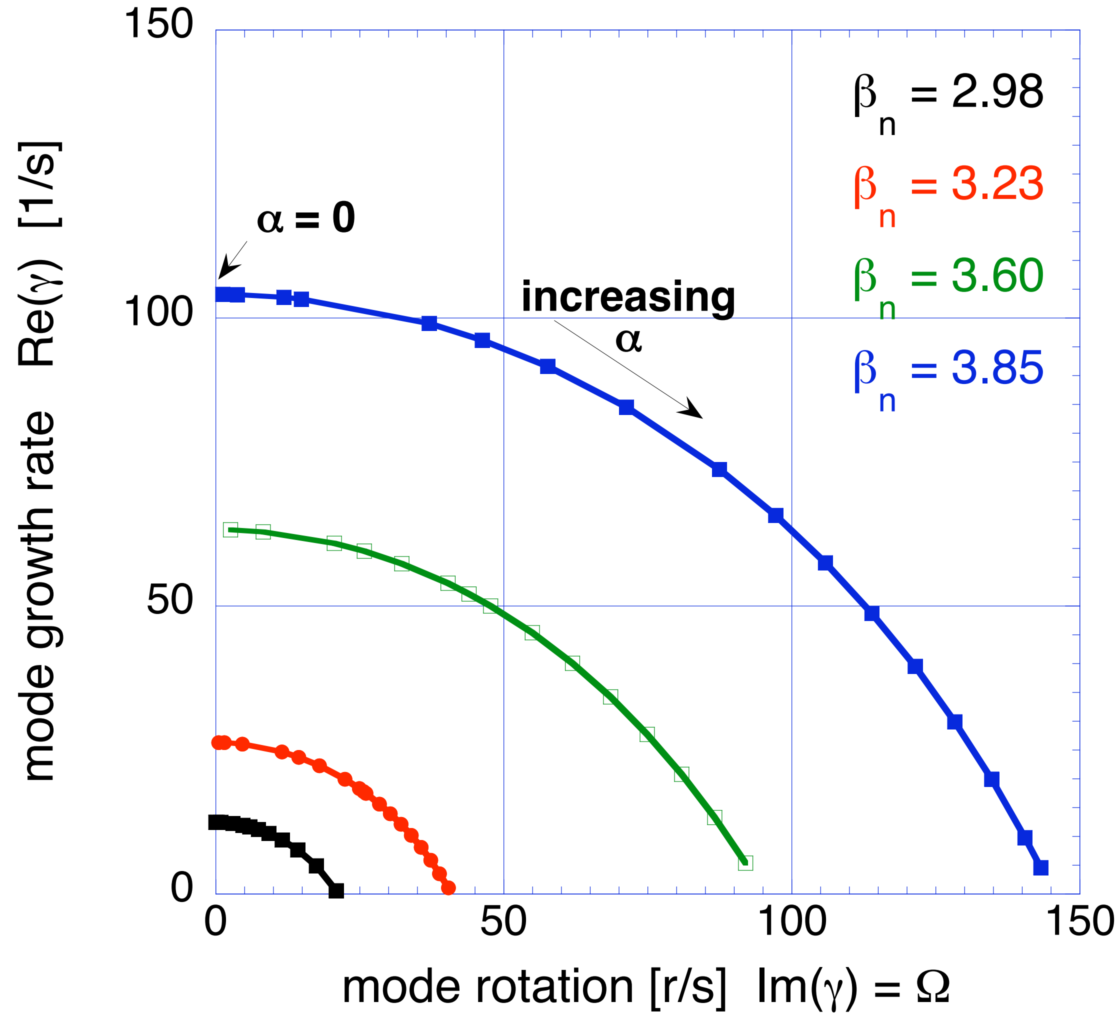
Different presentation of same results

VALEN prediction of growth rate vs. mode rotation

lines of constant β_n('s') as mode torque 'α' increases

Same data as previous page

All cases shown are stabilized by adequate rotation

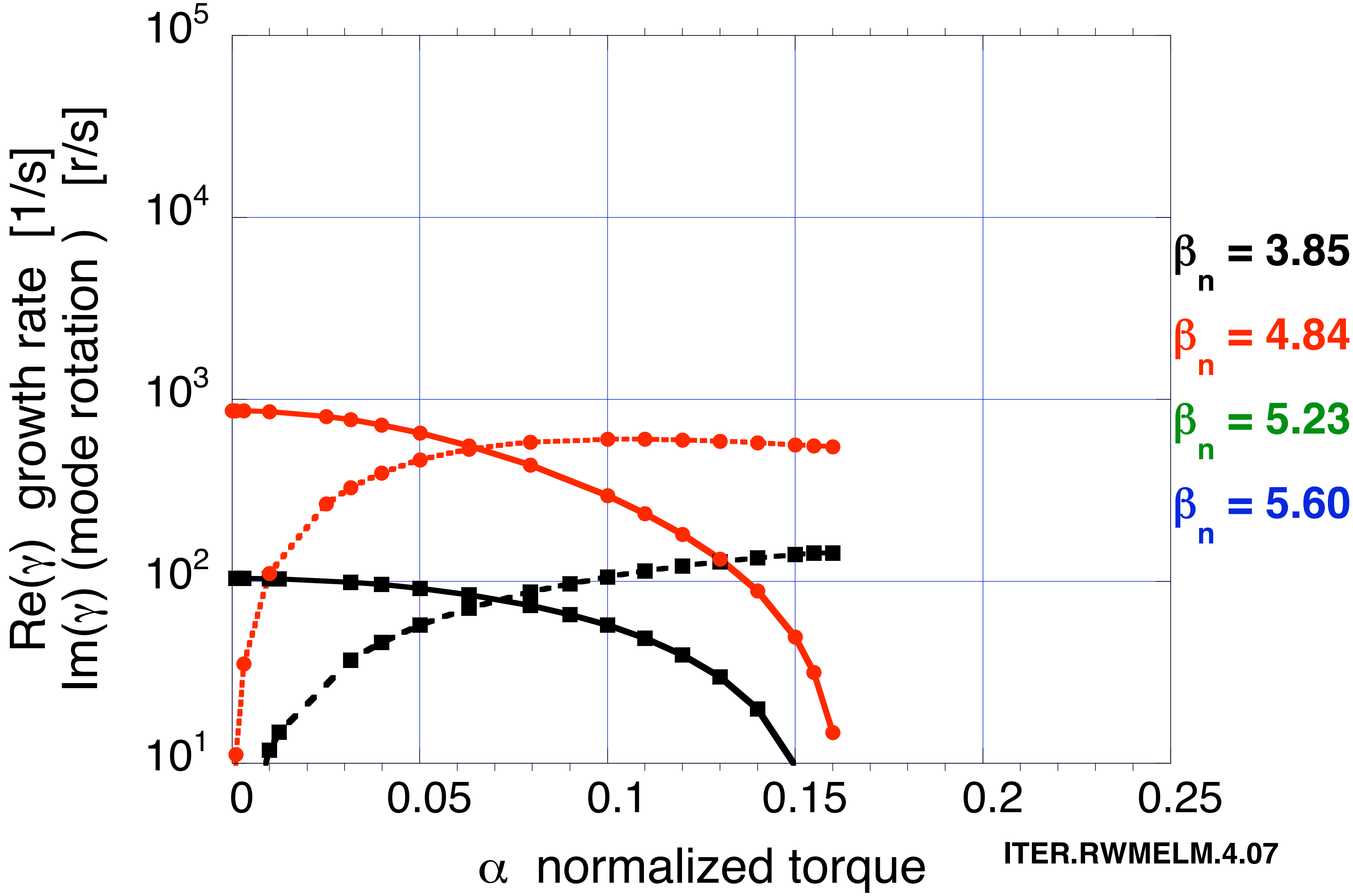


VALEN prediction of growth rate and mode rotation near ideal wall limit

Re(γ) Mode growth rate - solid lines

Im(γ) Mode rotation - dashed lines

Only cases with β_n <5.22, β_n below ideal wall limit are stabilized by rotation



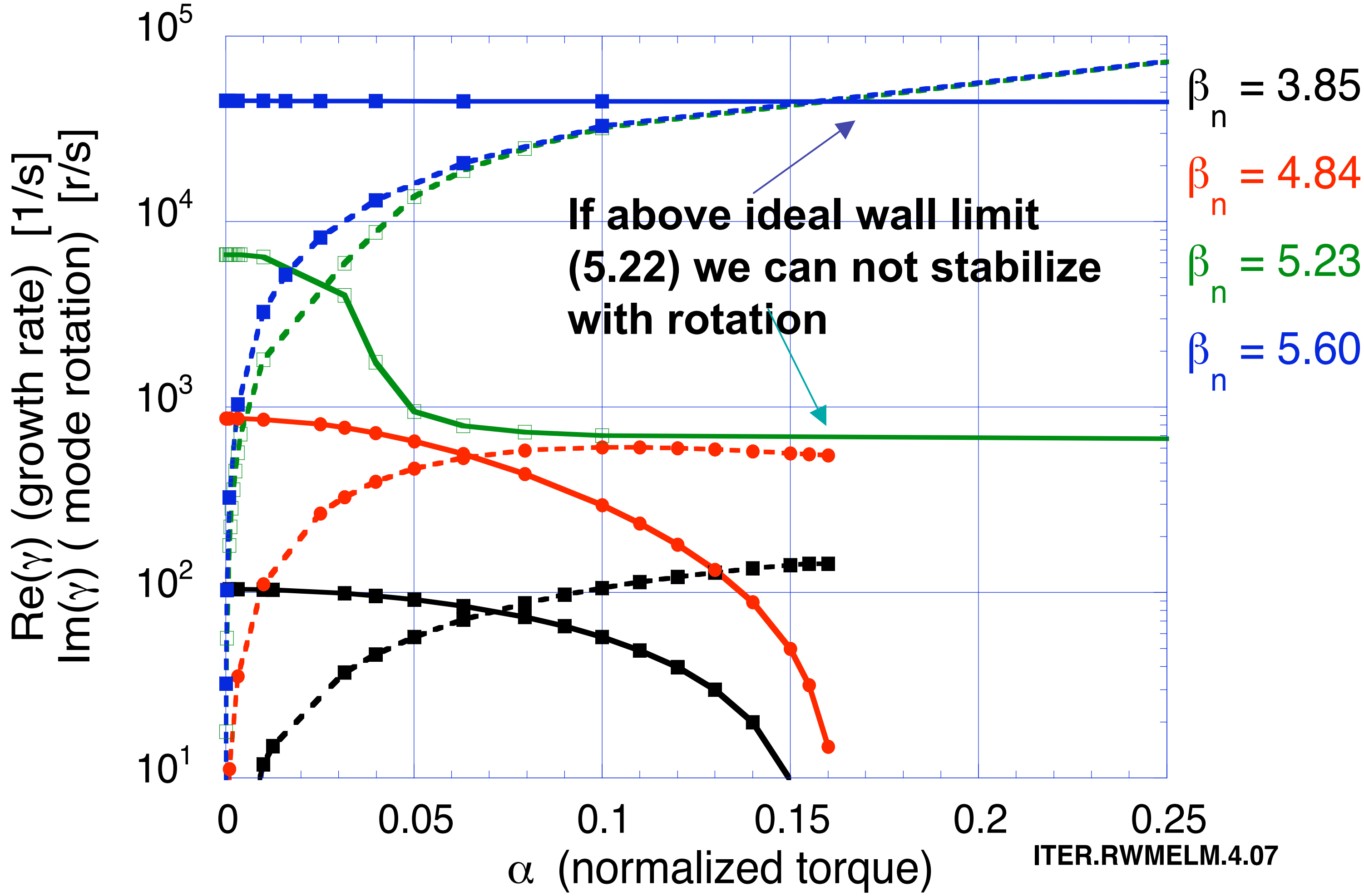
ITER.RWMELM.4.07

VALEN prediction of growth rate and mode rotation near ideal wall limit

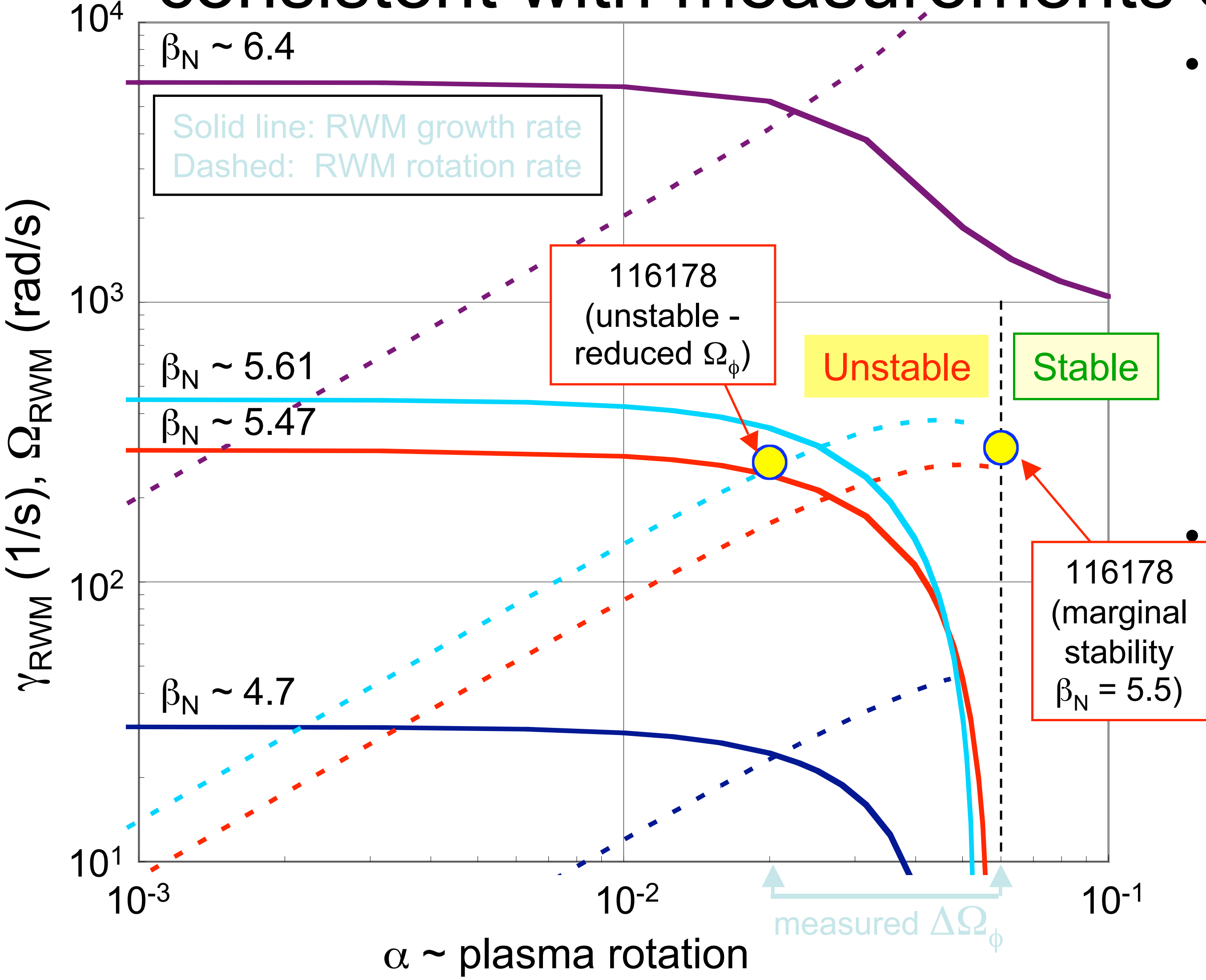
Re(γ) Mode growth rate - solid lines

Im(γ) Mode rotation - dashed lines

Only cases with β_n <5.22, β_n below ideal wall limit are stabilized by rotation



RWM growth/rotation modeled with VALEN consistent with measurements on NSTX



- Boozer RWM model in VALEN code
  - Plasma rotation
    - Normalized plasma torque a ⇔ W_f
  - RWM rotation
- Calibrate code using NSTX data
  - RWM rotation measured near marginal stability
  - RWM growth rate measured when edge W_f reduced

sas DPP-05

We use an ‘F-matrix’ approach to adjust feedback logic for toroidal phase of plasma mode

i.e., we do a least square fit to n=1 measured by a B_p sensor array.

Measure B_p or Φ_p in array of sensors (same radius, different toroidal position)

Identify magnitude & phase of sensor signals (n=1) here

Pick phase difference, δ, desired between sensors and control coil V

Choose gain Gp and run feedback,

$$\left\{V_{cc}\left(t\right)\right\}_{\mathrm{cx1}} = G_p\left[F\left(\delta\right)\right]_{\mathrm{cxN}}\left\{\Phi_{\mathrm{sensor}}\left(t\right)\right\}_{\mathrm{Nx1}}$$

We use an 'F-matrix' approach to adjust feedback logic for toroidal phase of plasma mode i.e., we do a least square fit to n=1 measured by a Bp sensor array.

$$
\begin{aligned}
S*\sin(n*\phi_1^{sensor}) + C*\cos(n*\phi_1^{sensor}) &= \Phi_1^{sensor}\\
S*\sin(n*\phi_2^{sensor}) + C*\cos(n*\phi_2^{sensor}) &= \Phi_2^{sensor}\\
&.\\
&.\\
S*\sin(n*\phi_N^{sensor}) + C*\cos(n*\phi_N^{sensor}) &= \Phi_N^{sensor}
\end{aligned}
$$

$$
[A]_{Nx2}\begin{Bmatrix} S \\ C \end{Bmatrix}_{2x1} = \left\{\Phi^{sensor}\right\}_{Nx1}
$$

$$
\begin{Bmatrix} S \\ C \end{Bmatrix}_{2x1} = \left([A]^t[A]\right)^{-1}_{2x2}[A]^t_{2xN}\left\{\Phi^{sensor}\right\}_{Nx1}
$$

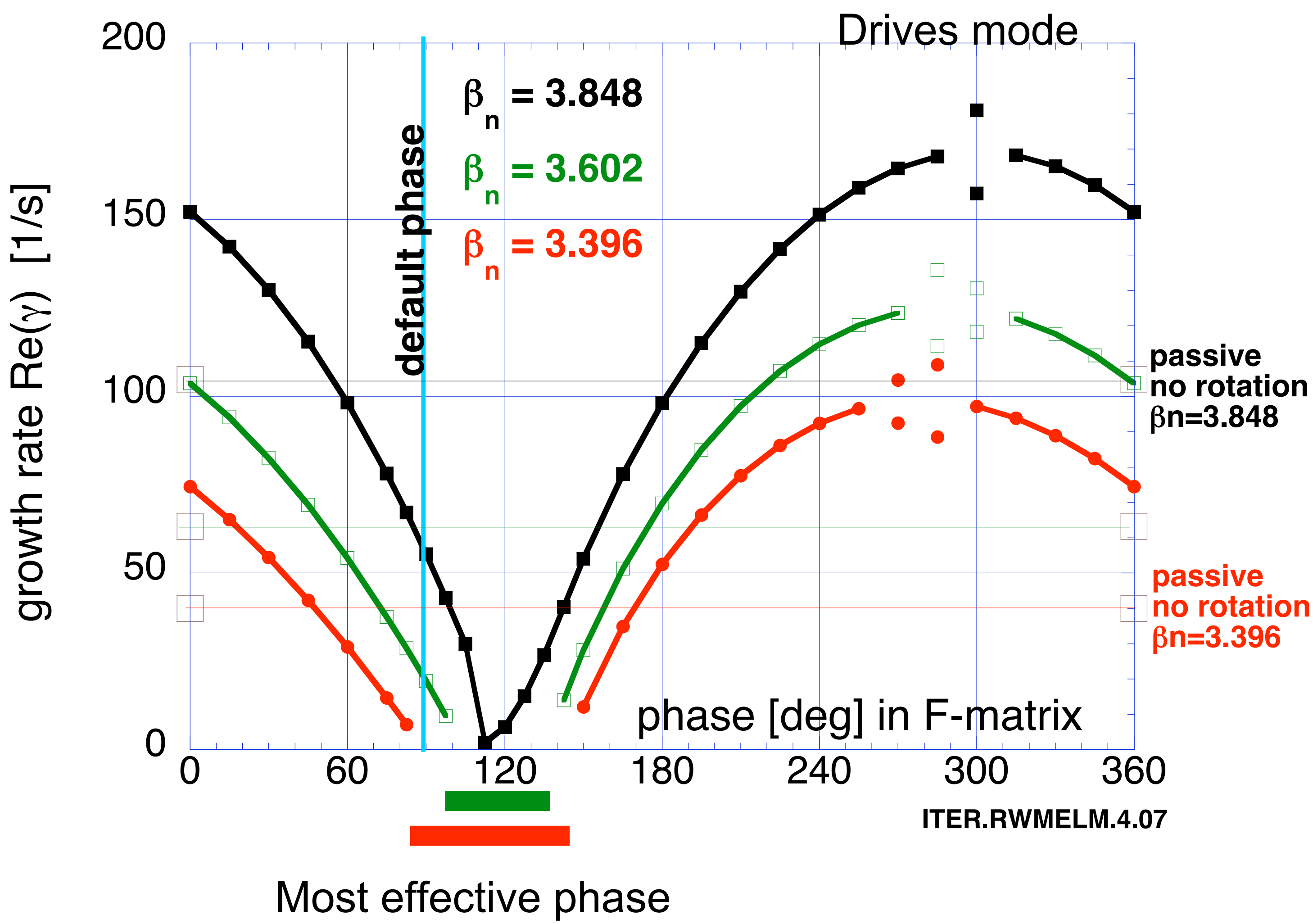
Pick phase δ between sensors and coil V

$$
\begin{Bmatrix} V_1^{coil} \\ . \\ V_C^{coil} \end{Bmatrix}_{Cx1} = G_p\begin{bmatrix} \sin(\phi_1^{coil}+\delta) & \cos(\phi_1^{coil}+\delta) \\ . & . \\ \sin(\phi_C^{coil}+\delta) & \cos(\phi_C^{coil}+\delta) \end{bmatrix}_{Cx2}\left([A]^t[A]\right)^{-1}_{2x2}[A]^t_{2xN}\left\{\Phi^{sensor}\right\}_{Nx1}
$$

VALEN results with rotation and feedback ($G_p=10^8$ [v/w]). Growth rate varies with F-matrix phase and β_n. The plasma has α=0 when feedback is applied

Thin horizontal Lines show results with no rotation

Solid lines show growth rate [1/s]



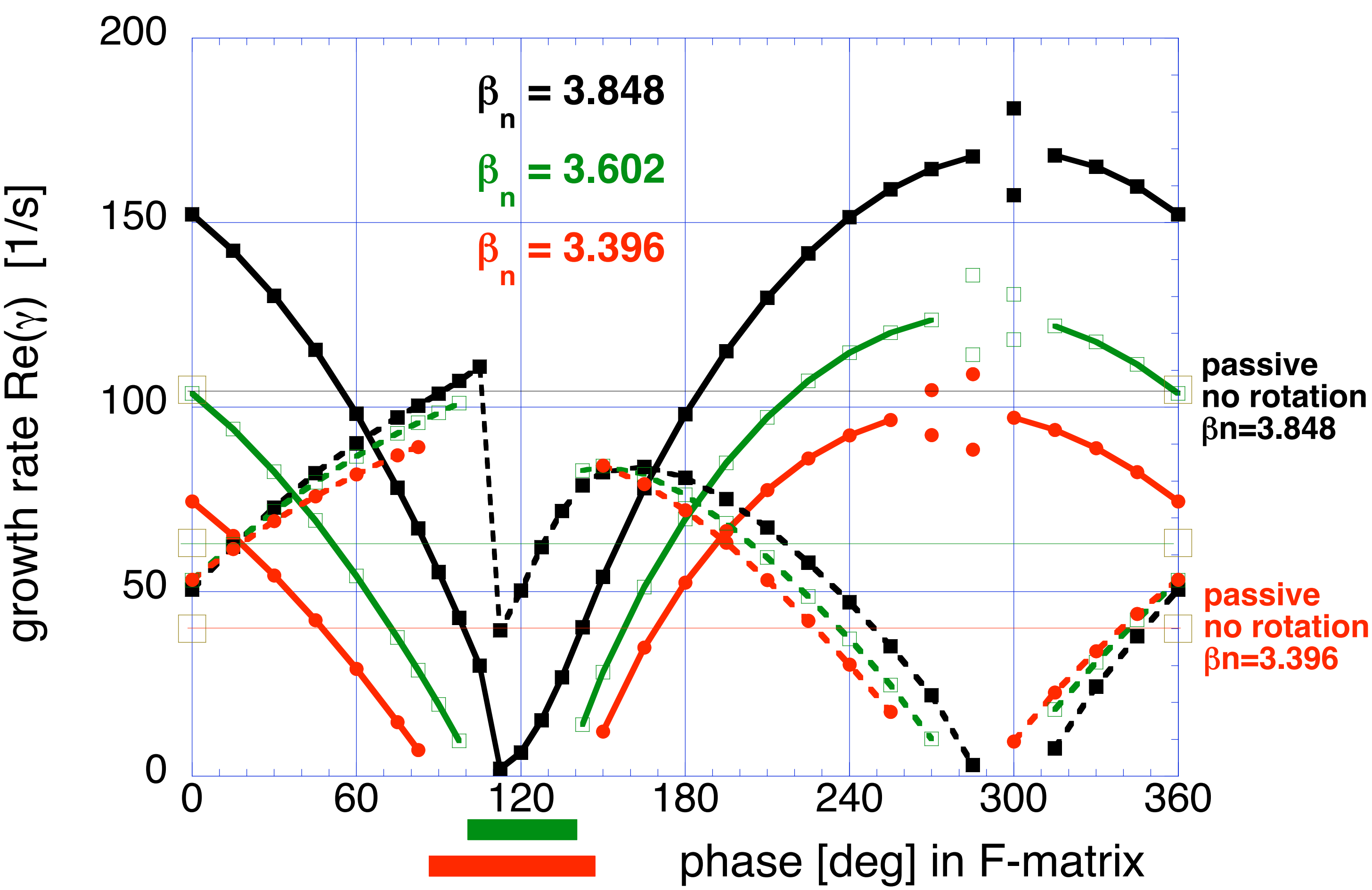
Feedback applies a torque which results in mode rotation.

VALEN with rotation and feedback ($G_p=10^8$ [v/w]), results vary with F-matrix phase and β_n

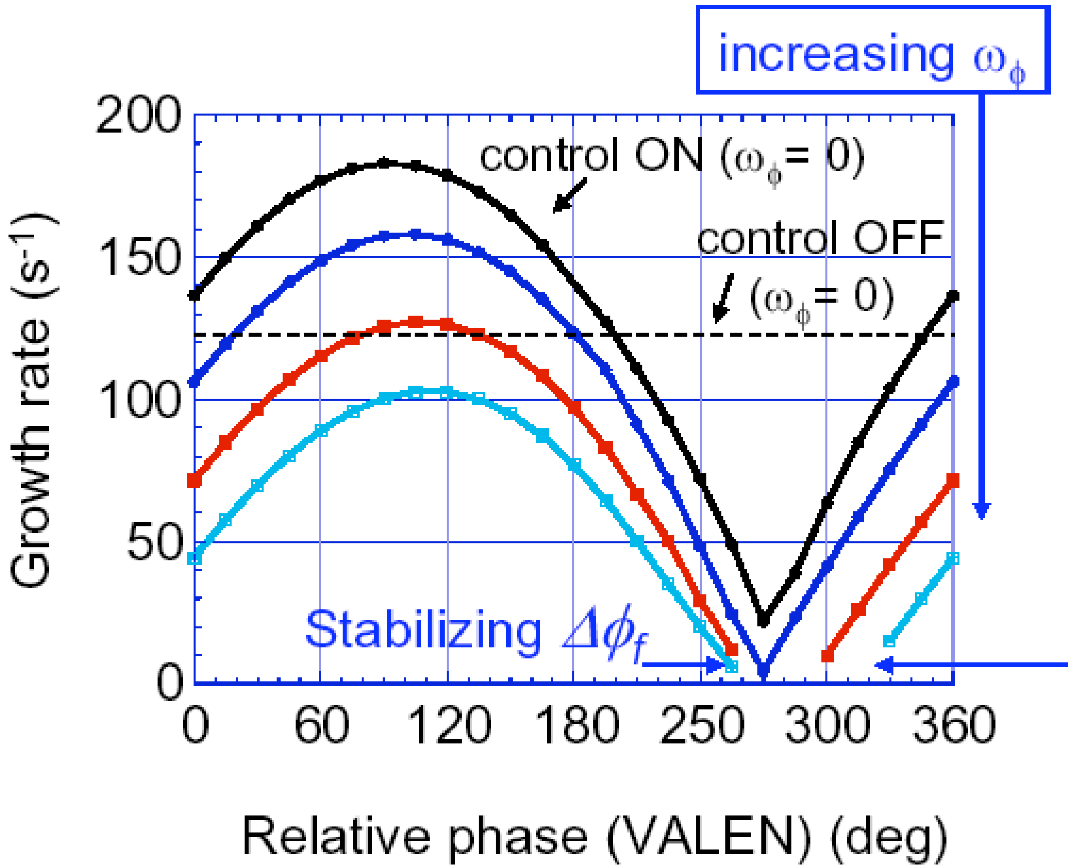
Thin horizontal Lines show results with no rotation

Solid lines show growth rate [1/s]

Dashed lines show mode rotation [r/s]



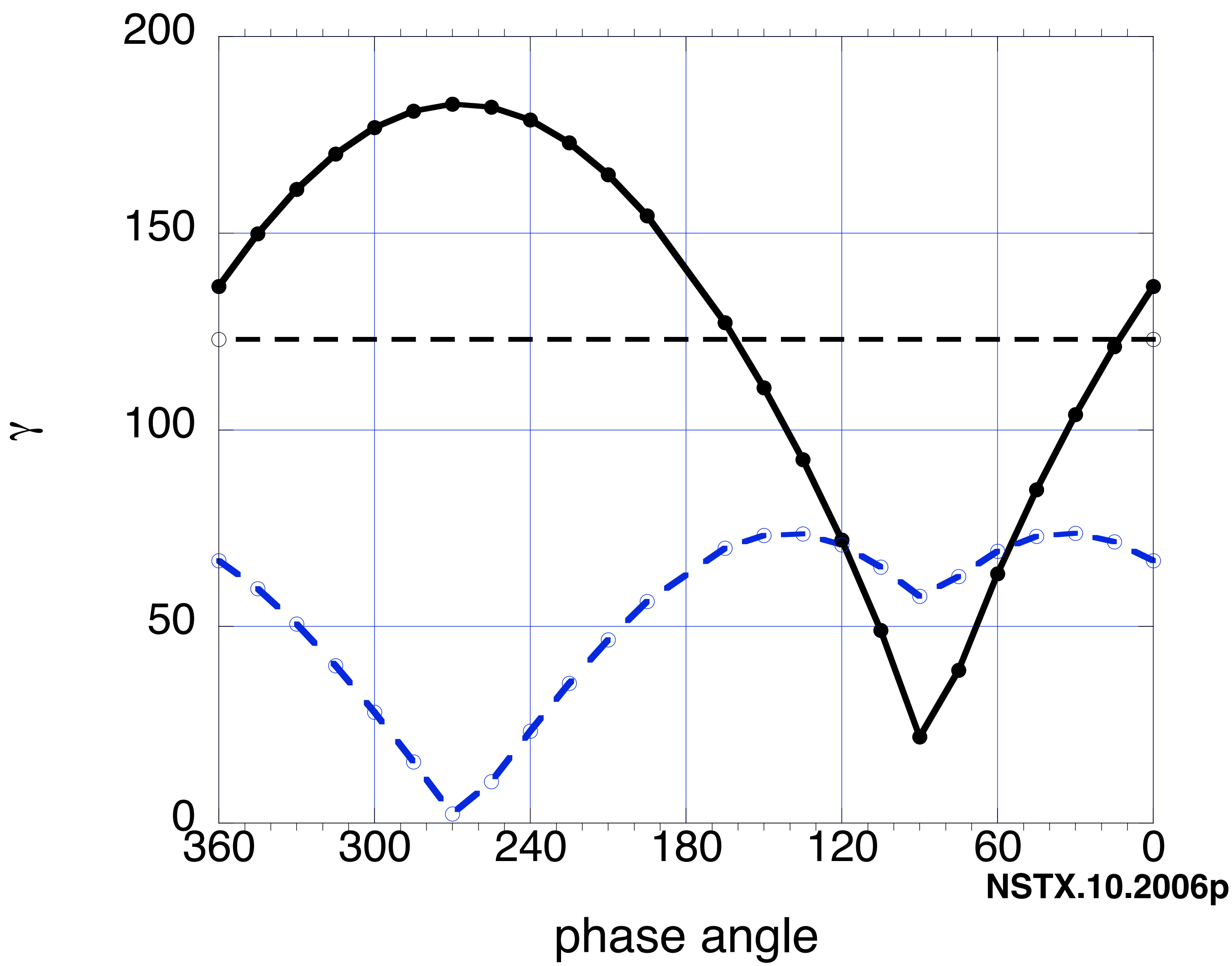
VALEN-3D analysis demonstrates optimal relative phase $\Delta\phi_f$ for RWM active control

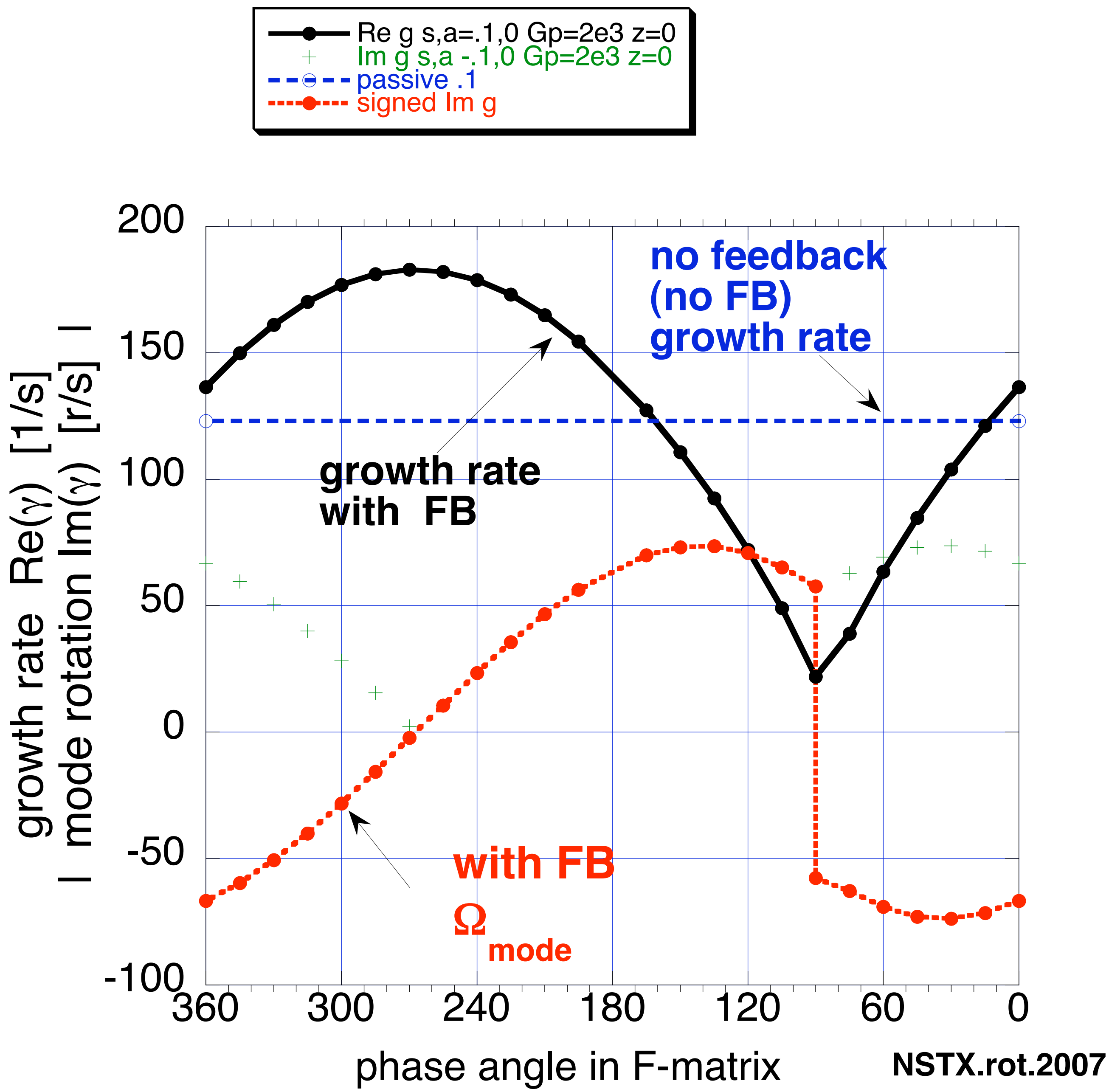


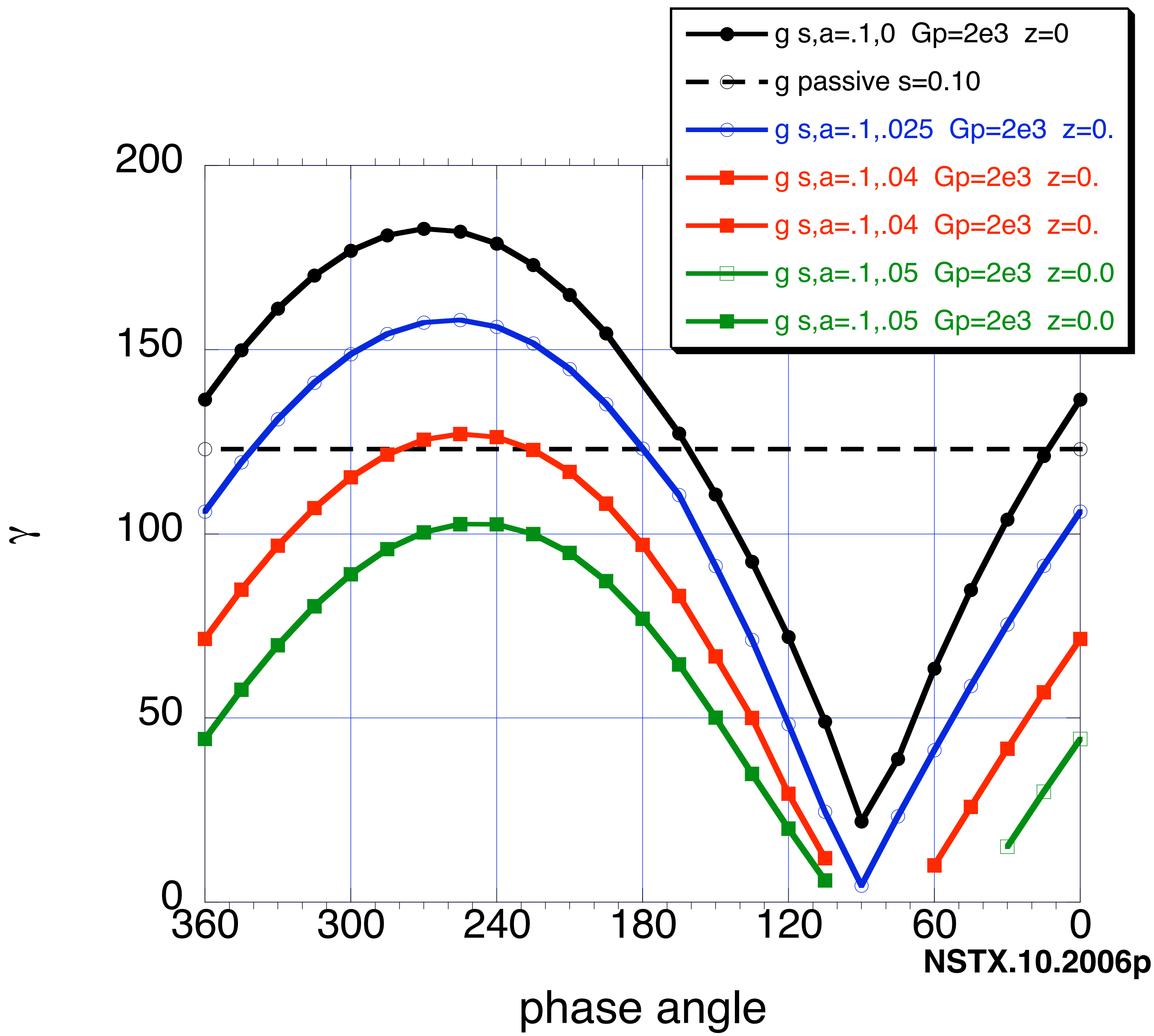
- First VALEN-3D analysis with both active and passive stabilization ($\omega_\phi > 0$)
- Unfavorable $\Delta\phi_f$ drives mode growth
- Stable range of $\Delta\phi_f$ increases with increasing ω_ϕ
- Optimal $\Delta\phi_f$ for active stabilization at $\omega_\phi = 0$ bracketed by results with $\omega_\phi > 0$.

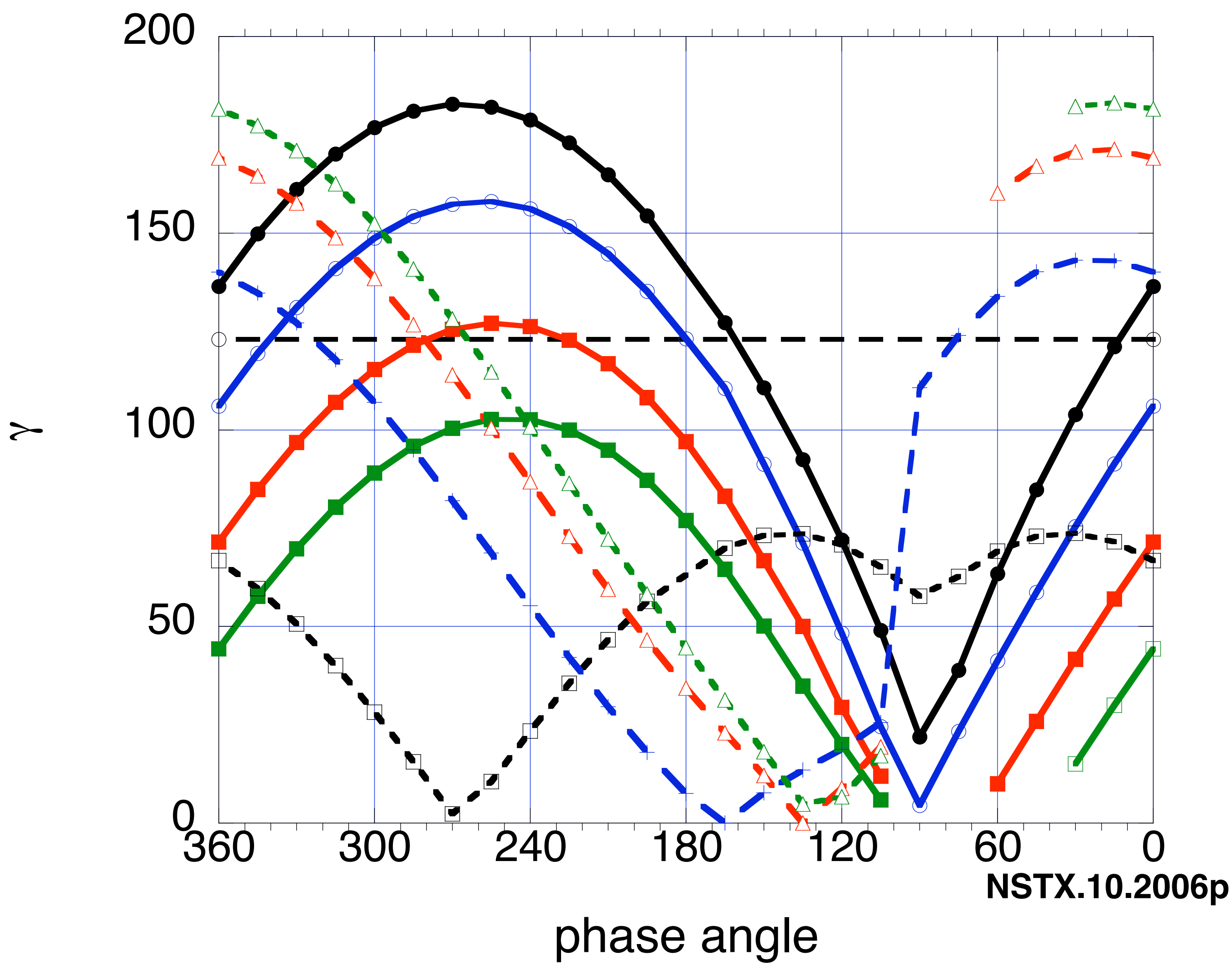
Conclusions & next steps

- VALEN with rotational stabilization includes a toroidal torque balance
- Have found good agreement with NSTX data
- We have investigated the effect of feedback using the 7 mid plane port plug coils with self consistent torque in the VALEN ITER model and found no degradation of feedback performance with $\alpha = 0$.
- Can now explore combination of $\alpha > 0$ with feedback for ITER port plug control coils.
- New capabilities in the time domain now available. Could examine 'ELM' driven RFA with rotation in torque balance.

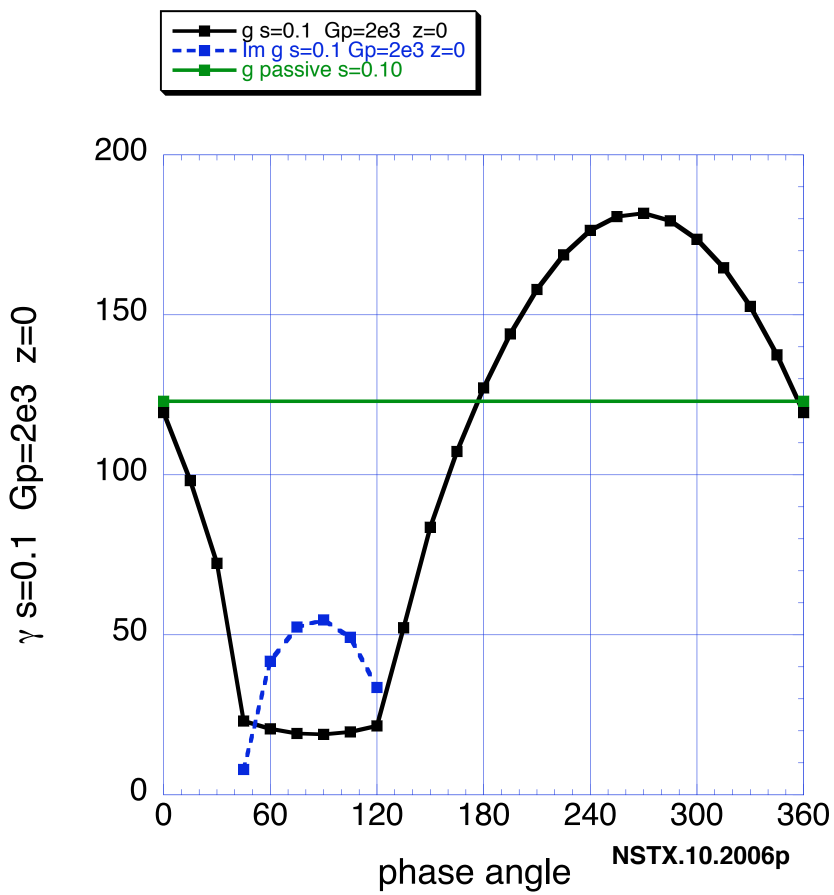

200
150
100
50
0
γ
360
300
240
180
120
60
0
NSTX.10.2006p
phase angle


Re g s,a=.1,0 Gp=2e3 z=0
Im g s,a -.1,0 Gp=2e3 z=0
passive .1
signed Im g
no feedback
(no FB)
growth rate
growth rate
with FB
with FB
Ω
mode
200
150
100
50
0
-50
-100
360
300
240
180
120
60
0
growth rate Re(γ) [1/s]
| mode rotation Im(γ) [r/s] |
phase angle in F-matrix
NSTX.rot.2007

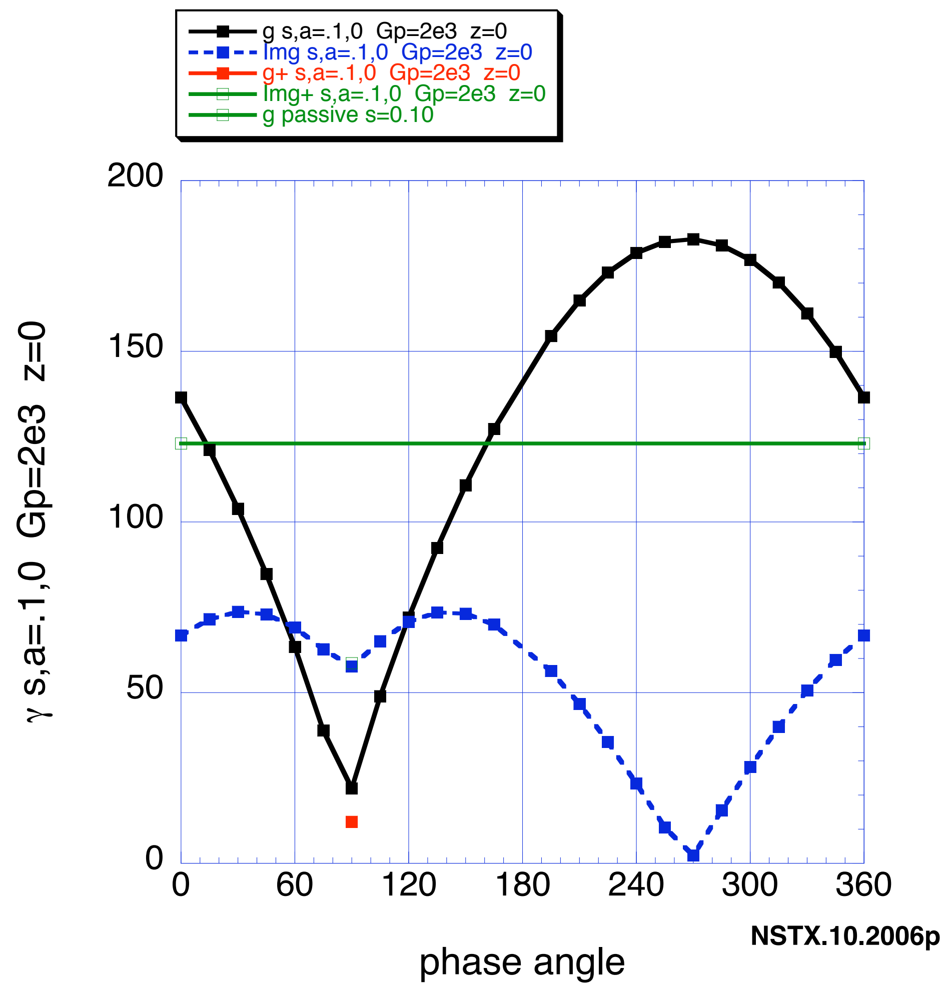

g s,a=.1,0 Gp=2e3 z=0
g passive s=0.10
g s,a=.1,.025 Gp=2e3 z=0.
g s,a=.1,.04 Gp=2e3 z=0.
g s,a=.1,.04 Gp=2e3 z=0.
g s,a=.1,.05 Gp=2e3 z=0.0
g s,a=.1,.05 Gp=2e3 z=0.0
200
150
100
50
0
γ
360
300
240
180
120
60
0
NSTX.10.2006p
phase angle



200
150
100
50
0
γ
360
300
240
180
120
60
0
NSTX.10.2006p
phase angle



g s=0.1 Gp=2e3 z=0
Im g s=0.1 Gp=2e3 z=0
g passive s=0.10
γ s=0.1 Gp=2e3 z=0
200
150
100
50
0
0
60
120
180
240
300
360
phase angle
NSTX.10.2006p



g s,a=.1,0 Gp=2e3 z=0
Img s,a=.1,0 Gp=2e3 z=0
g+ s,a=.1,0 Gp=2e3 z=0
Img+ s,a=.1,0 Gp=2e3 z=0
g passive s=0.10
γ s,a=.1,0 Gp=2e3 z=0
200
150
100
50
0
0
60
120
180
240
300
360
phase angle
NSTX.10.2006p