Feedback and Rotational Stabilization of Resistive Wall Modes in ITER

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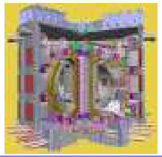

GENERAL ATOMICS

CRPP

Outline

- **Introduction**
- **Stabilization of RWM by toroidal plasma rotation**
  - Damping models
  - Benchmark I: Critical plasma rotation
  - Benchmark II: Resonant field amplification (RFA)
  - Predictions for ITER
- **Feedback stabilization of RWM**
  - Choice of feedback logic
  - Choice of sensors
  - Choice of feedback coils
  - Control optimization for ITER
- **Conclusions**

Introduction

- Advanced tokamaks have good transport properties but low β limits, $\beta_N = \beta/[I_p/(aB_0)] \lesssim 2$.
- $\beta_N > 3$ can be achieved by wall stabilization, but finite wall conductivity gives rise to unstable resistive wall modes (RWM). Steady state advanced scenarios in ITER require RWM stabilization.
- RWM can be stabilized by plasma rotation in present tokamaks (DIII-D, JET), but rotational stabilization may not be robust for ITER.
- For ITER prediction, it is important to understand damping physics of RWM in rotating plasmas: comparison with experiments on critical rotation and on resonant field amplification (RFA).
- Active feedback control opens another possibility for stabilizing (n=1) RWM, thus allows pressure increase up to 40% in ITER advanced scenario.

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Damping models

- **Alfvén continuum damping (MHD)**

$$\gamma\tau_w = -\frac{|\omega_A'|\psi_0 - \delta_0 j\pi\omega_0}{|\omega_A'|\psi_\infty - \delta_\infty j\pi\omega_0} \quad \text{(cylinder)}$$

- **Ion Landau damping, modeled in MARS-F as**
  - **parallel sound wave damping (with free parameter $\kappa_{||}$)**

$$\vec{F}_{\mathrm{visc}} = -\kappa_{||}|k_{||}|v_{th,i}\rho\vec{v}_{||}$$

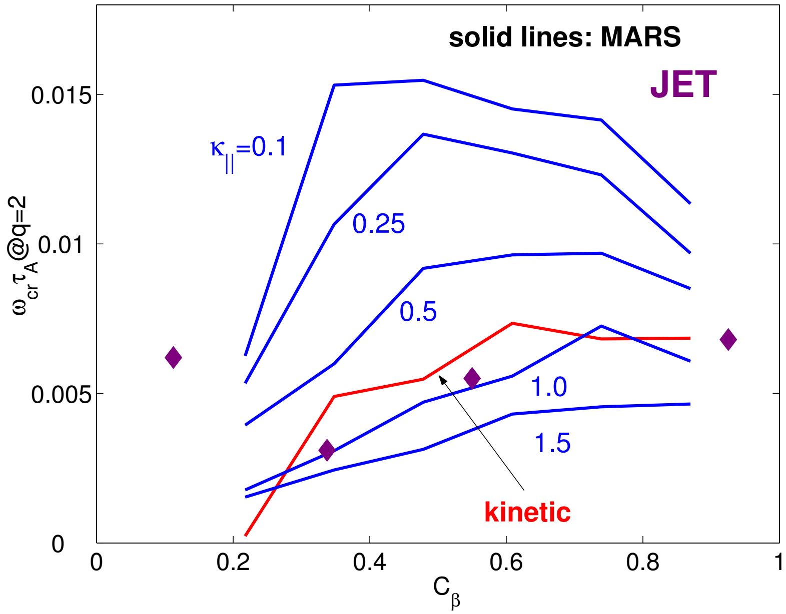
  - **semi-kinetic damping (Bondeson&Chu PoP96)**

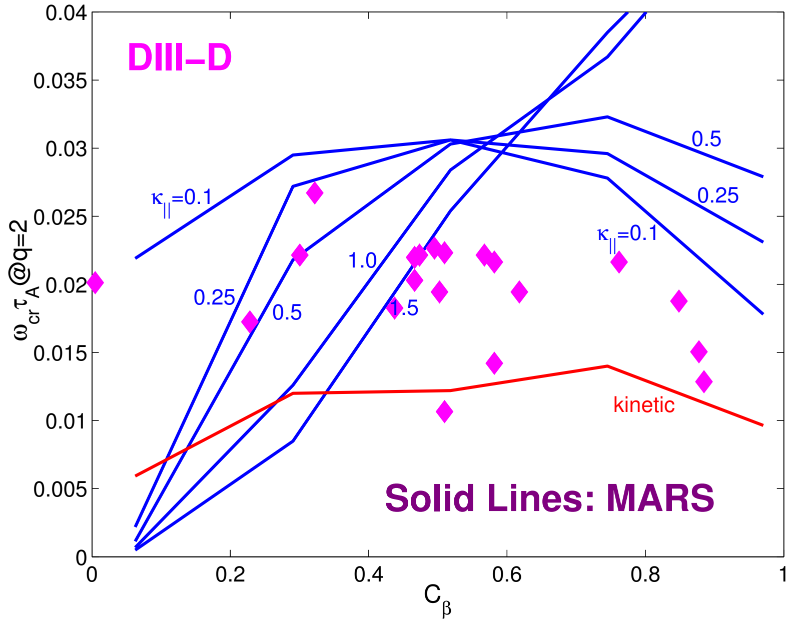
$$j\mathrm{Im}(\Delta W_C + \Delta W_T) = -\frac{1}{2}\int \vec{F}_{\mathrm{diss}} \cdot \vec{\xi}_\perp^* d^3x$$

- **Both critical rotation and RFA experiments offer good benchmark for damping models**

Benchmark I: critical rotation

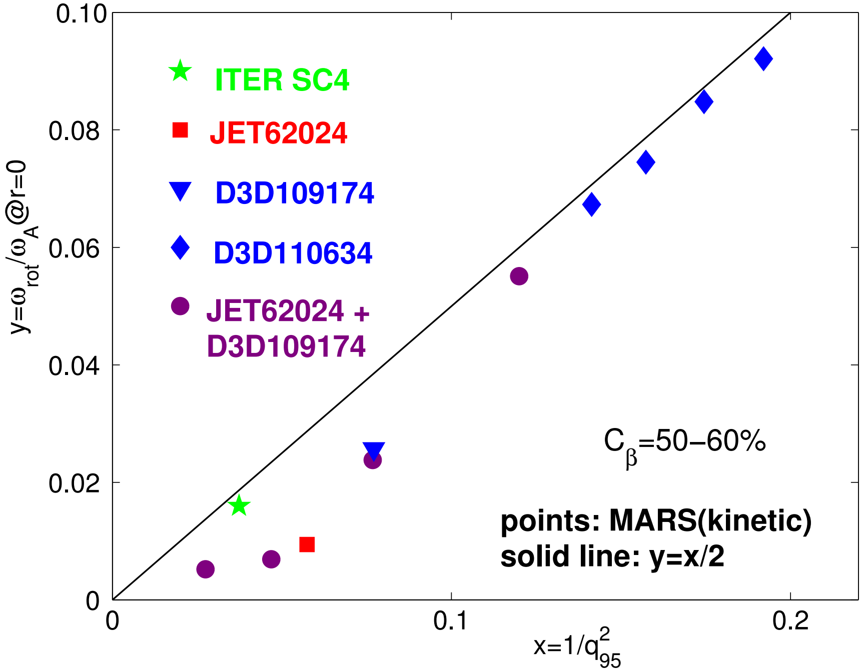
- **Critical rotation $\equiv$ minimal rotation frequency required for complete stabilization of RWM**
- **Usually normalized by Alfvén frequency at plasma center**

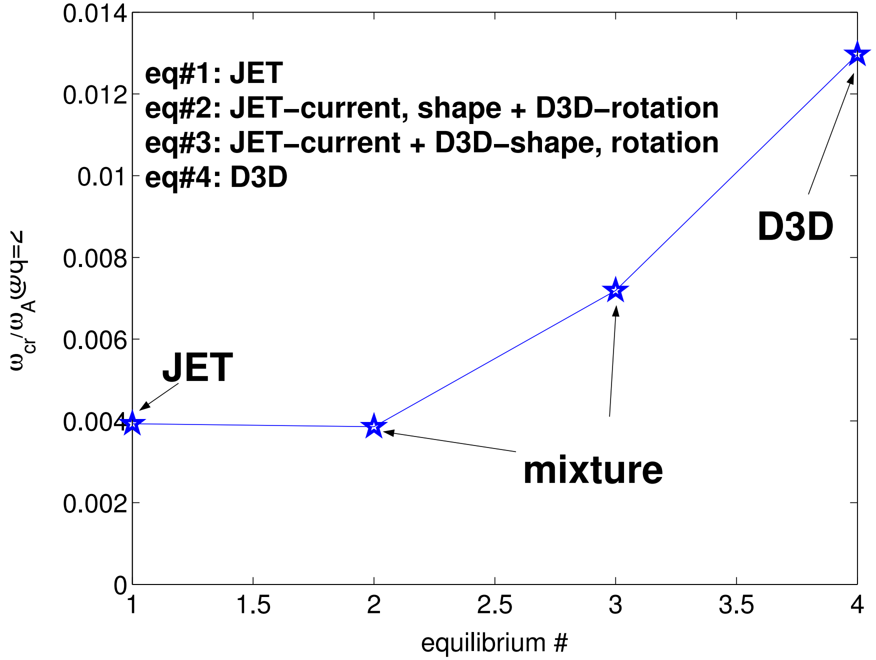




- **MARS-F simulations for JET#62366 and DIII-D#109174**
- $C_\beta = (\beta_N - \beta_N^{no-wall})/(\beta_N^{ideal-wall} - \beta_N^{no-wall})$
- **Parallel sound wave damping has difficulty to model both JET and DIII-D**
- **Semi-kinetic damping seems reasonable**
- **Why critical rotation in JET is 2-4 times lower than in DIII-D?**

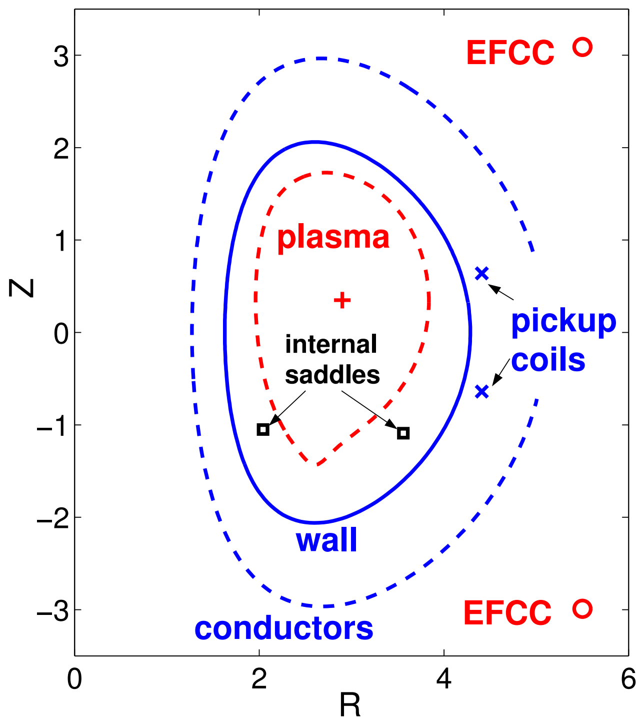
Benchmark I: critical rotation (cont.)



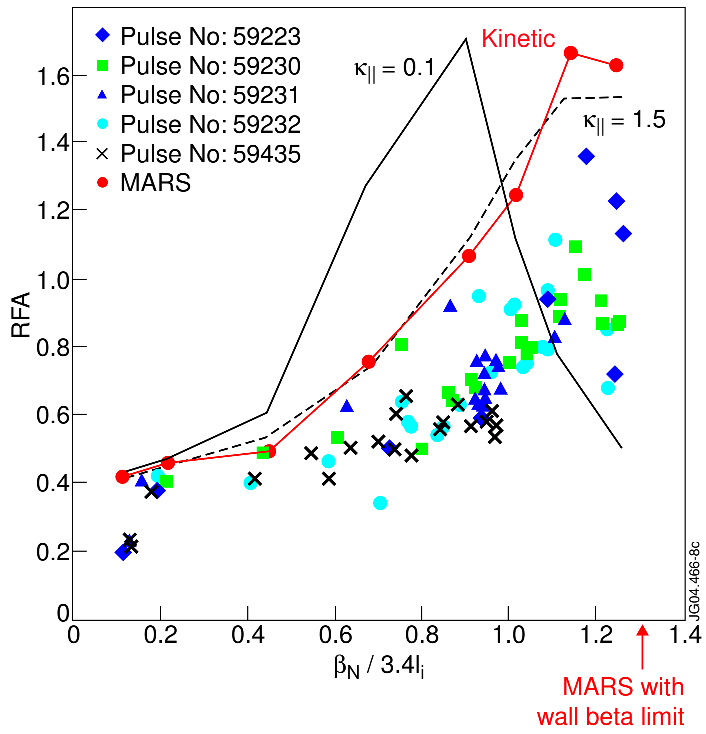


- **Points are MARS-F predictions, not experimental data**
- **Theory (Bondeson&Chu, PoP96) predicts** $\omega_{\rm rot}^{\rm cr} \propto 1/q^2$
- **Rotational stabilization of RWM seems in favor of low-aspect-ratio (high-q)**
- **Difference between JET and DIII-D in equilibria profiles and plasma-wall shapes also change critical rotation**

Benchmark II: resonant field amplification



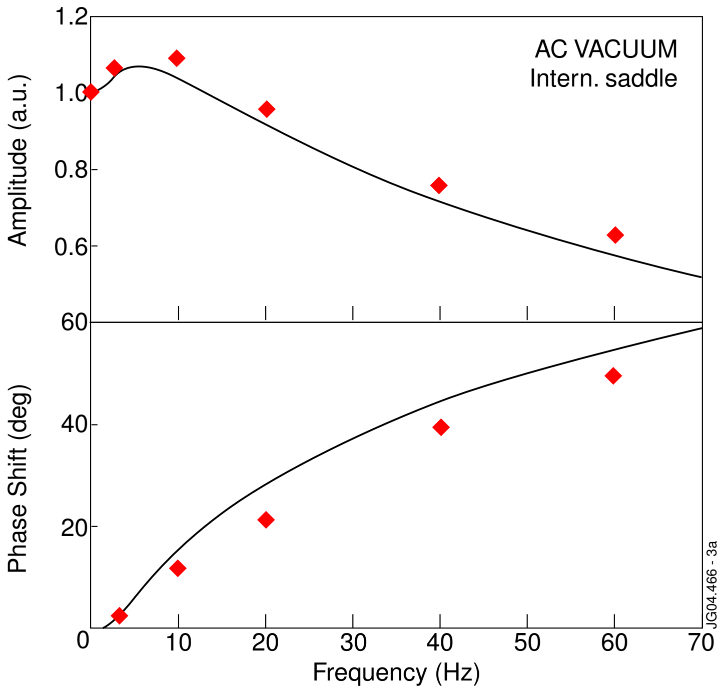
JET



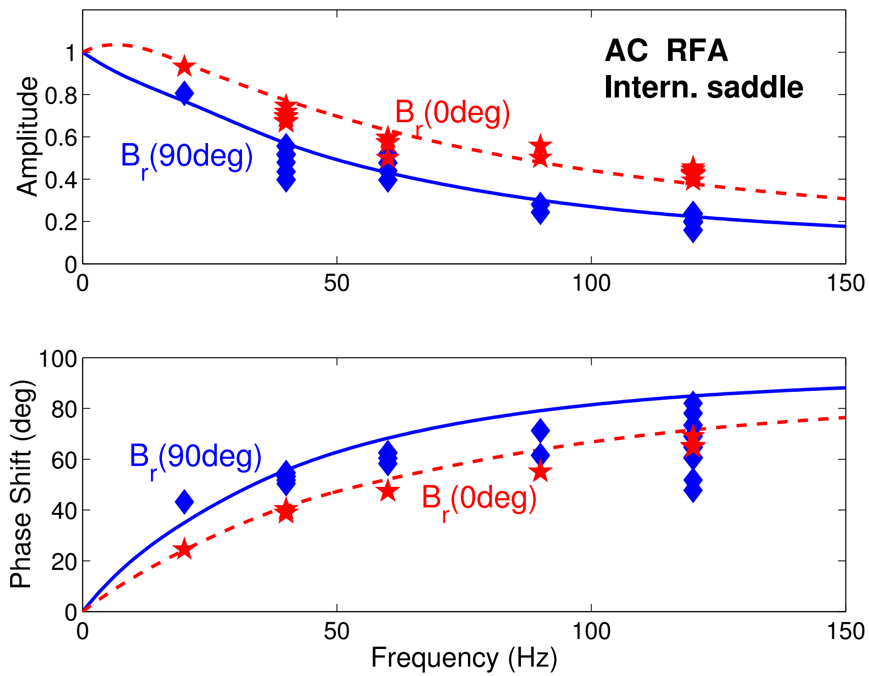
- **RFA in JET: use internal/external saddle coils**
- **Excitation currents: DC(static error field) vs. AC(standing waves)**
- **Comparison: RFA amplitude with DC pulses and internal saddles**
- **MARS-F: both kinetic damping and strong sound wave damping ($\kappa_{\|} = 1.5$) reproduce experimental behavior**

More results in EX/P2-22 by T.C. Hender et al.

Benchmark II: RFA (cont.)

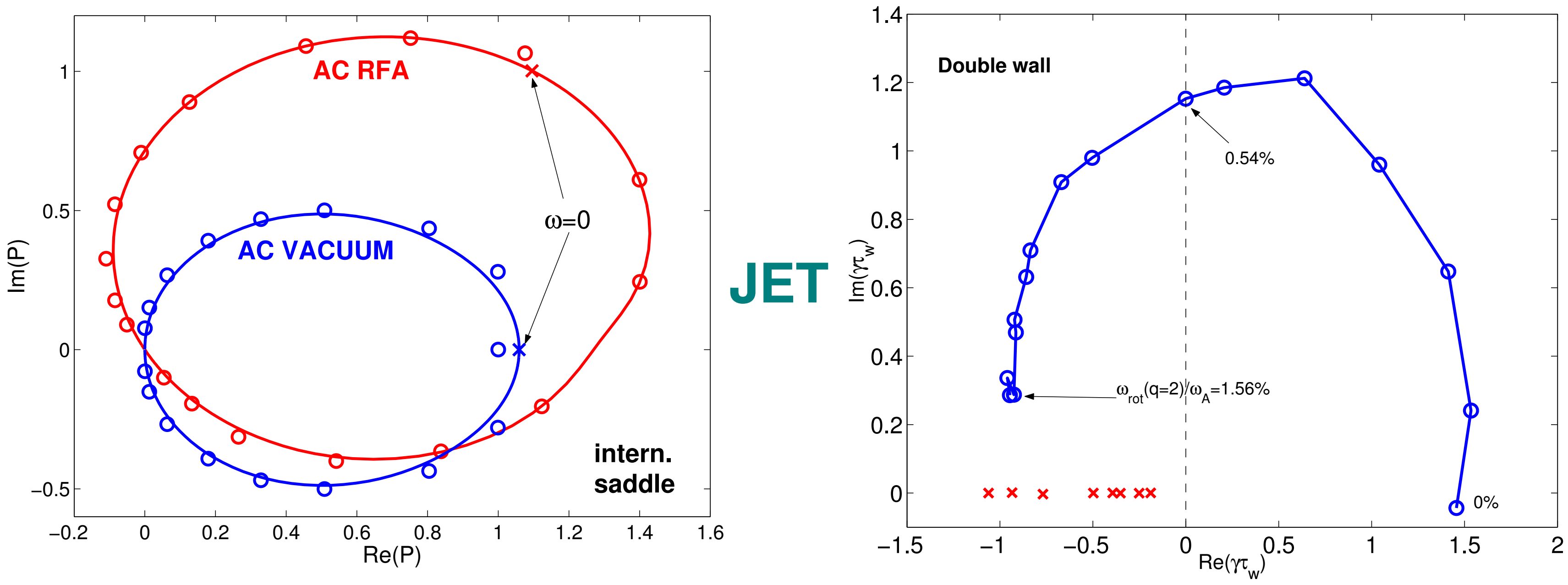


JET



- **Standing waves by internal saddle coils, semi-kinetic damping in modeling**
- **MARS-F results match well with experiments for vacuum shots in both amplitude and phase shift**
- **Reasonable match for plasma responses in both amplitude and phase**
- **Also obtained reasonable agreement for external saddles**

Benchmark II: RFA (cont.)



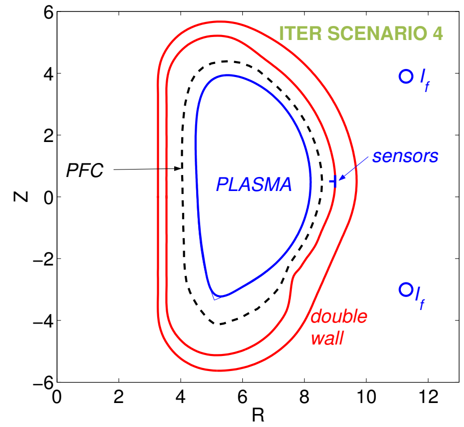
- **Transfer function (for traveling waves) $P(j\omega_c) \equiv \Psi_s(\omega_c)/\Psi_s(\omega_c = 0|\text{vacuum})$ describes completely plasma response**
- **With internal saddles, plasma significantly modifies vacuum response**

$$P(j\omega_c) = \frac{1.008 + j0.535}{j\omega_c + 0.884 - j0.281} + \frac{0.045 + j0.031}{j\omega_c + 0.176}$$

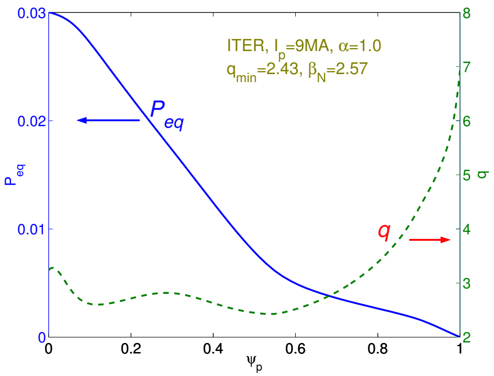
- **The 1st pole of P shows that internal saddle coils indeed excite RWM that is stabilized by strong plasma rotation**

Predictions for ITER

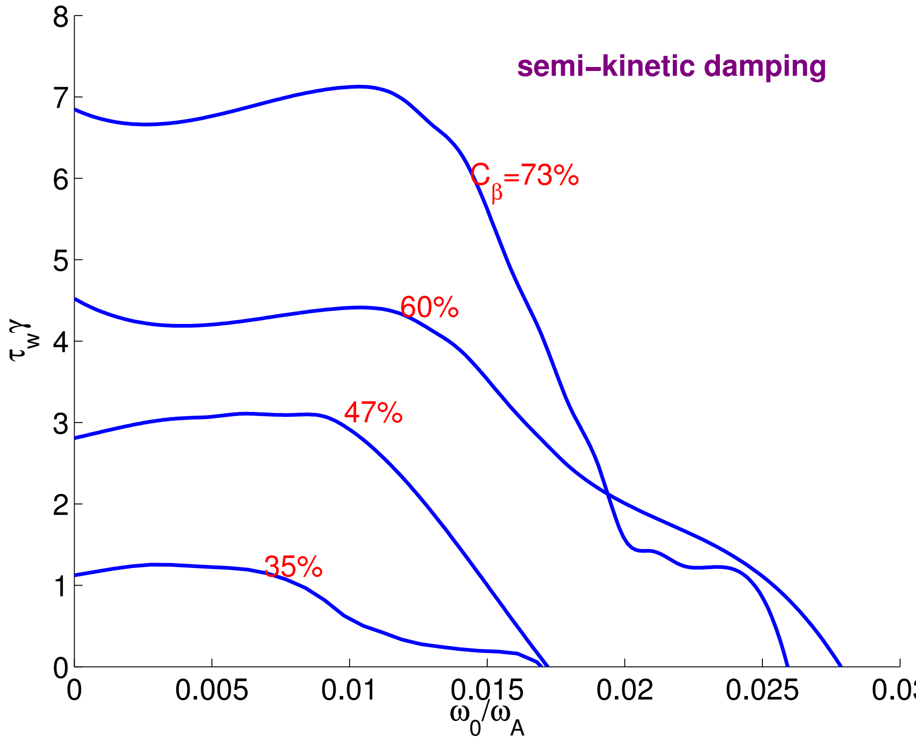
- **ITER steady state Scenario-4 with weak negative magnetic shear and highly shaped plasma**
- **Total plasma current = 9MA, fusion power production = 340MW at $Q = 5$**



ITER geometry



Equilibrium profiles



RWM growth rate vs toroidal rotation frequency. Critical rotation frequency about 1.5-3%ω_A at plasma center. ASTRA prediction: $\leq$ 2%.

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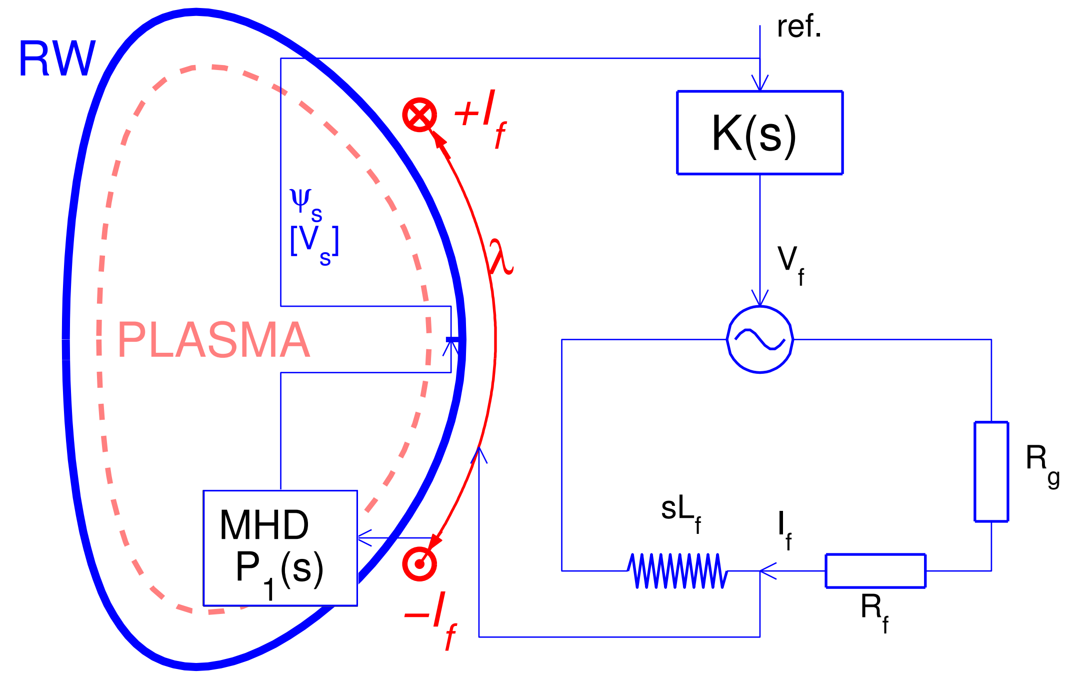
Choice of feedback logic



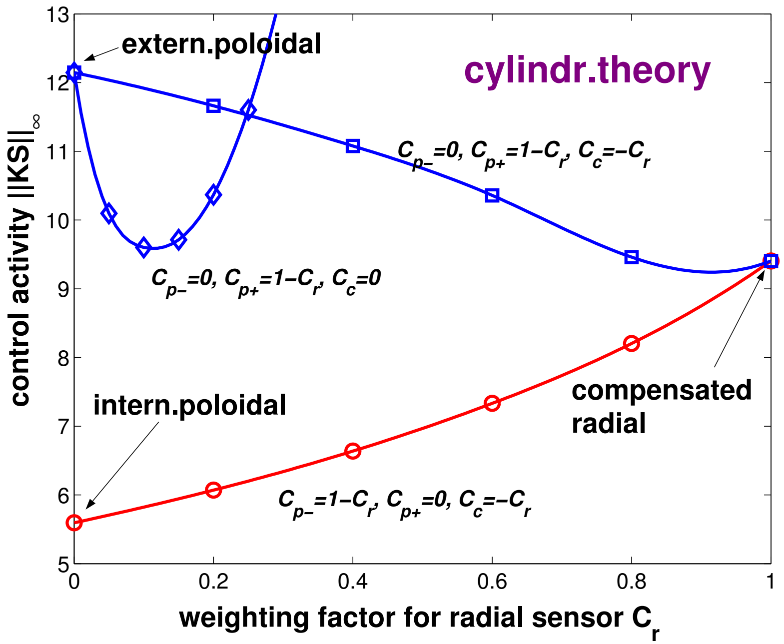
- **Voltage-to-voltage control:** $V_f = -KV_s$

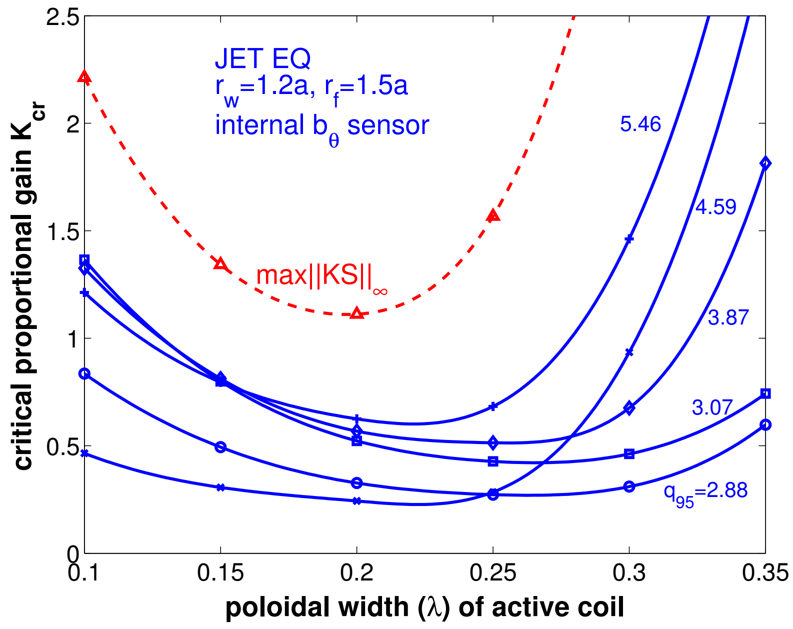
$$V_f = \frac{d\Psi_f}{dt}, \qquad V_s = \frac{L_f}{M_{sf}}\frac{d\Psi_s}{dt}$$

- **Plasma dynamics determined by** $P_1 = \frac{\Psi_s}{M_{sf}I_f}$, $P_2 = \frac{\Psi_f}{L_f I_f}$ **– frequency dependent transfer functions, computed by MARS-F**

- $\lambda \equiv$ **fraction of poloidal width subtended by active coil**

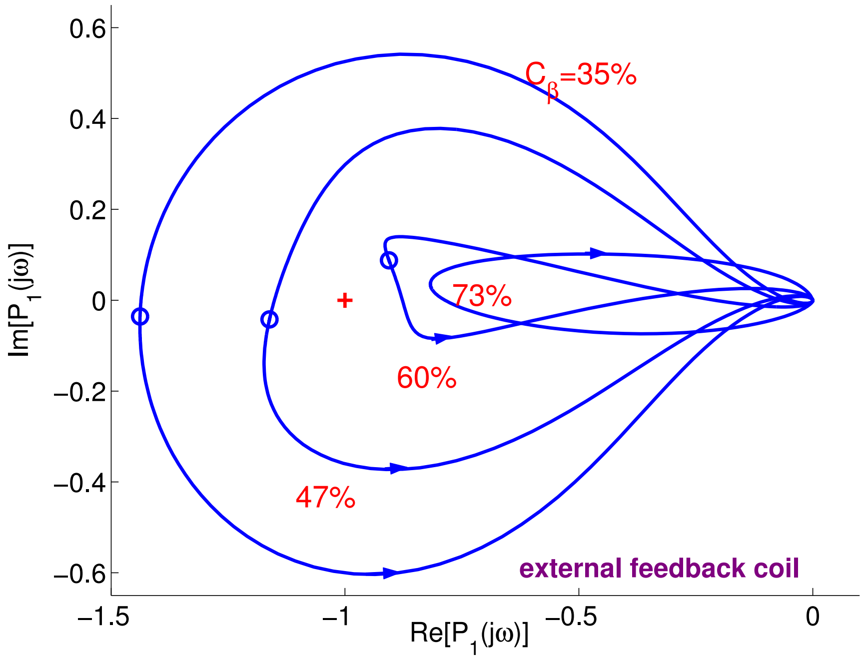
Choice of sensors

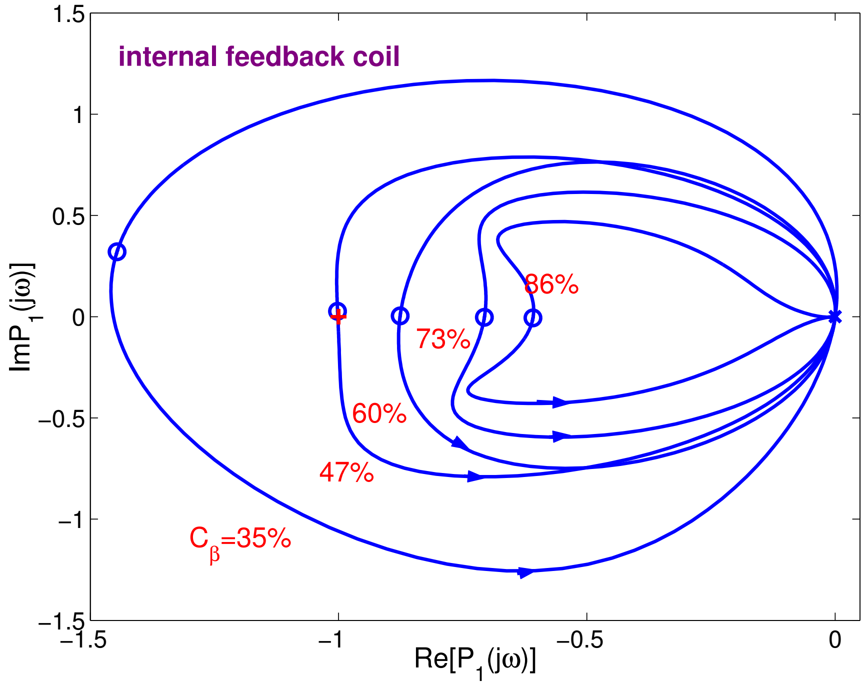




- One can consider various sensors: radial, internal/external poloidal, compensated radial, their combinations
- Cylindrical theory $\Longrightarrow$ internal poloidal sensors the best
- Main reason: less coupling to feedback coils, better coupling to plasma
- Toroidal calculations $\Longrightarrow$ internal poloidal sensors allow robust control against variations of feedback coil geometry, as well as global plasma parameters

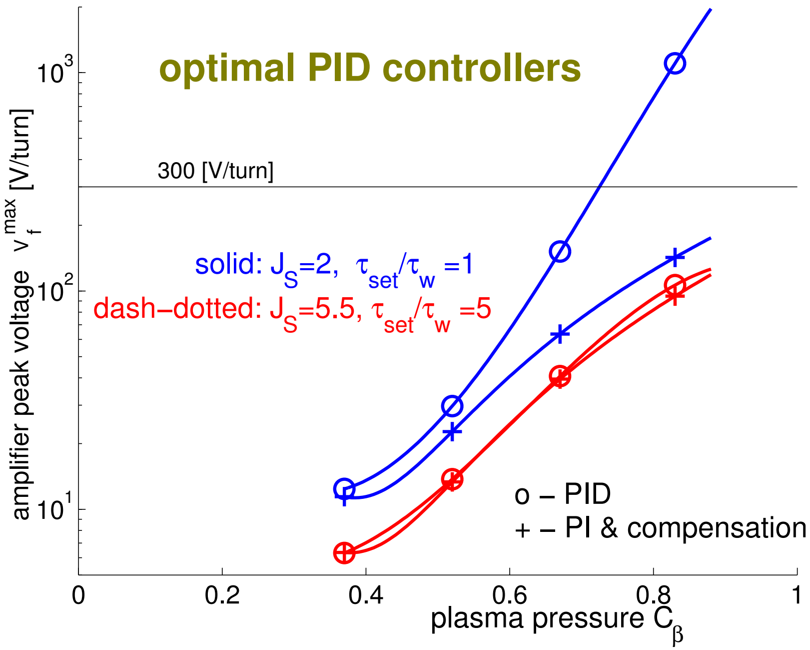
Choice of feedback coils





- **Present ITER design uses Side Correction Coils (superconducting, external to the ITER walls) for $n = 1$ RWM feedback control**
- **Nyquist diagram for open loop $K(j\omega)P_1(j\omega)$ shows stability and (partly) performance of closed loop: Stability $\Longleftrightarrow$ Nyquist curve encircles -1 once counterclock-wise**
- **External coils allow stabilization for $C_\beta \lesssim 60\%$, using large enough proportional gains**
- **Internal coils (just inside first wall) allow stabilization of RWM for plasmas close to ideal wall limit, using large enough proportional gains**

Control optimization for ITER



- **Required peak voltage of amplifier vs. plasma pressure (C_β)**
- **Blue: good control performance**
- **Red: loose control performance**
- **"o": Optimal PID with poloidal sensors**
- **"+": Optimally compensated poloidal sensors**

- **For ITER: voltage-to-voltage control, internal poloidal sensors, Side Correction Coils, PID controllers, controls turn on at sensor field $\geq$ 1.5mT**
- **With good(loose) control performance, RWM can be stabilized up to $C_\beta = 60\%(80\%)$ within voltage limit of 300V/turn**
- **Optimally compensated sensor signals $\Rightarrow C_\beta > 80\%$ and good performance reachable**
- **Assumed ideal amplifier, neglected: 3D effect of ITER walls, sensitivity to model disturbances, superconducting coils ac losses**

Conclusions

- **Toroidal ideal-MHD model is close to correct for modeling RWM, and ion Landau damping needs to be correctly modeled.**

- **New semikinetic model from drift-kinetic theory gives reasonable description of ion Landau damping, both for critical rotation and RFA experiments.**

- **MARS-F with kinetic damping predicts critical rotation speed for RWM stabilization in ITER at 1.5-3%v_A (at plasma center). ITER may not have sufficient rotation to stabilize the mode.**

- **The $n = 1$ RWM in ITER can be feedback controlled for β up to $\beta^{\text{no wall}} + C_\beta(\beta^{\text{ideal wall}} - \beta^{\text{no wall}})$ with $C_\beta \sim 0.6 - 0.8$, by**
  - **single feedback coil outside the resistive wall**
  - **poloidal sensors inside the vessel**
  - **PID controller**

- **Future work:**
  - **Rotation: kinetic damping with more physics**
  - **Feedback: realistic amplifier, 3D wall effects, system noises, superconducting coil AC losses etc.**