Modeling Resonant Field Amplification in JET

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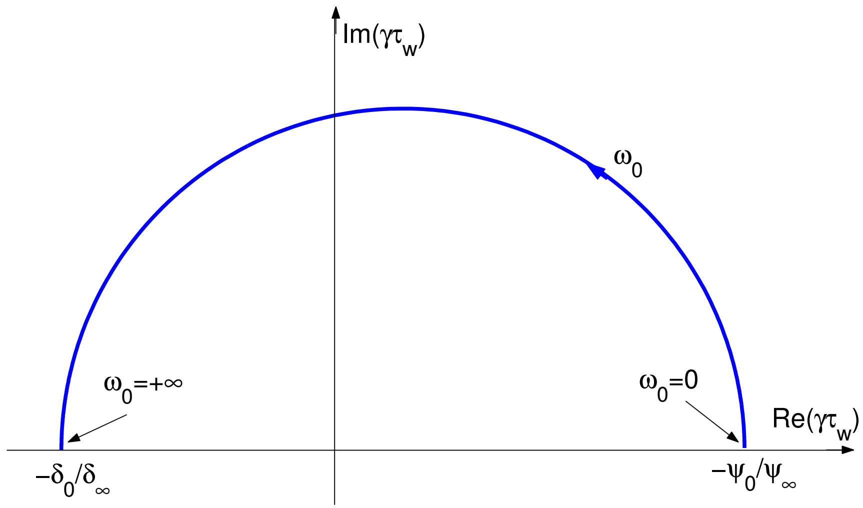
Outline

- Damping models in MARS-F
  - Benchmark: critical rotation for RWM stabilization
- Simulations of RFA experiments in JET
  - internal saddles/external coils (EFCC)
  - static error fields/traveling waves
- Conclusions and discussions

Alfvén continuum damping (MHD) – cylindrical theory

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

- $\psi_0 < 0$: no-wall solution @ r_s
- $\psi_\infty > 0$: ideal-wall solution @ r_s
- $\delta_0 \equiv \psi_0'(r_s^+) - \psi_0'(r_s^-) > 0$
- $\delta_\infty \equiv \psi_\infty'(r_s^+) - \psi_\infty'(r_s^-) > 0$
- $\omega_0 =$plasma rotation frequency



- **Resonances:** $\omega_0 = \pm k_{\|} v_A = \pm\omega_A(x)$ **near rational surfaces.**
- **Assumption: RWM growth rate** $\gamma = O(1/\tau_w) \ll \omega_0$**, so** $\gamma \simeq 0$ **is a good approximation inside the plasma.**

Ion Landau damping (kinetic), modeled in MARS-F as

A. parallel sound wave damping

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

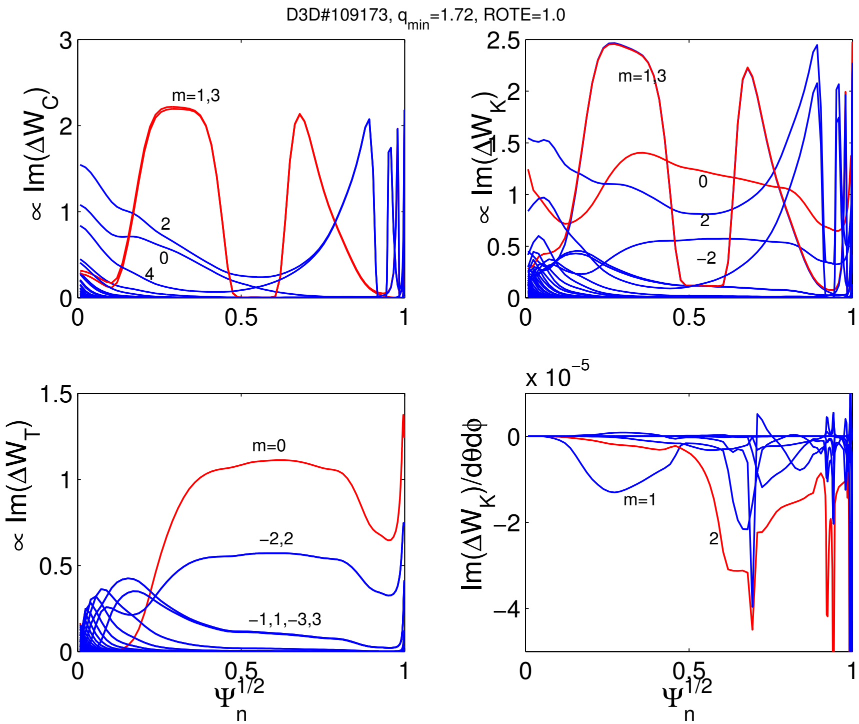
- $\kappa_{\parallel}$ is free parameter in model
- $\kappa_{\parallel} = \sqrt{\pi}$ in cylinder
- thought to be small due to trapped particles in torus

B. semi-kinetic damping

- **Follow simplified drift-kinetic large-aspect-ratio analysis (Bondeson & Chu 1996)**
- **Take imaginary part of kinetic ΔW evaluated for $\omega = \omega_0$ and add as a force acting on $\vec{v}_\perp$**

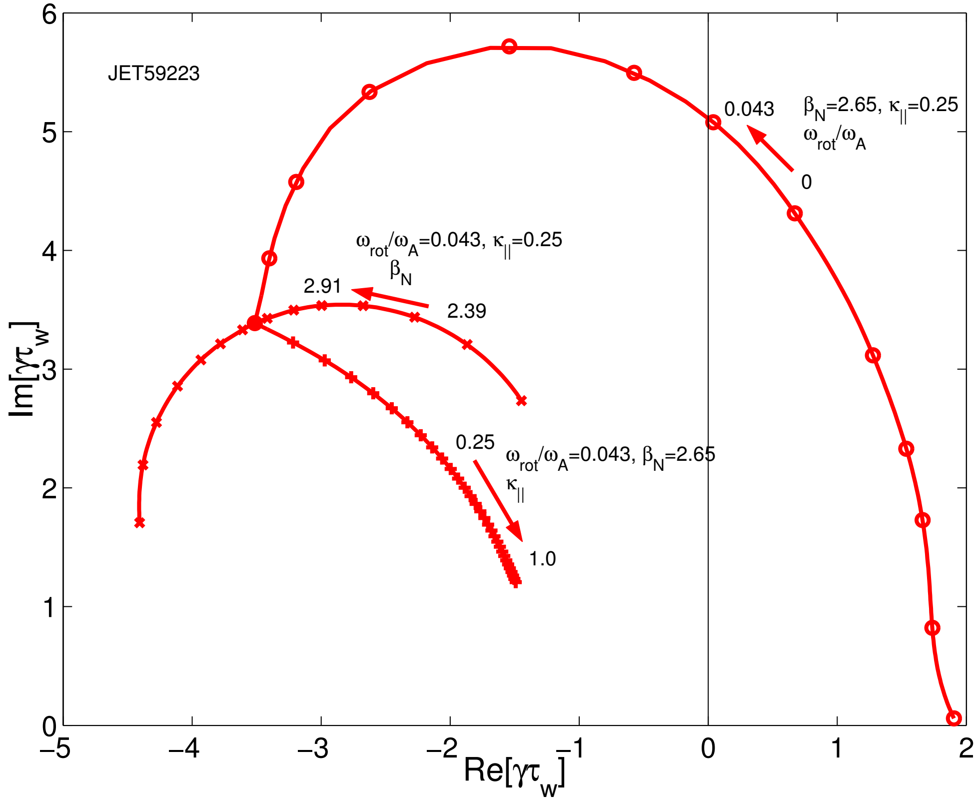
$$j\mathrm{Im}(\Delta W_C + \Delta W_T) = -\frac{1}{2}\int \vec{F}_{\mathrm{diss}} \cdot \vec{\xi}^*_\perp d^3x$$

- **Toroidal coupling: m component of $\vec{b}$ couples to $m \pm 1$ components of parallel motion**
- **Provides non-local, strong damping**
- **Assumptions:**
  - $\omega_0 >> \omega_{RWM}$
  - **diamagnetic drift frequency $\omega_* = 0$**
  - **gyrocenter drift frequency $\omega_d = 0$**
  - **electrostatic potential $\Phi = 0$**



Damping models in MARS-F

Typical toroidal calculations with sound wave damping

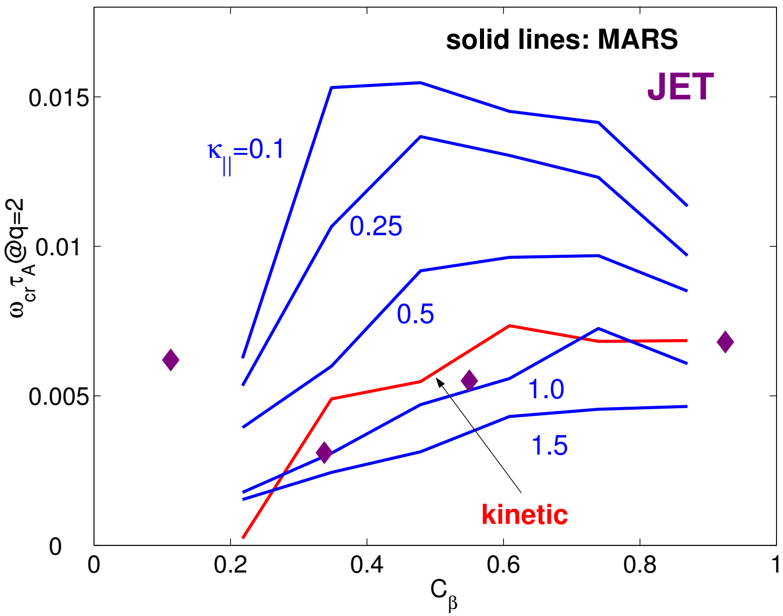


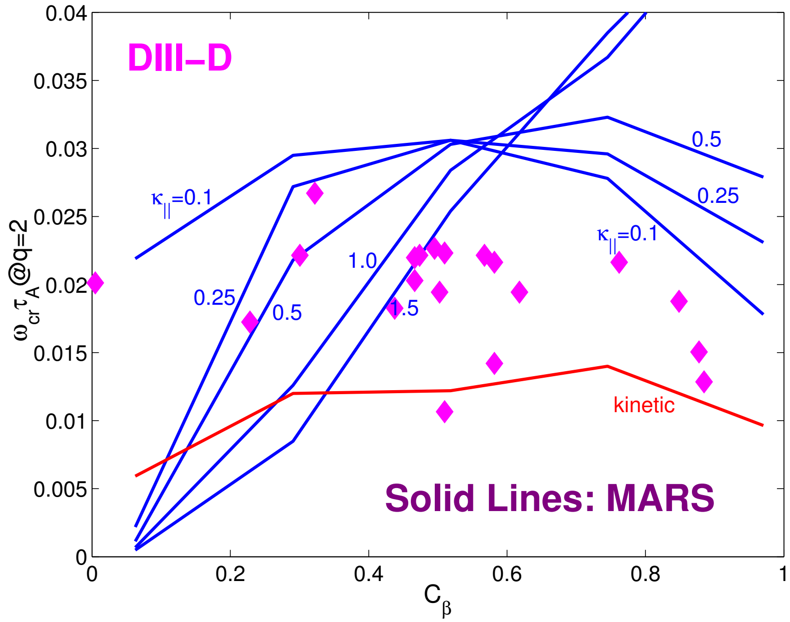
Vary parameters:

- **plasma toroidal rotation frequency** $\omega_{\rm rot}/\omega_A = 0 - 0.043 \quad @ \quad \kappa_{\|} = 0.25, \beta_N = 2.65$
- **free parameter** $\kappa_{\|} = 0.25 - 1.0 \quad @ \quad \omega_{\rm rot}/\omega_A = 0.043, \beta_N = 2.65$
- **plasma pressure** $\beta_N = 2.39 - 2.91 \quad @ \quad \omega_{\rm rot}/\omega_A = 0.043, \kappa_{\|} = 0.25$

Benchmark: critical rotation

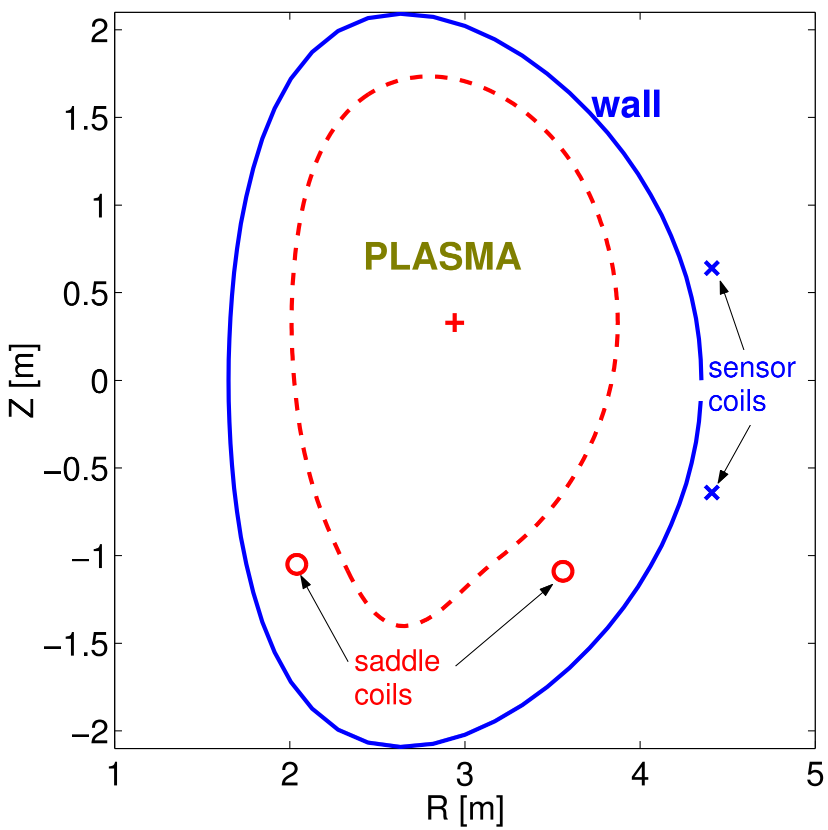
- **Critical rotation $\equiv$ minimal rotation frequency required for complete stabilization of RWM**
- **Usually normalized by Alfvén frequency at plasma center**

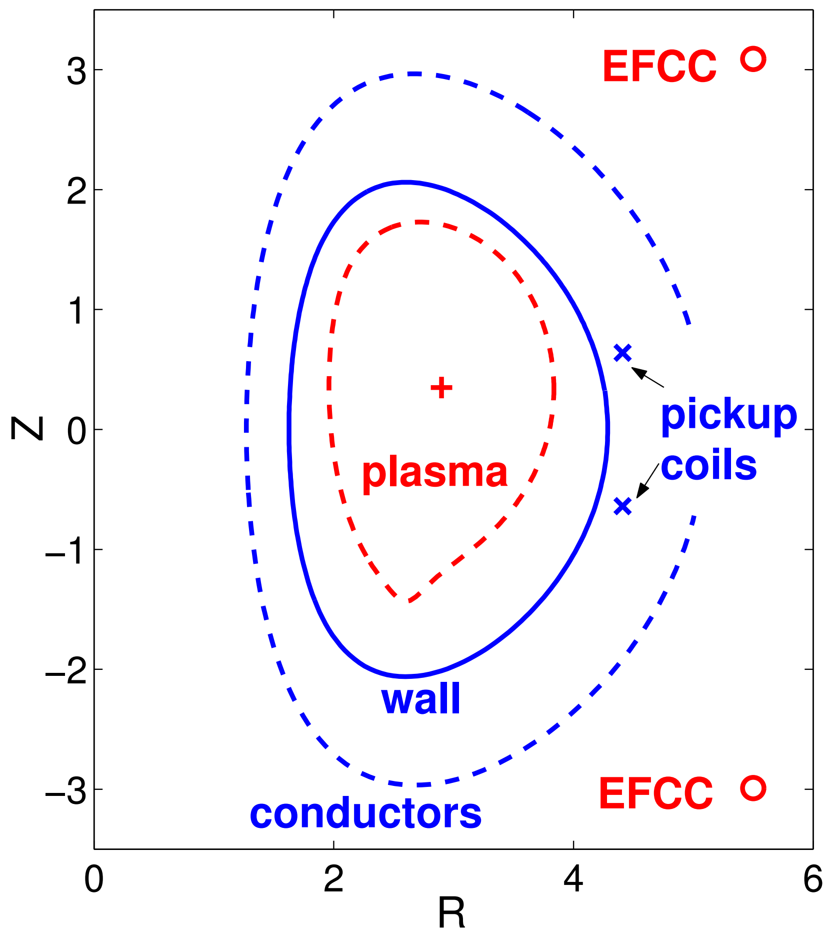




- **MARS-F simulations for JET#62366 and DIII-D#109174**
- $C_\beta = (\beta_N - \beta_N^{\mathrm{no-wall}})/(\beta_N^{\mathrm{ideal-wall}} - \beta_N^{\mathrm{no-wall}})$
- **Parallel sound wave damping has difficulty to model both JET and DIII-D**
- **Semi-kinetic damping seems reasonable**
- **Critical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

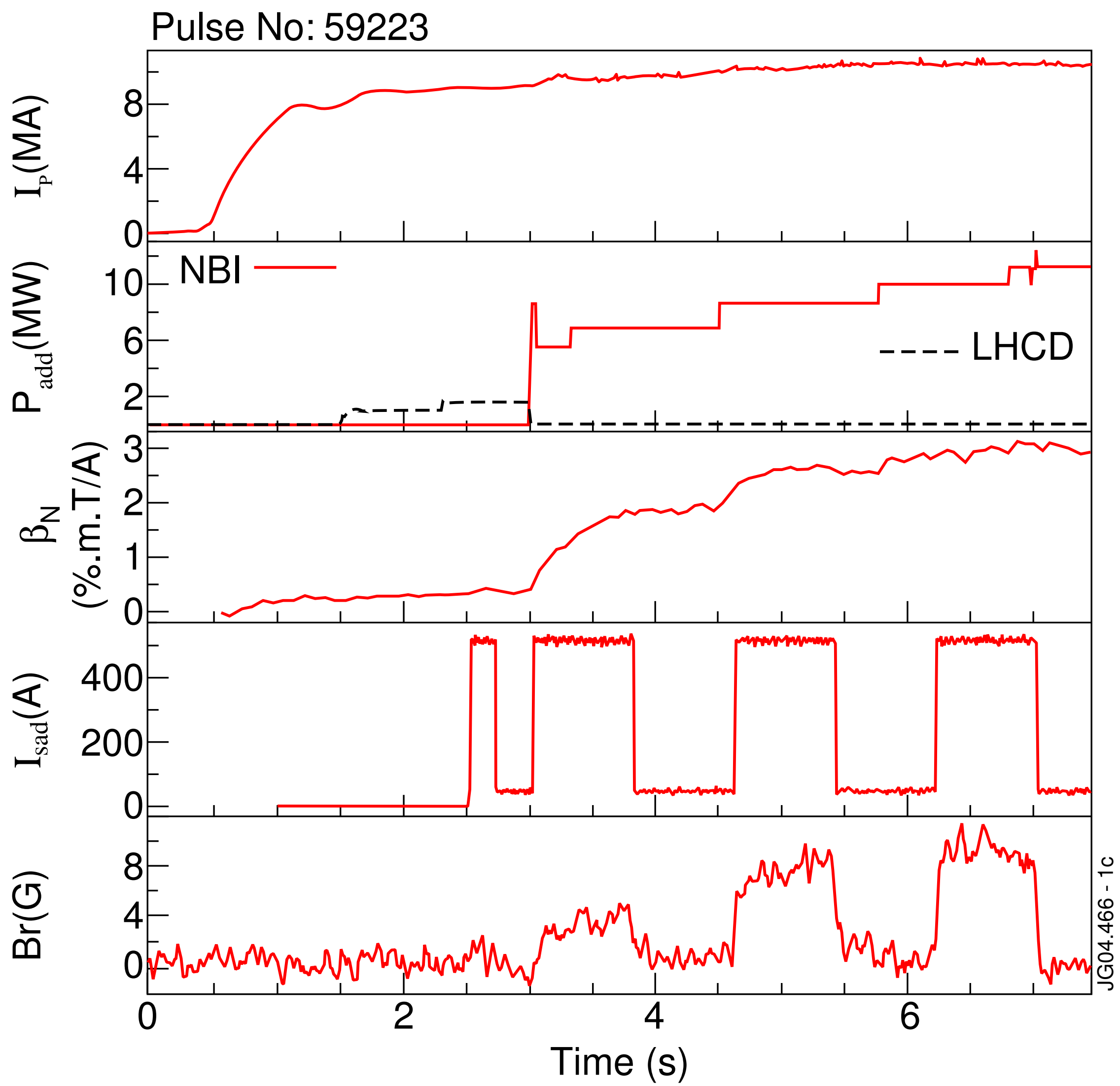
RFA geometry in JET





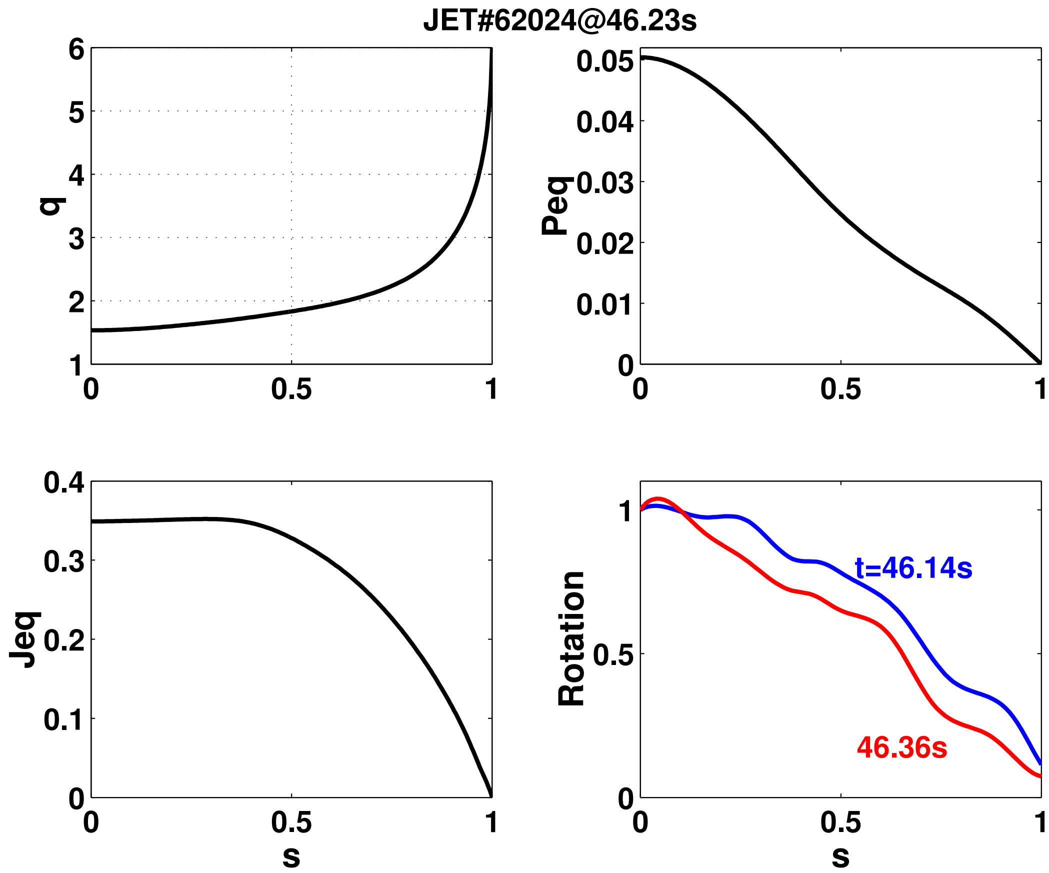
- RFA in JET: internal saddles/external coils (EFCC)
- Excitation currents: DC(static error field) vs. AC(standing waves)
- For EFCC+AC, conducting structures outside JET wall have significant influence, modeled in MARS-F by a partial thin wall

DC response: experiments



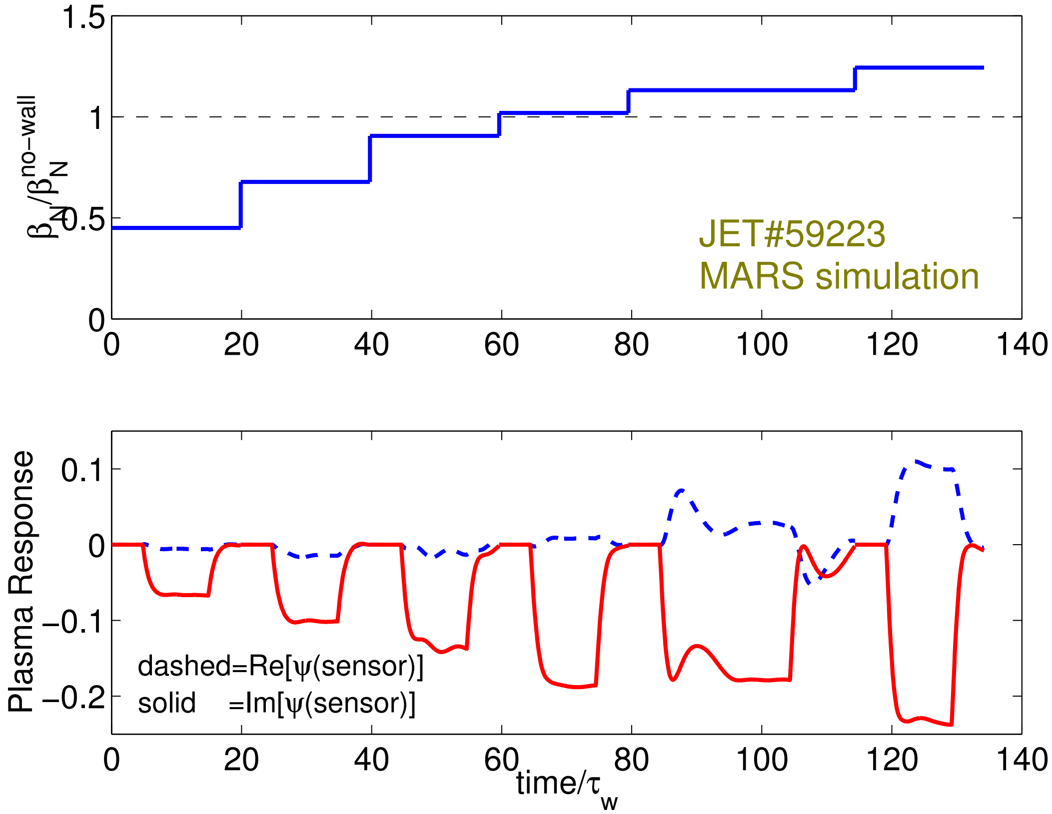
- Square wave $n = 1$ fields applied with internal saddles during pressure rise
- Measured radial field has no direct vacuum pick-up

Typical equilibrium in simulations



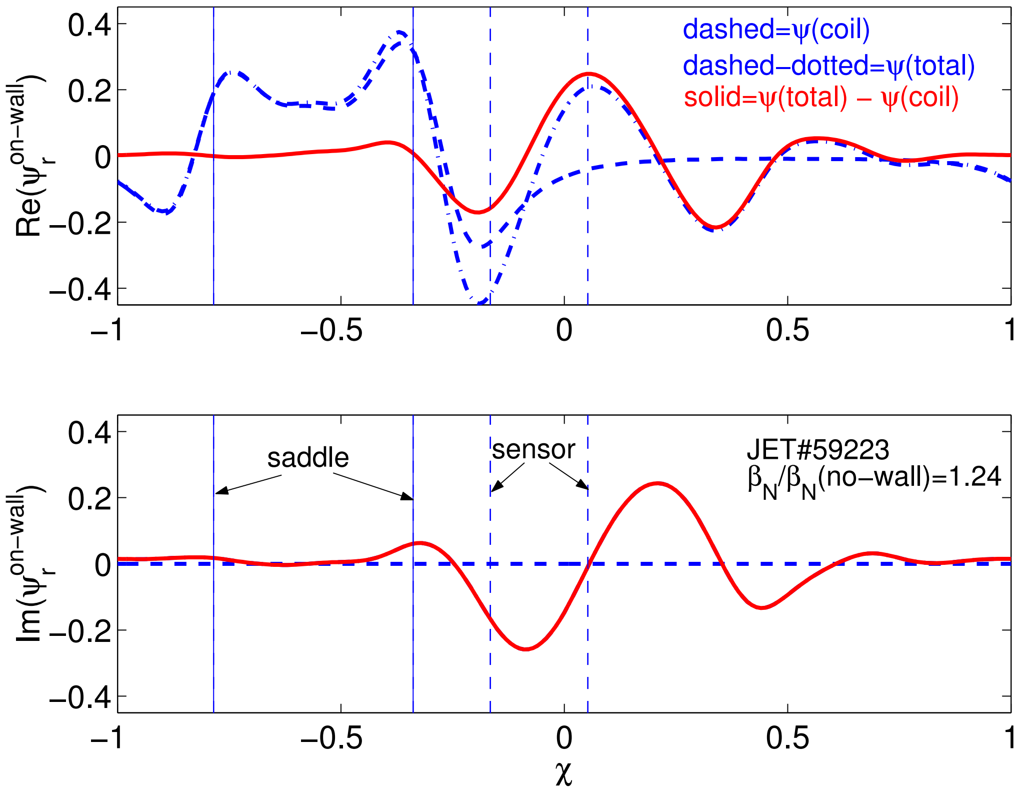
- SHOT#62024
- Equilibrium: CHEASE
- Stability & RFA: MARS-F

DC response: MARS-F



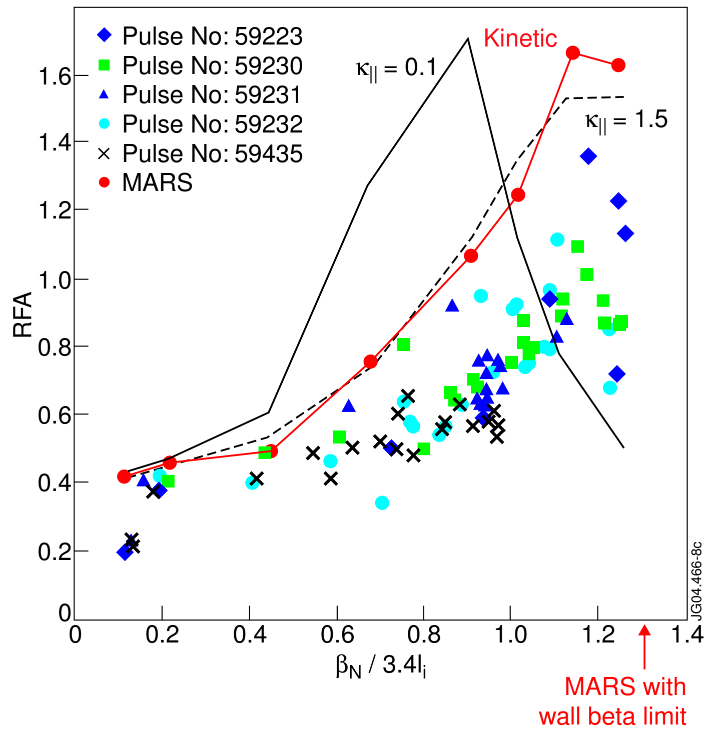
- **Run MARS-F as initial-value code**
- **RFA increases with increasing** β_N
- **However, no clear threshold effect near** $\beta_N(\mathrm{no-wall})$

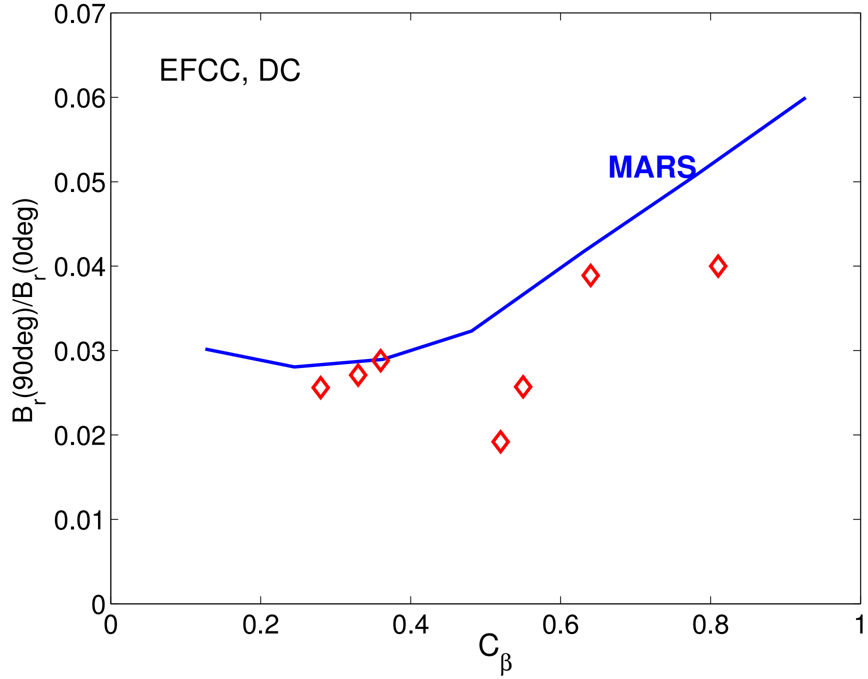
Mode structure



- **Plasma response is ballooning (RWM)**
- **RFA results may be sensitive to where the fields are measured**

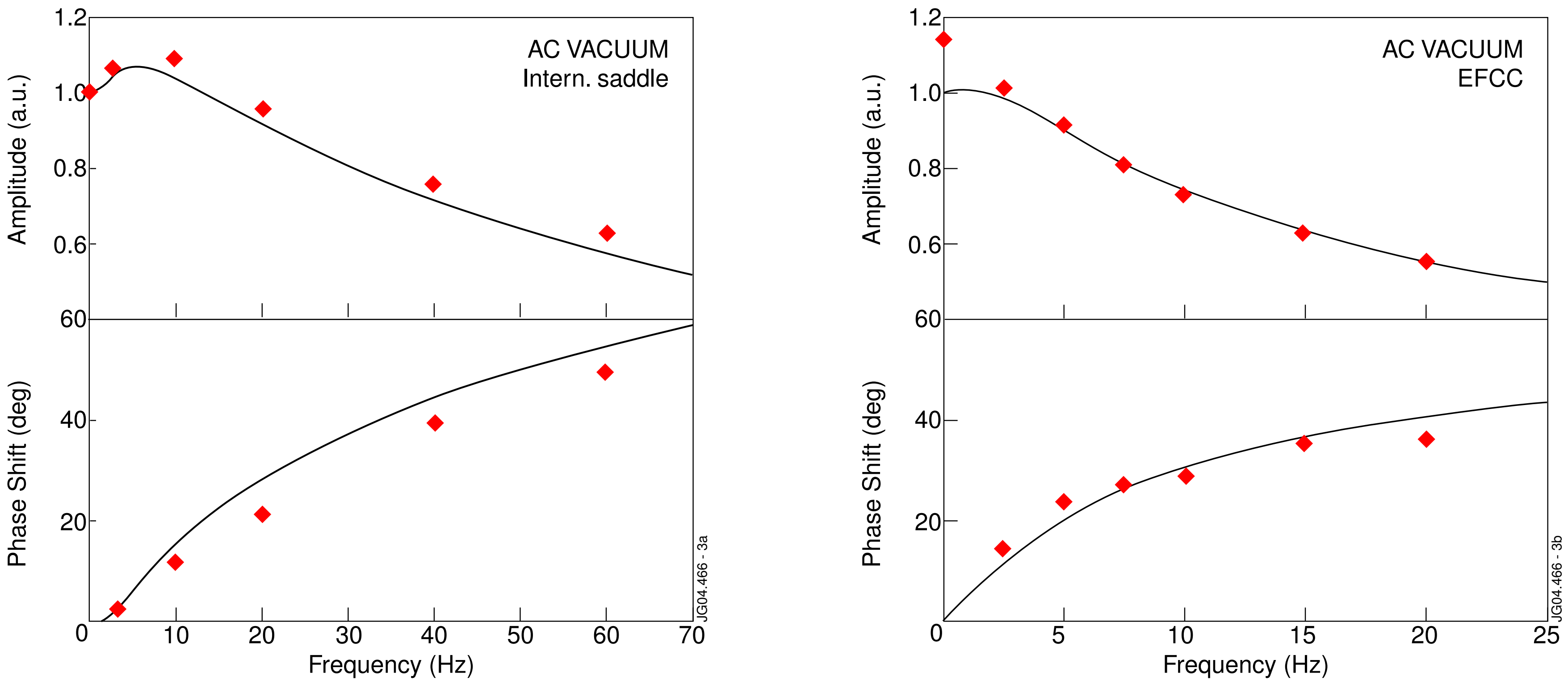
DC response: experiments vs. MARS-F





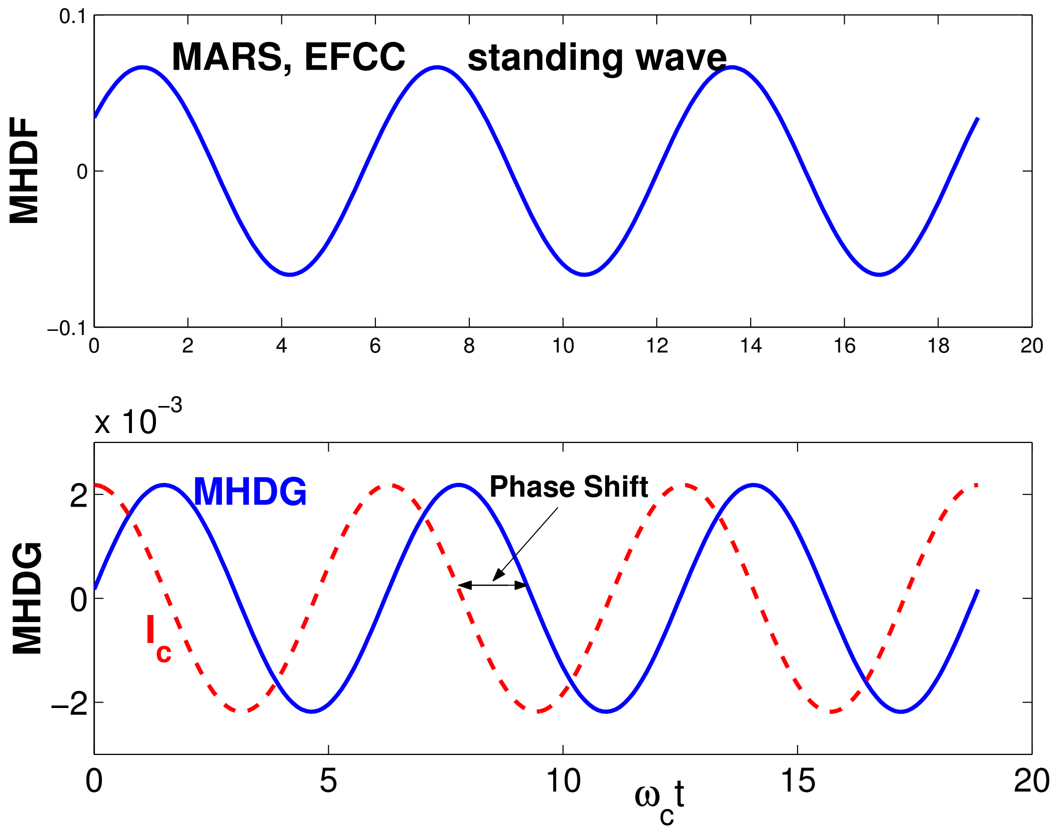
- **RFA amplitude vs. pressure with internal (left) and external (right) saddle coils**
- **Kinetic damping model gives reasonable prediction**

AC response: vacuum



- **Vacuum response to standing waves with internal (left) and external (right) saddle coils**
- **Reasonable agreement for both amplitude and phase shift**
- **Double wall used in simulations. The second (partial) wall essential to obtain agreement with the same wall time.**

AC response: with plasma

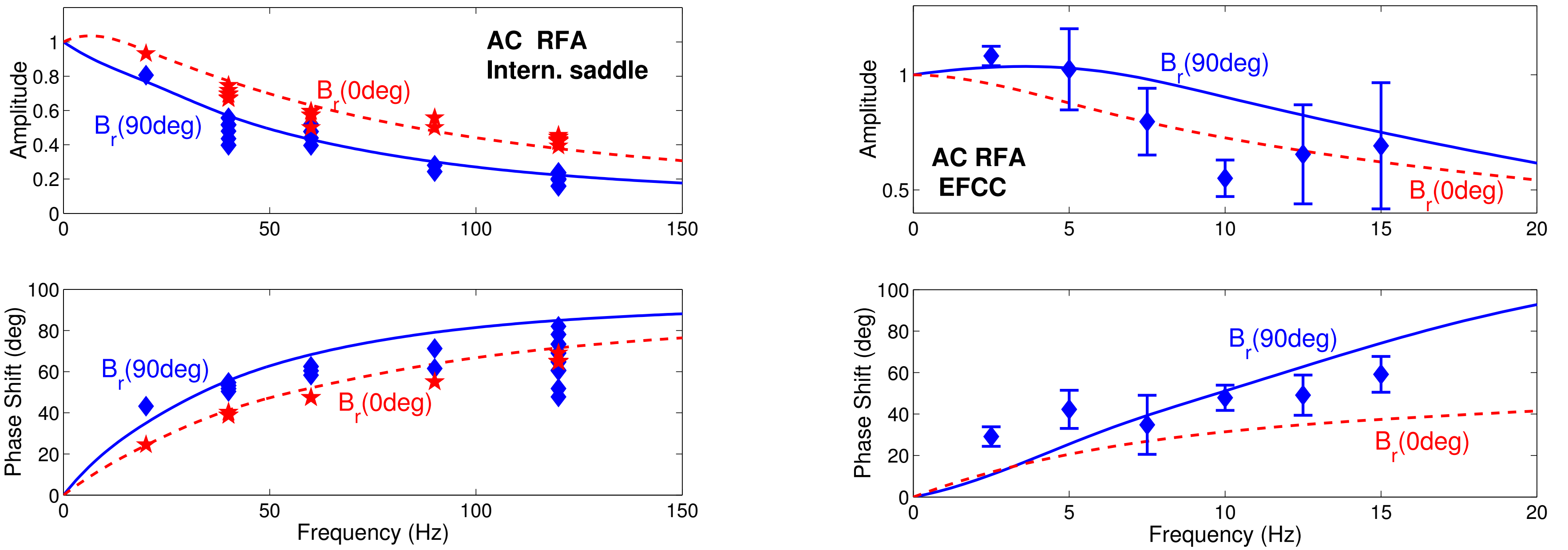


- **JET: standing wave** $I_c(t) = I_0 \cos(\omega_c t)$**, MHDF**$=$ $\cos$**-signal, MHDG**$=$ $\sin$**-signal**
- **MARS-F: traveling wave** $I_c(t) = I_0 e^{j\omega_c t}$ $\Rightarrow$ **complex response** $\Psi_s(\omega_c) \Rightarrow$

  MHDF(t)$= \Re\left\{\Psi_s(\omega_c)e^{j\omega_c t} + \Psi_s(-\omega_c)e^{-j\omega_c t}\right\}/2$

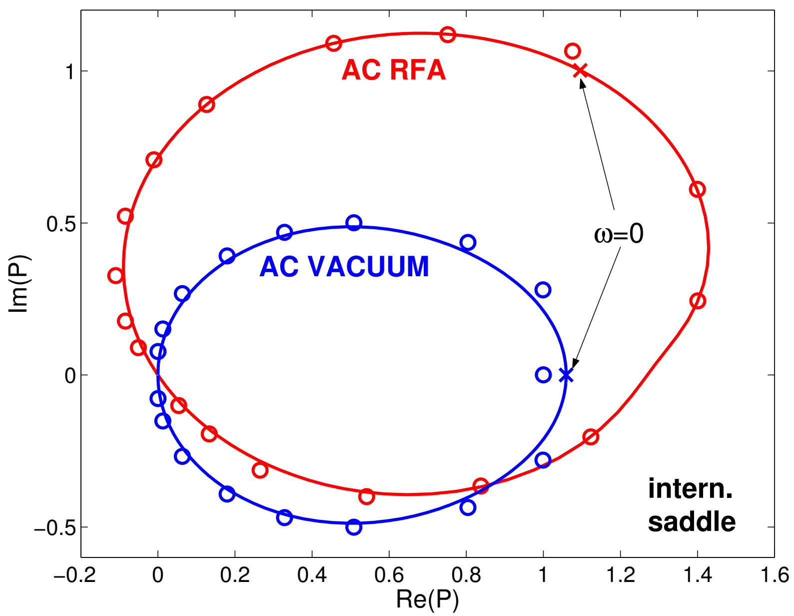
  MHDG(t)$= \Im\left\{\Psi_s(\omega_c)e^{j\omega_c t} + \Psi_s(-\omega_c)e^{-j\omega_c t}\right\}/2$

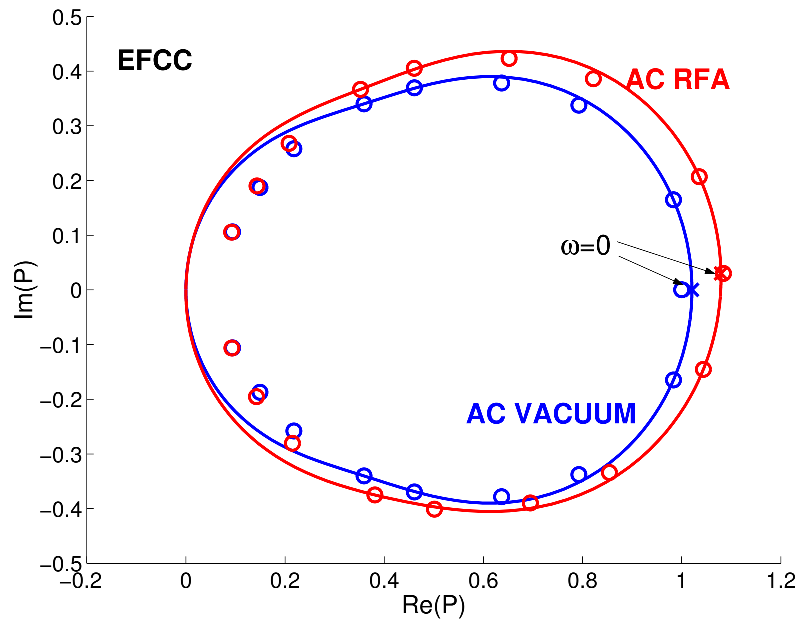
AC response: with plasma



- **Plasma response to standing waves with internal (left) and external (right) saddle coils**
- **Kinetic damping model gives good agreement for internal coils but worse agreement for EFCC (probably due to weaker plasma response)**
- **Need more experiments in JET (traveling waves, higher frequencies) with EFCC**

AC response: Padé approximations





- **Define transfer function for traveling wave** $P(j\omega_c) \equiv \Psi_s(\omega_c)/\Psi_s(\omega_c = 0|\text{vacuum})$
- **Plot** $P(j\omega_c)$ **in complex plane for real frequency** $-\infty < \omega_c < +\infty$
- **With internal saddles (left), plasma significantly modifies vacuum response**

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

- **With EFCC (right), vacuum response is dominating**

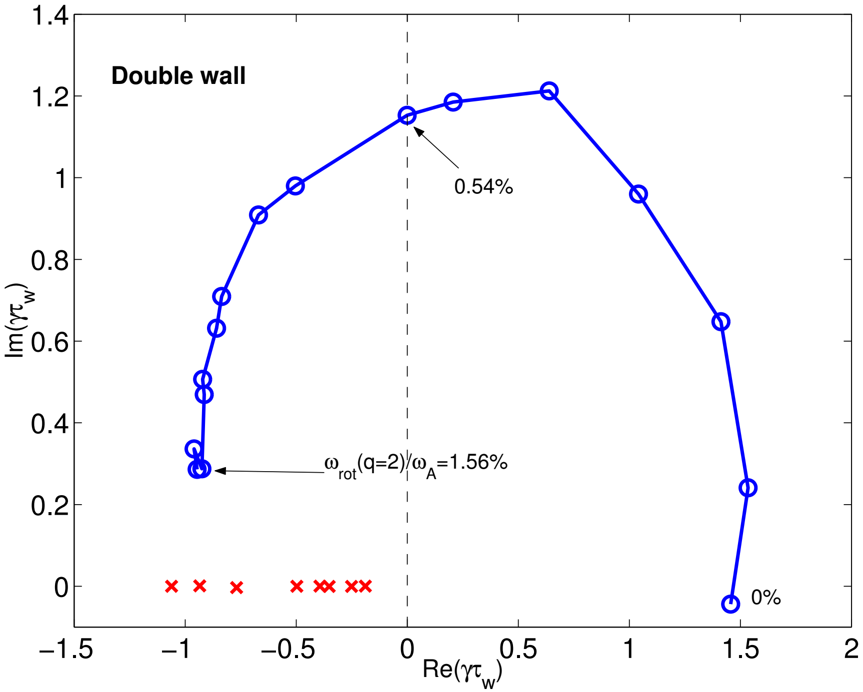
$$P(j\omega_c) = \frac{0.35 - 0.018j}{j\omega_c + 0.88 - 0.009j} + \frac{0.11 + 0.012j}{j\omega_c + 0.16 + 0.007j}$$

RFA: MHD spectroscopy

- Generally,

$$P(j\omega_c) = \frac{r_1}{j\omega_c - p_1} + \frac{r_2}{j\omega_c - p_2} + \cdots$$

- Poles of transfer function $P(j\omega_c)$ show damping rate and frequency of stable (maybe lumped) RWM
- Residues of $P(j\omega_c)$ show response of the stable RWM to error fields
- In JET, internal saddles clearly excite the RWM that is unstable without plasma rotation, and is stabilized by strong plasma rotation



- EFCC may also excite those RWM that are stable even without plasma rotation. More study needed.

Conclusions and discussions

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

- Using kinetic damping model, MARS-F simulations of RFA agree well with the experimental data in JET. Conducting structures outside the JET wall have significant effect on RFA with EFCC and AC excitation. These are modeled in MARS-F by a partial thin wall.

- Internal saddle coils do excite the RWM that is stabilized by strong plasma rotation. However, EFCC may also excite intrinsically stable RWM.

- Further study:
  - Improve kinetic damping model by adding more physics
  - More study on RFA with EFCC coils, both in simulations and in experiments