Investigation of RWM stability in Flexi-DEMO

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Outline

- Flexi-DEMO 2019 equilibrium

- Ideal kink stability

- Feedback coil geometry

- Plasma response models

- Feedback with ideal proportional controller

- Time-stepping simulation & output B-field

- Summary

Equilibrium (1)

The Flexi-DEMO upper operational point scenario has been simulated with the ASTRA code (E. Fable)

The target equilibrium for MARS-F modeling in particular, has been extracted from the ASTRA simulation and solved with the CHEASE equilibrium code
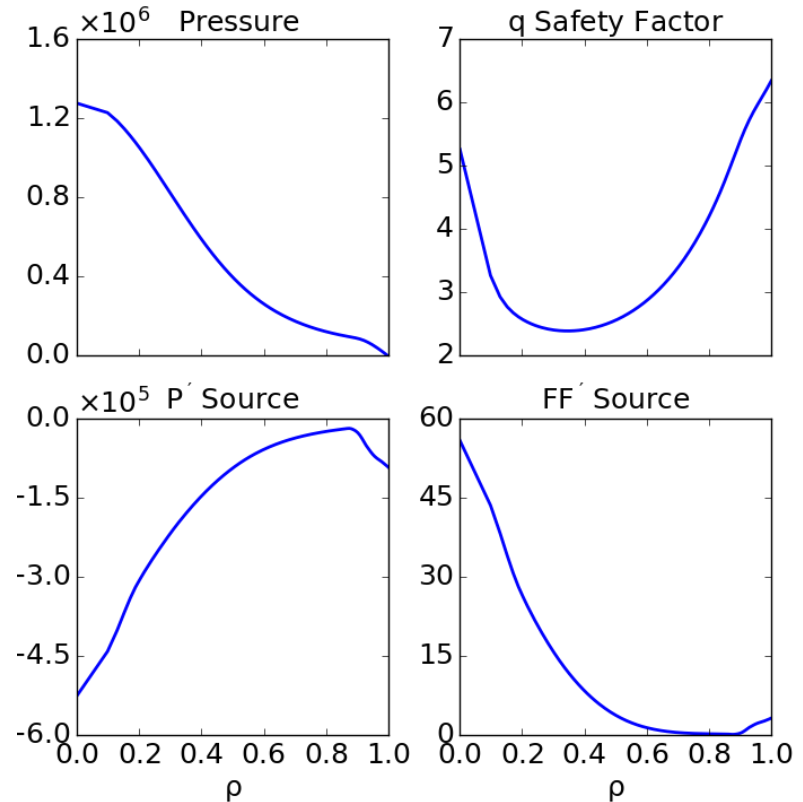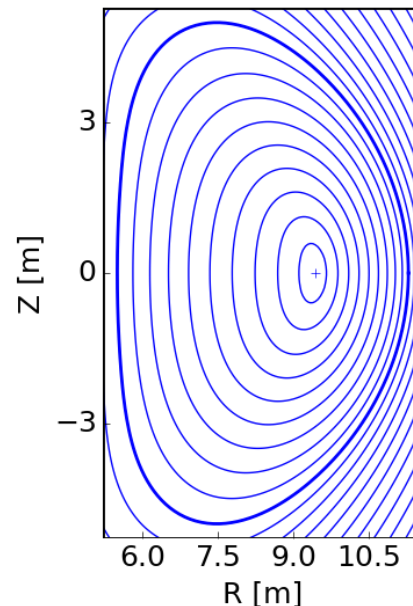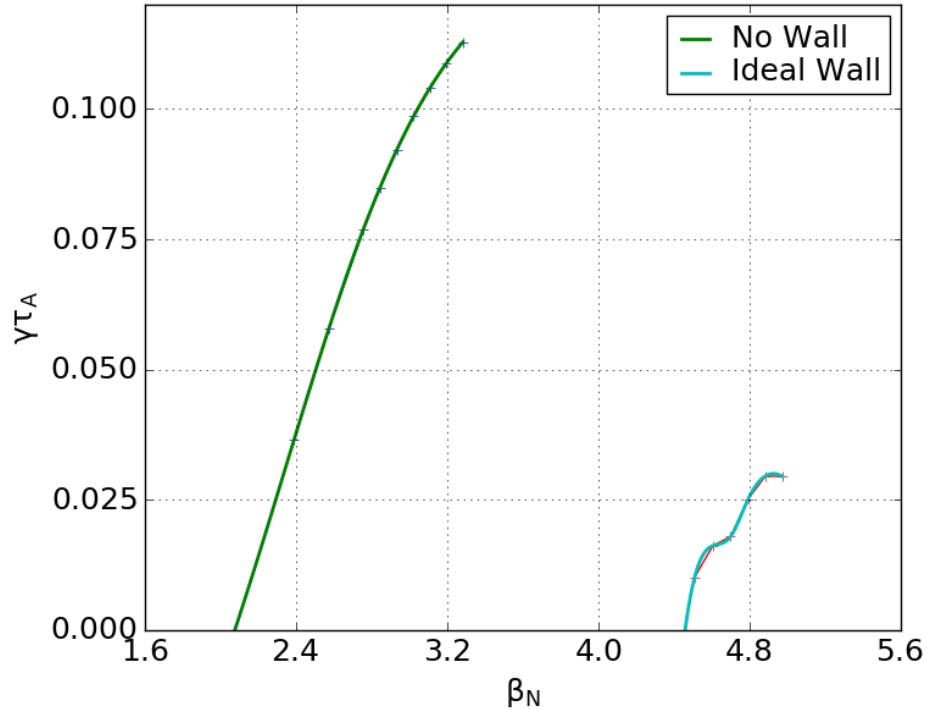
Equilibrium (2)

The Flexi-DEMO upper operational point scenario has been simulated with the ASTRA code (E. Fable)

The target equilibrium for MARS-F modeling in particular, has been extracted from the ASTRA simulation and solved with the CHEASE equilibrium code

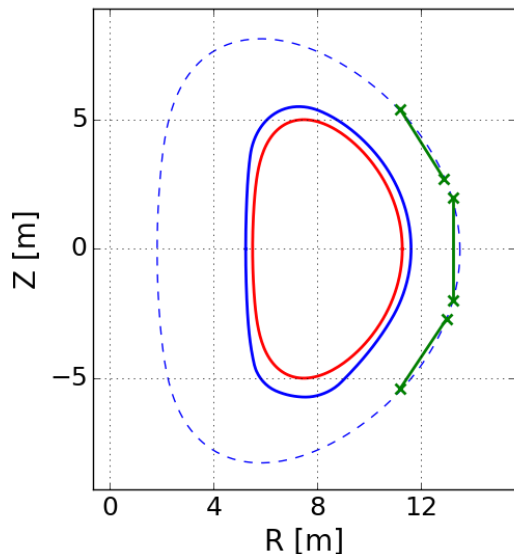| Key params.	
l_i	0.6
q_a	6.3
R_0	8.4 m
B_0	5.8 T
R/a	2.9
I_p	1.45 MA
β_N	~ 3.0

n=1 no-wall & ideal-wall limits

Stability limits for the pressure-driven external kink calculated by pressure scans

$\beta_N^{no-wall}$	$\beta_N^{ideal-wall}$
2.0	4.5

Feedback coils optimal setup

UPPER: $\theta_c = 32.8°$ $\Delta\theta = 26.5°$

LOWER: $\theta_c = -32.8°$ $\Delta\theta = 26.5°$

MIDPLANE: $\theta_c = 0°$ $\Delta\theta = 27.5°$

Design of active coils geometry based on:
[*L. Zhou et al 2018 Nucl. Fusion 58 076025*]

Optimal geometry is a trade-off between the requirements:

- Use **Out-Outer-VV coils** which match the performance of in-vessel coils in terms of last pitch resonant radial field component for ELM control
- Take into account the location of VV ports (for the DEMO design in the paper above)
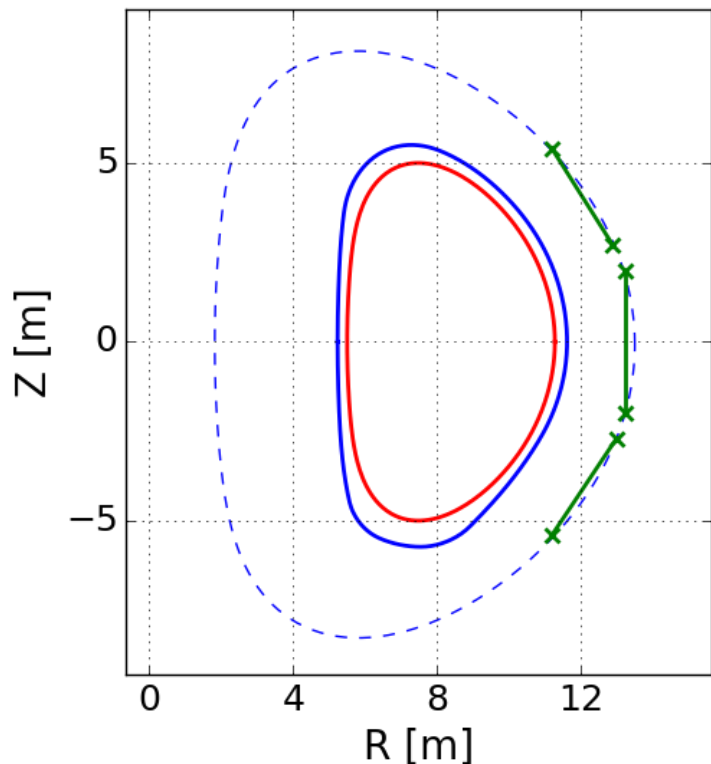- **Up-down symmetric** configuration

The ELM coils are assumed to be used for RWM stabilization.

Feedback coils optimal setup

Solid – plasma boundary
Solid – resistive wall (~first wall)
Dashed -- auxiliary coil surface
X- coil positions (geometric)

Poloidal point-like and radial field sensors will be considered, placed on the plasma facing side of the resistive wall. Current control logic is assumed with an **ideal amplifier**.

The active coils are placed outside of the outer VV, which has not been considered as a real wall in the modeling.

The resistive wall is **at r/a = 1.08**, resulting in a growth rate $\gamma\tau_w \sim 7$

Plasma Response Model (PRM)

To assess the stability properties of the system, the open-loop transfer function is calculated by full toroidal computations with the MARS-F code

Plasma Response Model approach used to calculate the open-loop transfer function of the system and assess stability with Nyquist criterion

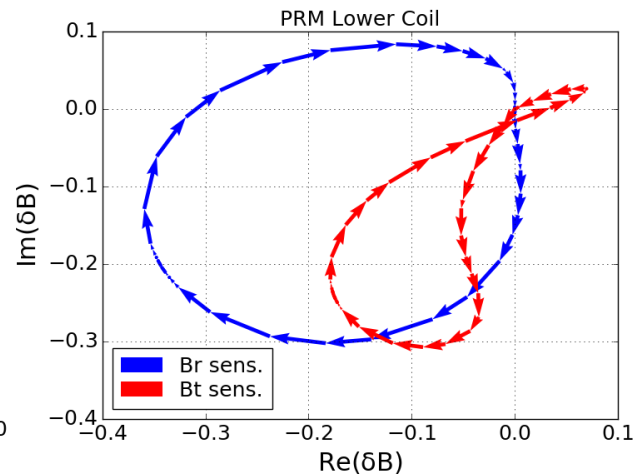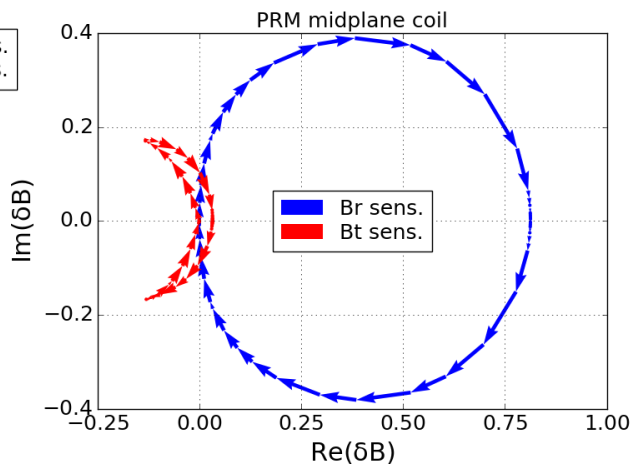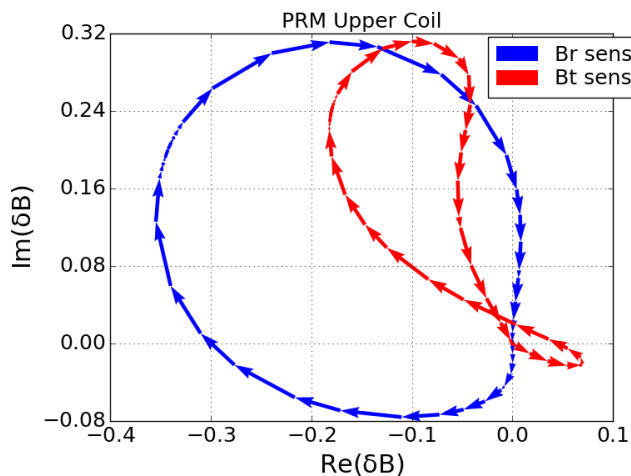Transfer function: $P(s) = \dfrac{\Psi(s)}{M_{sf}I_f}$

Closed-loop stability with negative feedback and a general controller $K(s)$ is determined by the characteristic equation:

$$1 + K(s)P(s) = 0$$

Plasma Response Model (PRM)

MARS-F computed full model response for each coil treated separately with single point-like sensor at the resistive wall position

Plasma Response Model (PRM)

The **linear combination** of single-coil response gives the PRM for the complete system

We can apply the **Nyquist criterion** to assess the stability of the single pole closed-loop system from the PRM.

If the counter-clockwise trajectory of the PRM from f=-∞ to f=+∞ encircles the (-1,0) point then the system can be stabilized with a given proportional gain

A scan of the phasing between upper and lower coils (i.e. the phase of the complex gains) has been carried out to assess the optimal phasing to achieve a stabilizing effect.

Optimal phasing to achieve stabilization

PRM Total
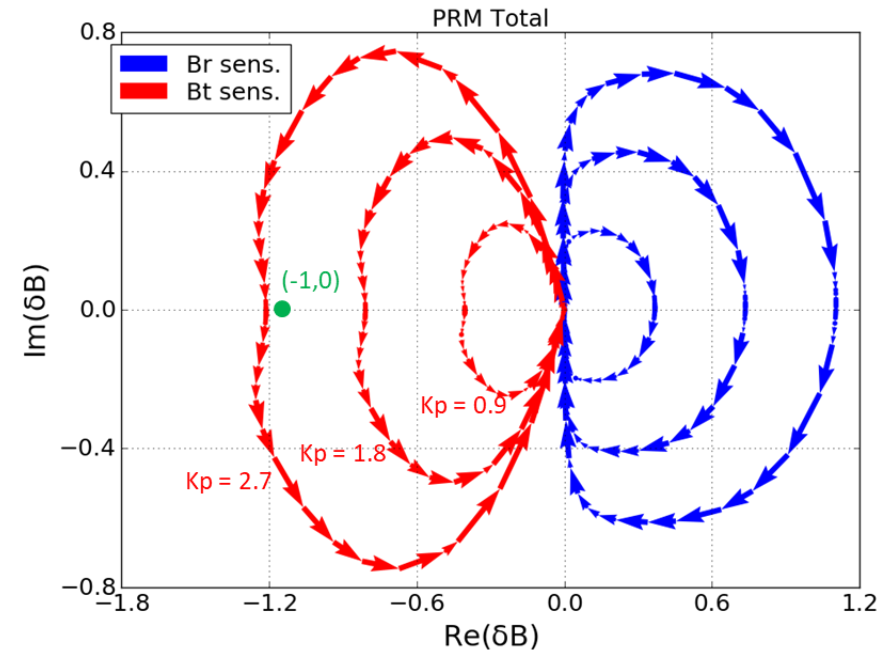
Seeking optimal phasing to achieve stabilization

$$P_{tot}(j\omega) = P_M(j\omega) + e^{j\phi_U}P_U(j\omega) + e^{j\phi_L}P_L(j\omega)$$

Promising results found with $\phi_U = \frac{\pi}{2}$ & $\phi_L = -\frac{\pi}{2}$

- Plotting $\boldsymbol{K_P \cdot P_{tot}(j\omega)}$

- The system can **only** be stabilized using **poloidal field** sensors.

- The system appears to be stabilized by a proportional gain of $\boldsymbol{K_p \sim 2.6 - 2.7}$

Closed-loop eigenvalue study

Scan of proportional gain (K_P) using inner poloidal field sensors

- **The n=1 RWM is stabilized with $K_P = 2.7$**

- Test with radial field sensors shows decreasing growth rate but very slow slope, no stabilization is achieved.

- According to the Nyquist criterion stabilization with radial field sensors should not be possible.
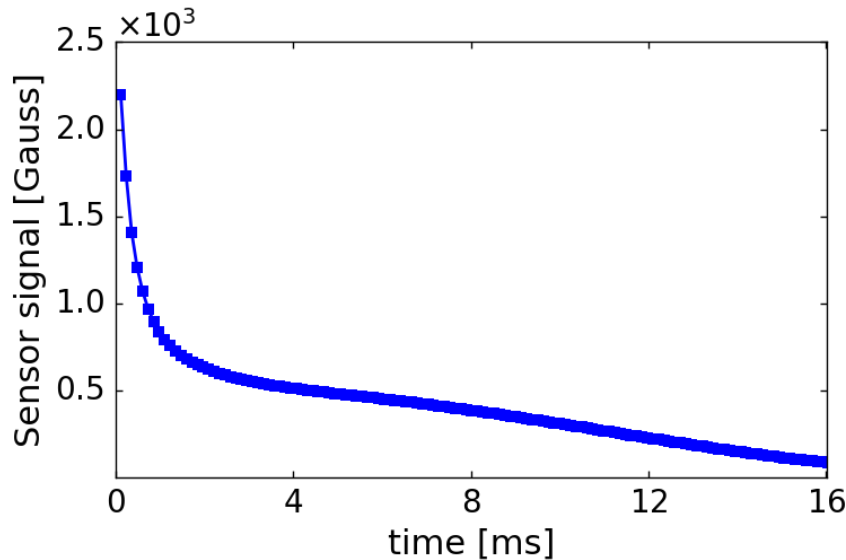
Output: total B-field
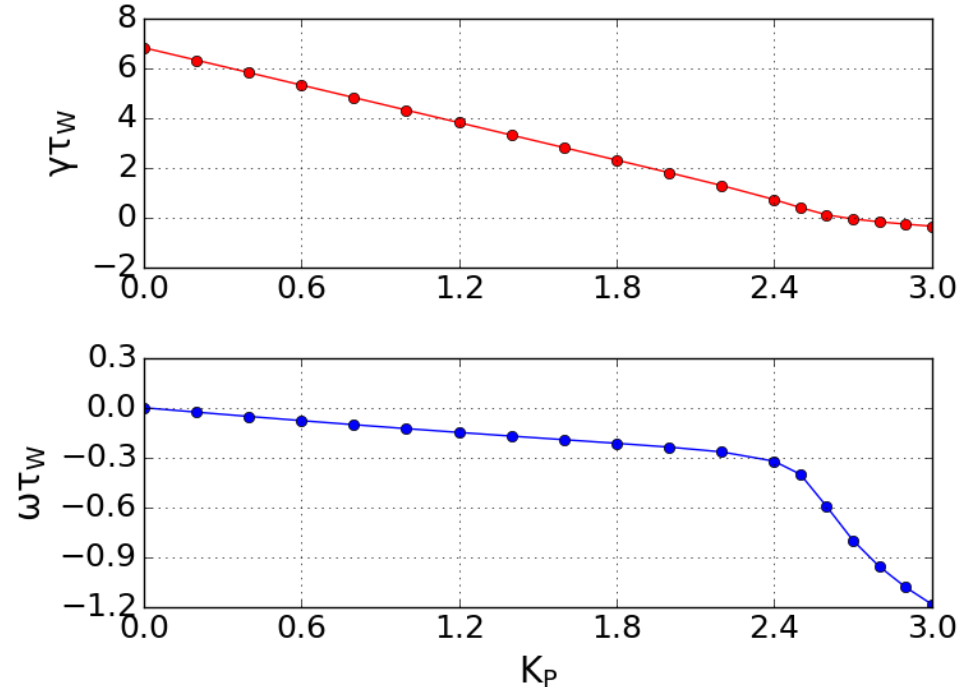
The eigenvalue study does not yield the overall amplitude of the perturbed magnetic field.

This amplitude can be determined by assuming a tolerable level of sensor signal, i.e. a **threshold** after which we switch the feedback on.

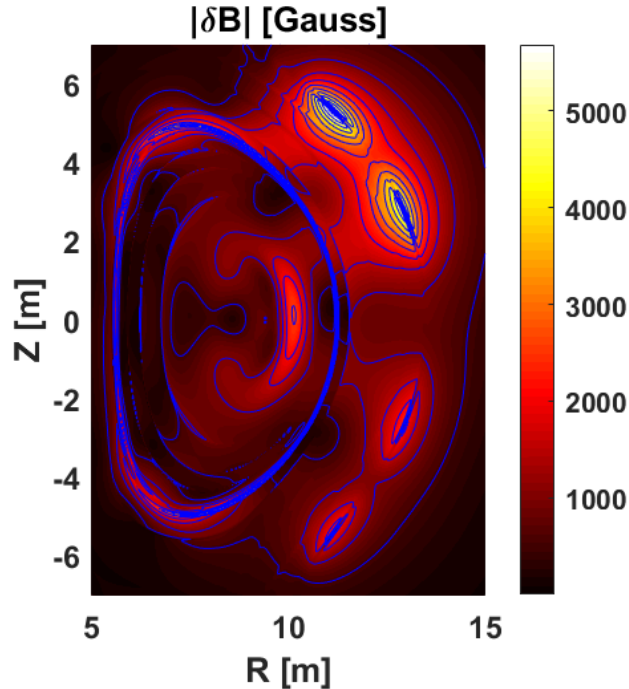-> A time stepping simulation is carried out with given mode detection threshold

Time-stepping run: sensor signal

Assuming a mode detection threshold of 250 Gauss, the amplitude of perturbed magnetic field is obtained

Proportional feedback control with 90° phasing between coils and ideal current amplifier

Time-stepping run

$|\delta B|$ [Gauss]

Assuming a mode detection threshold of 250 Gauss, the amplitude of perturbed magnetic field is obtained

Proportional feedback control with 90° phasing between coils and ideal current amplifier

The perturbed field at sensor position is ~ 150 Gauss, while inside the plasma the perturbation is ~ 1000 Gauss

Summary

- The linear stability of **n=1 Resistive Wall Mode** has been studied for the Flexi-DEMO upper operational point.

- **Plasma Response Model** obtained by computing full model response with MARS-F

  - **Nyquist** plot of plasma response measured by poloidal field point-like mid-plane sensors
  - Typical pattern for unstable RWM
  - Tests with different phases (**complex gain**) indicate that the system can be stabilized with the given coil geometry

Summary

- **Stabilization** is also recovered with a feedback gain scan
  - A critical gain $K_P = 2.7$ has been found for the closed-loop scan with **poloidal field sensors**
  - A similar scan with **radial field sensors** yields a mild reduction of the growth rate but no stabilization within the considered range of proportional gains

- A t**ime-stepping** simulation has been carried out to calculate the amplitude of the perturbed magnetic field from RWM and feedback
  - B-field exported to rectangular grid in physical units for input to other codes
  - The **strong magnetic field perturbation** (~ 1000 Gauss) inside the plasma, resulting from the time simulation of feedback control -> possible strong impact on particle confinement.