Investigation of RWM stability in Flexi-DEMO

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CONSORZIO RFX
Ricerca Formazione Innovazione

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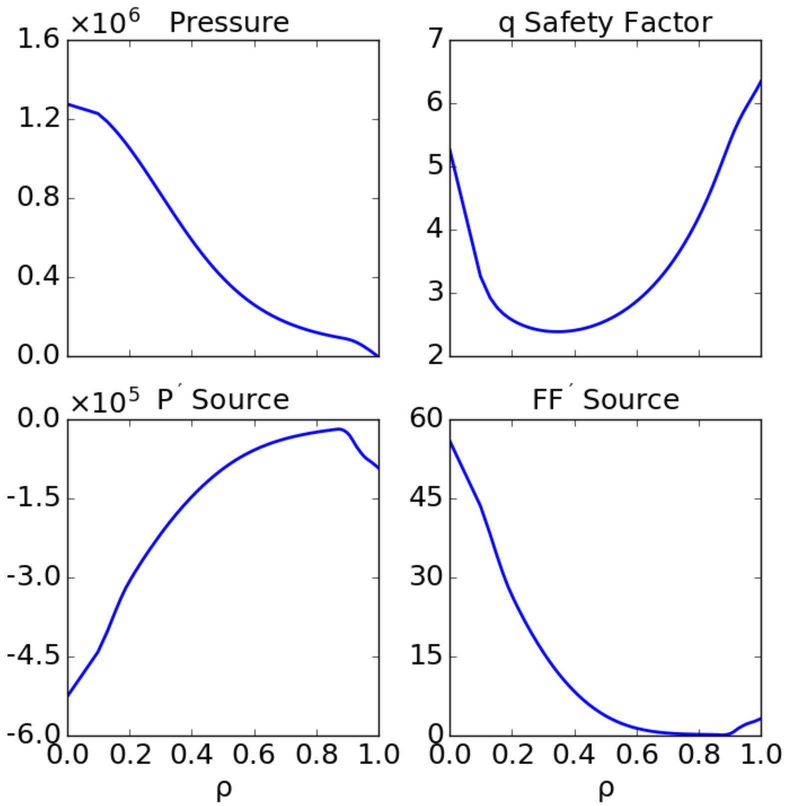
Outline

- Flexi-DEMO 2019 equilibrium
- Ideal kink stability
- Position of the ideal wall
- Feedback coil geometry
- Plasma response models
- Feedback with ideal proportional controller
- Output B-field

Equilibrium (1)

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

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.

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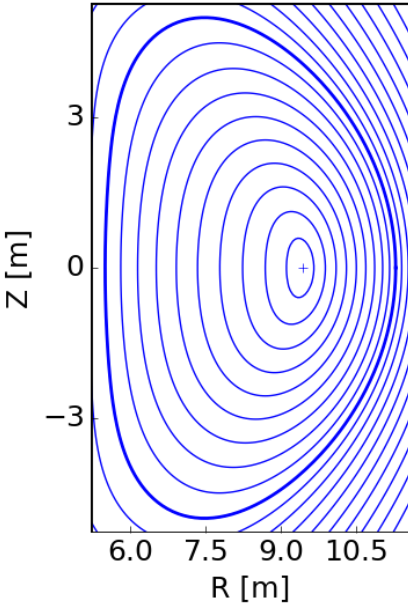
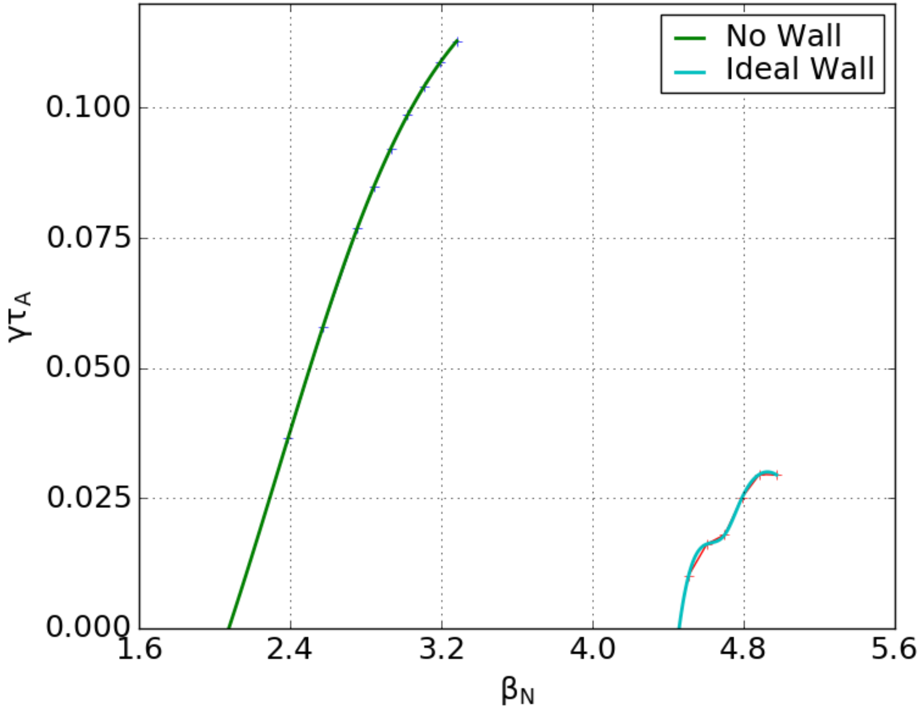


Key params.	
l_i	0.6
q_a	6.3
R_0	8.4 m
B_0	5.8 T
R/a	2.9
I_p	1.45 MA
β_N	~ 3.0

n=1 no-wall & ideal-wall limits



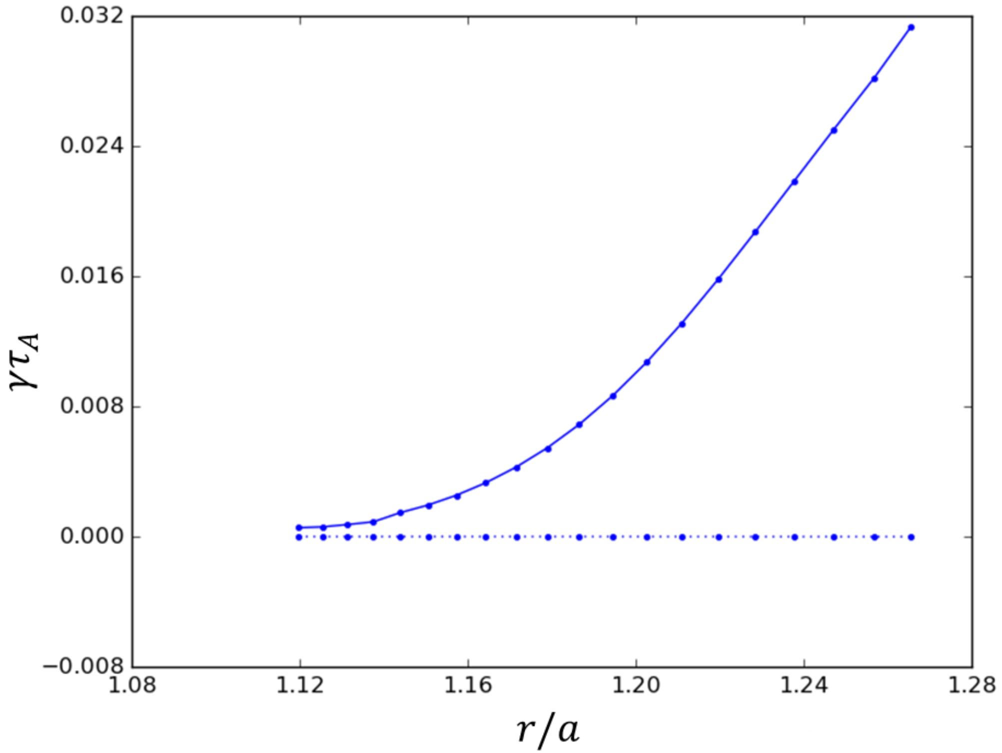
Stability limits for the pressure-driven external kink calculated by pressure scans

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

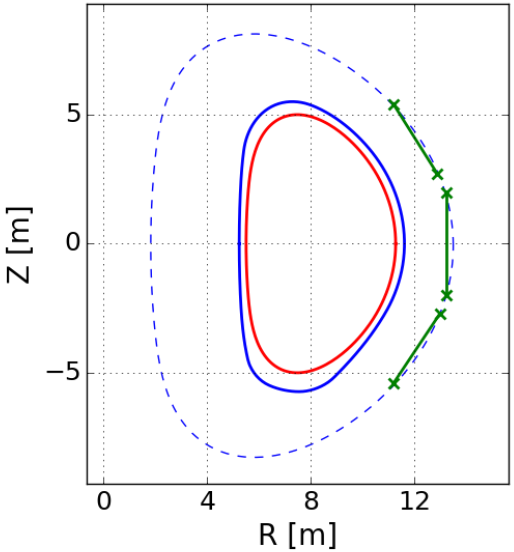
Ideal wall position

The position for the ideal wall (and conducting wall afterwards) has been calculated for the target scenario ($\beta_N \sim 3$) with a scan of plasma-wall distance

-> r/a = 1.08



Feedback coils optimal setup



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

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

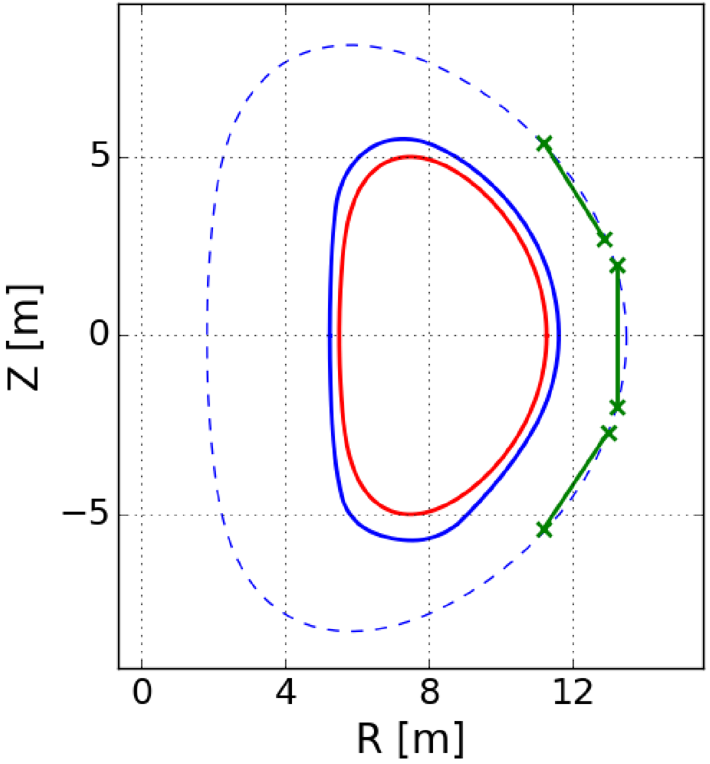
MIDPLANE: $\theta_c = 0°$ $\Delta\theta = 27.5°$

The first geometry of active coils has been designed based on [*L. Zhou et al 2018 Nucl. Fusion 58 076025*]. The ELM coils are assumed to be used for RWM stabilization.

Optimal geometry found with 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

Feedback coils optimal setup



Solid – plasma boundary

Solid – resistive wall (~first wall)

Dashed -- auxiliary coil surface

X- coil positions (geometric)

Point-like poloidal 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

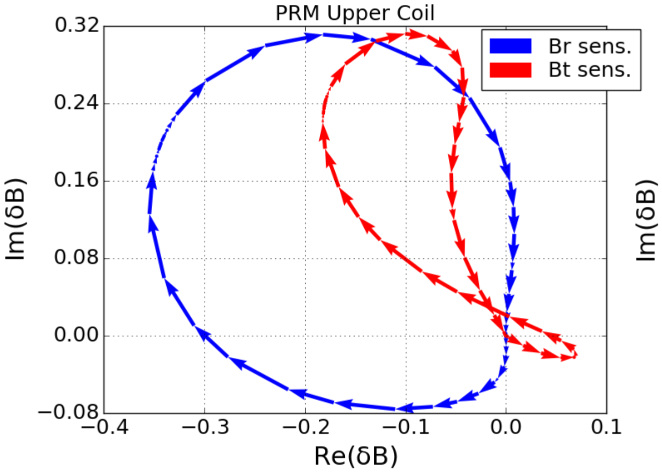
Transfer function: $P(s) = \frac{\Psi(s)}{M_{sf} I_f}$

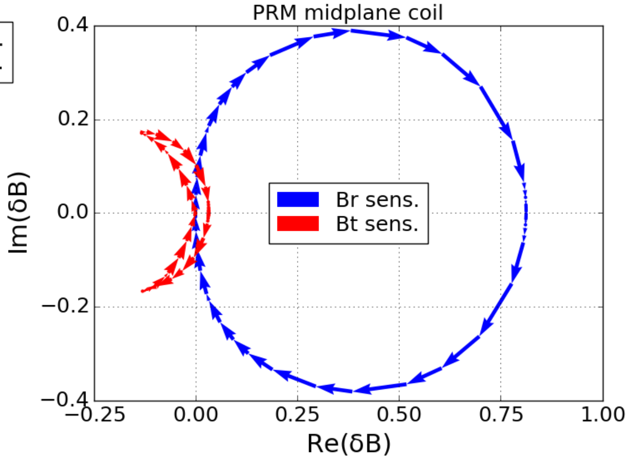
Closed-loop stability with negative feedback and a general controller $K(s)$ is determined by the characteristic equation:

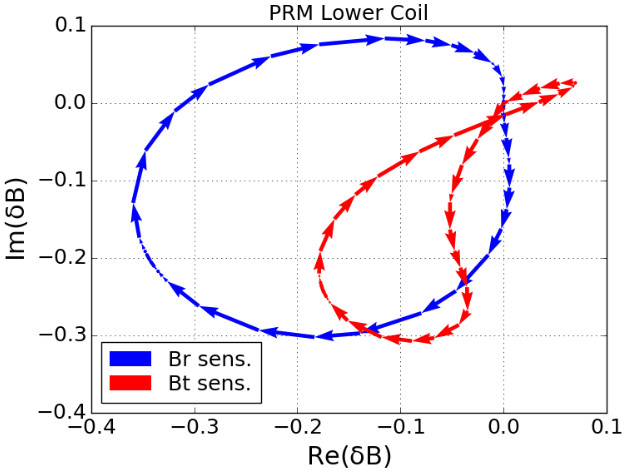
$$1 + K(s)P(s) = 0$$

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)

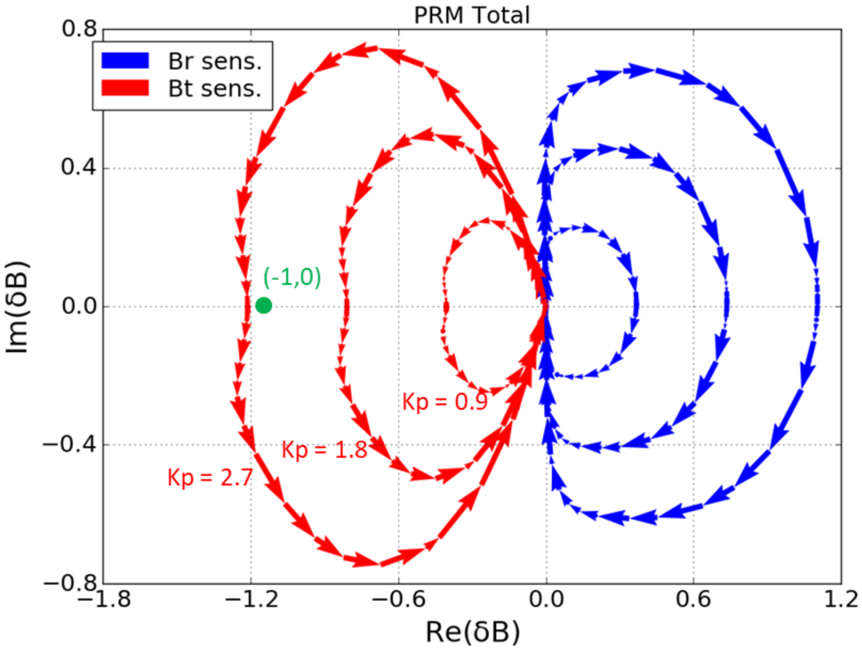
The **linear combination** of single-coil response gives the PRM for the complete system

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



Seeking optimal phasing to achieve stabilization

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

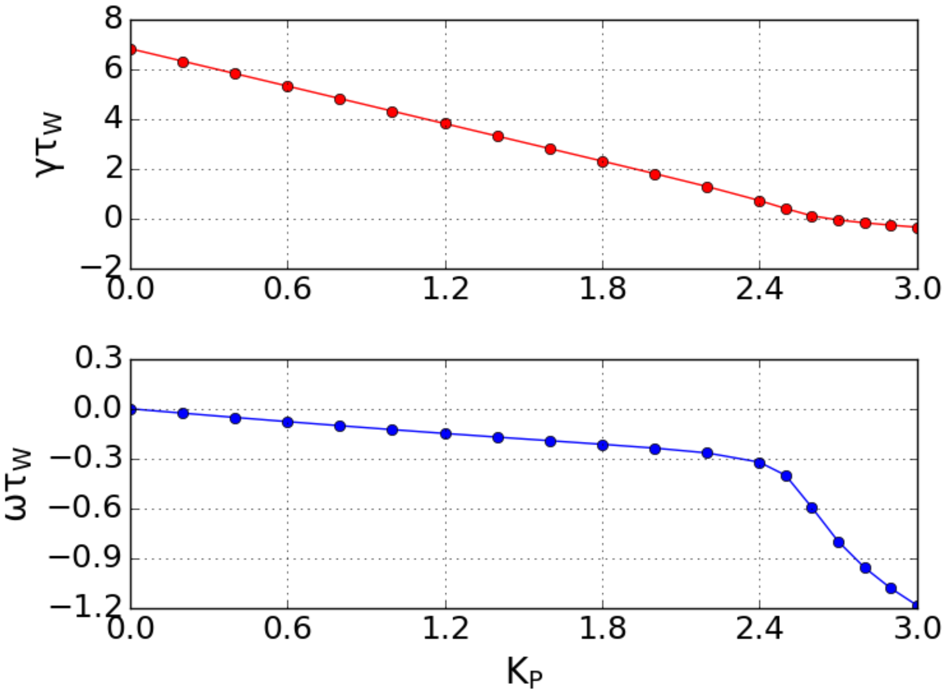
Promising results found with $\phi_U = \frac{\pi}{2}$ & $\phi_L = -\frac{\pi}{2}$

- 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 $\boldsymbol{K_p \sim 2.6 - 2.7}$

Gain Scan

Scan of proportional gain (Kp) 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.



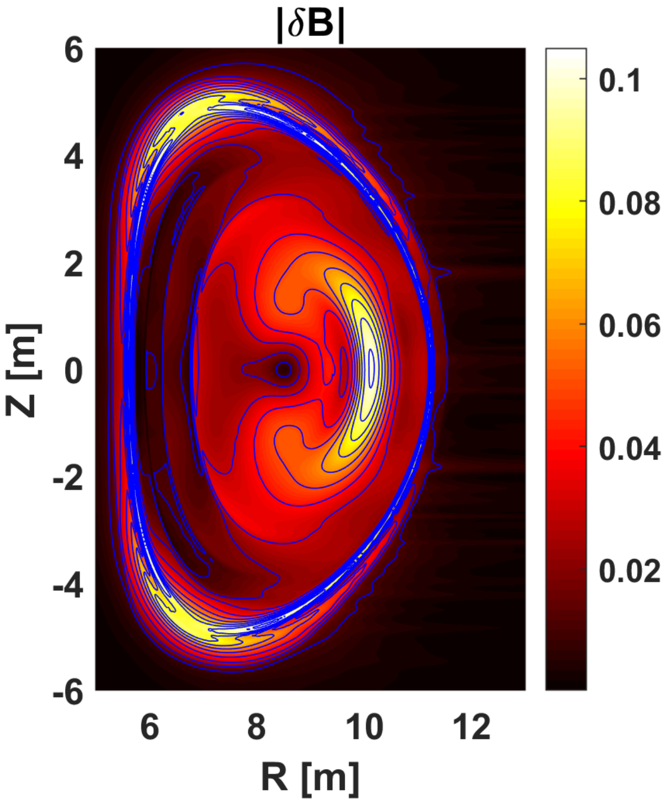
Resulting B-field

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

Test: 5 Gauss threshold



Assuming a mode detection threshold of 5 Gauss, the amplitude of perturbed magnetic field is obtained

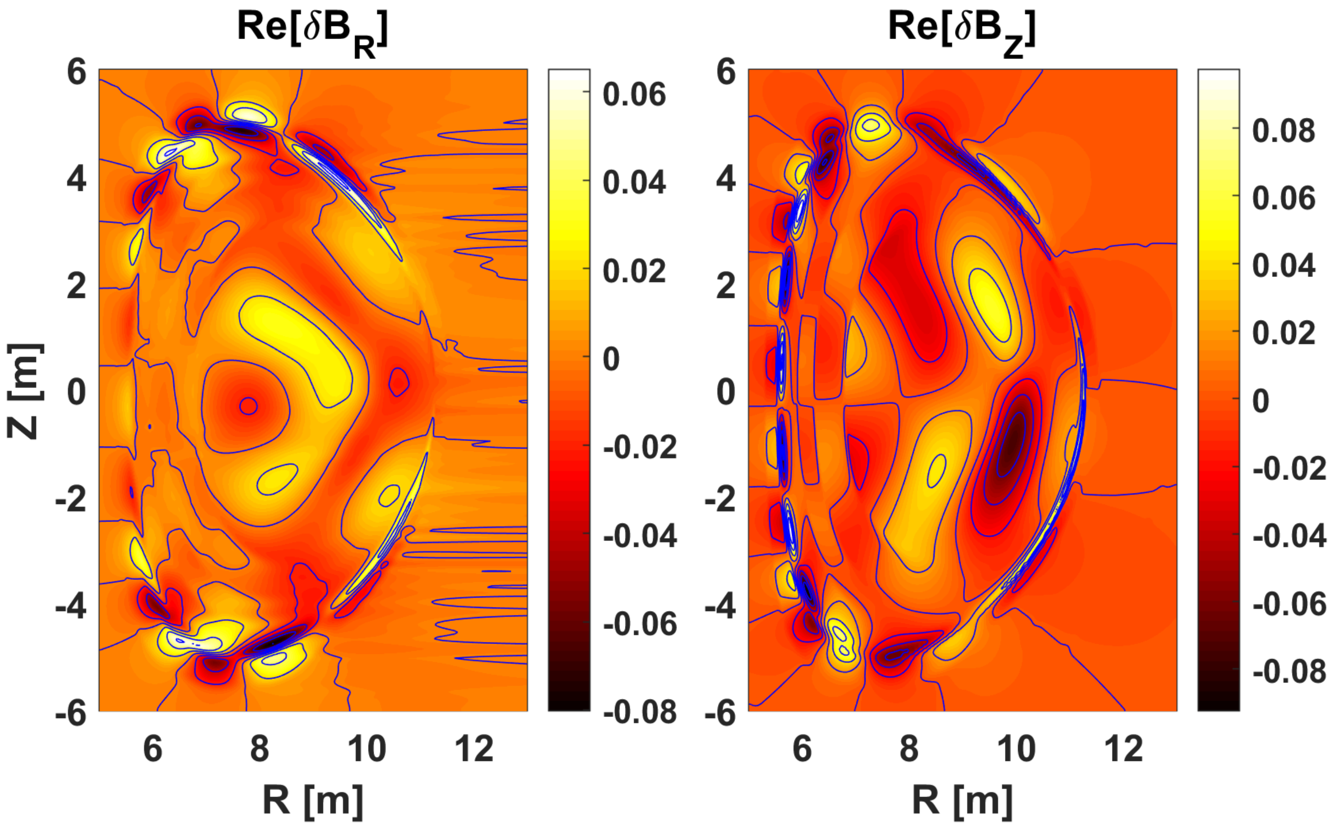
-> Plasma response field

(physical units in plots)

Test: Output field

Br & Bz on rectangular grid

(physical units in plots)



Summary

- 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

- Same result has been recovered in closed-loop 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 time 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