CONSORZIO RFX
Ricerca Formazione Innovazione

Progress in MHD feedback control in RFX-mod

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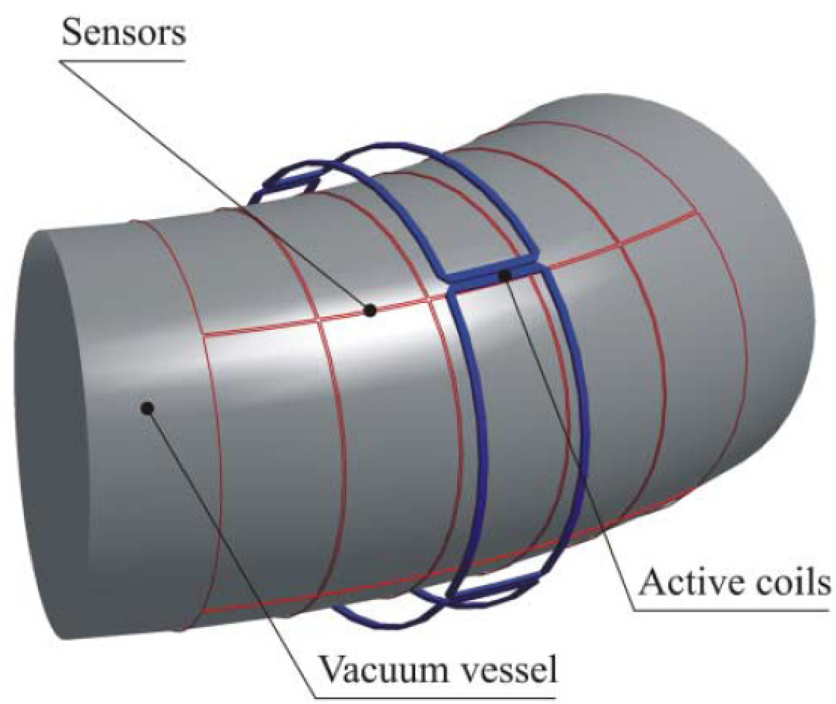
Outline

- Upgrades of the control system
  - Identification of systematic errors and real time correction: Clean Mode Control
  - improved architecture reduced latency
- Improved control of m=1 Tearing Modes
  - Spontaneous and driven Tearing Modes rotations: wall and phase unlocking
  - Development of Quasi Single Helicity scenario
- Improvement of plasma performances

Zeroing the *measured* field is not enough!

- In the **Mode Control** approach, each harmonic measured by the sensors is locally cancelled by a suitable saddle coil current (obtained by FFT $^{-1}$)



- **GENERAL ISSUE: the system CAN ONLY cancel the** ***measurement of a mode*****, not the "real mode" itself**

Sidebands aliasing (I)

$$b^r(r,\theta,\phi) = \sum_{m,n\in Z} b_r^{m,n}(r)\ e^{i(m\theta+n\phi)}$$

"ideal" FFT

- Identical grid (M×N) of sensors (measures: $b^r{}_{i,j}$) and active coils (corrents: $I_{i,j}$)

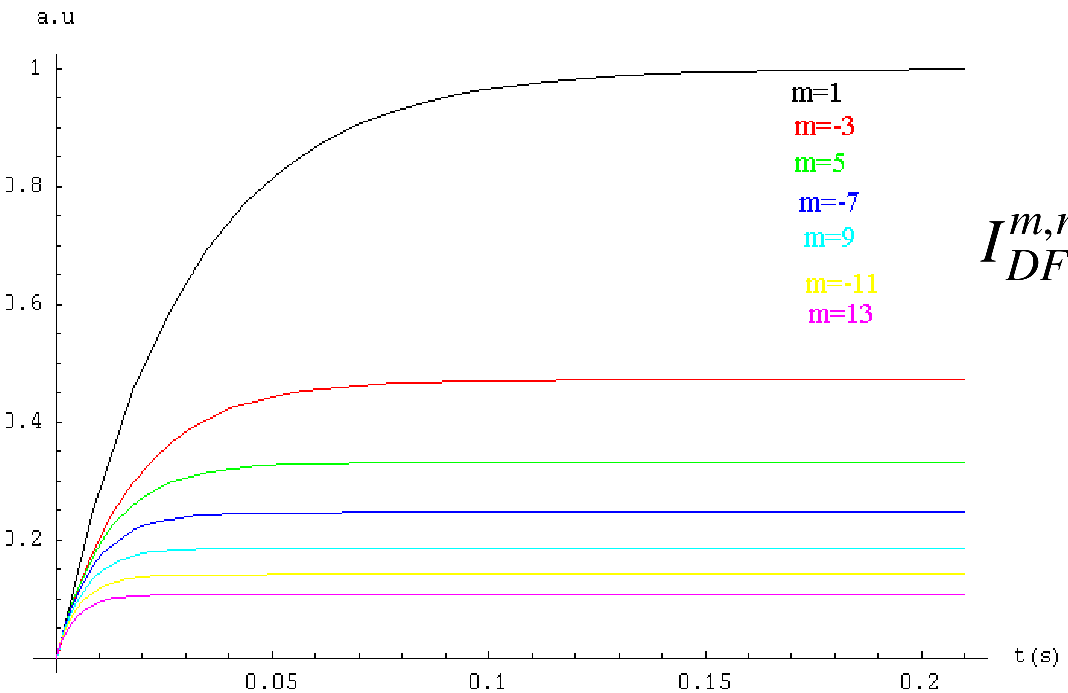
$$b_{r,DFT}^{m,n} = b_r^{m,n} f(m,n) + \sum_{\{l,k\}\in Z^2-\mathbf{0}} b_r^{m+lM,n+kN} f(m+lM,n+kN)$$

aliasing

R. Paccagnella et al Nucl. Fusion (2002) 42 1102

Sidebands aliasing (II)

Due to their discrete nature the radial field produced by the coils (and also measured) contains not only the *m=0,..M-1, n=0,...N-1* modes but also higher order sidebands

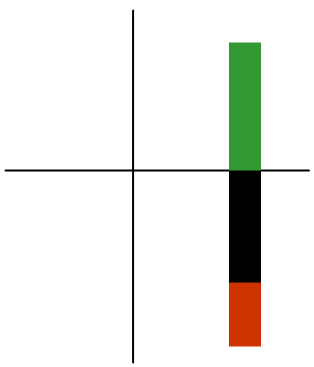


$$I_{DFT}^{m,n} \quad \rightarrow \quad b_{r,c}^{m+l\,M,n+k\,N} \qquad l,k \in \mathrm{Z}$$

The sideband $b_{r,c}$ (l≠0 and k ≠0) can be computed from the coil currents using the standard vacuum formulas in cylindrical geometry (shell penetration taken into account).

Sidebands aliasing can be corrected

- Sidebands are *unavoidable*, but aliasing can be removed from measurements
  - *it is not a geometrical constant, but it depends on the dynamics of the coils currents*



$$\boxed{b_n^{plasma}} - \left(\boxed{b_n^{ext}} + \boxed{\sum_k b_{n+kN}^{ext}} \right) \longrightarrow \text{DFT harmonics}$$

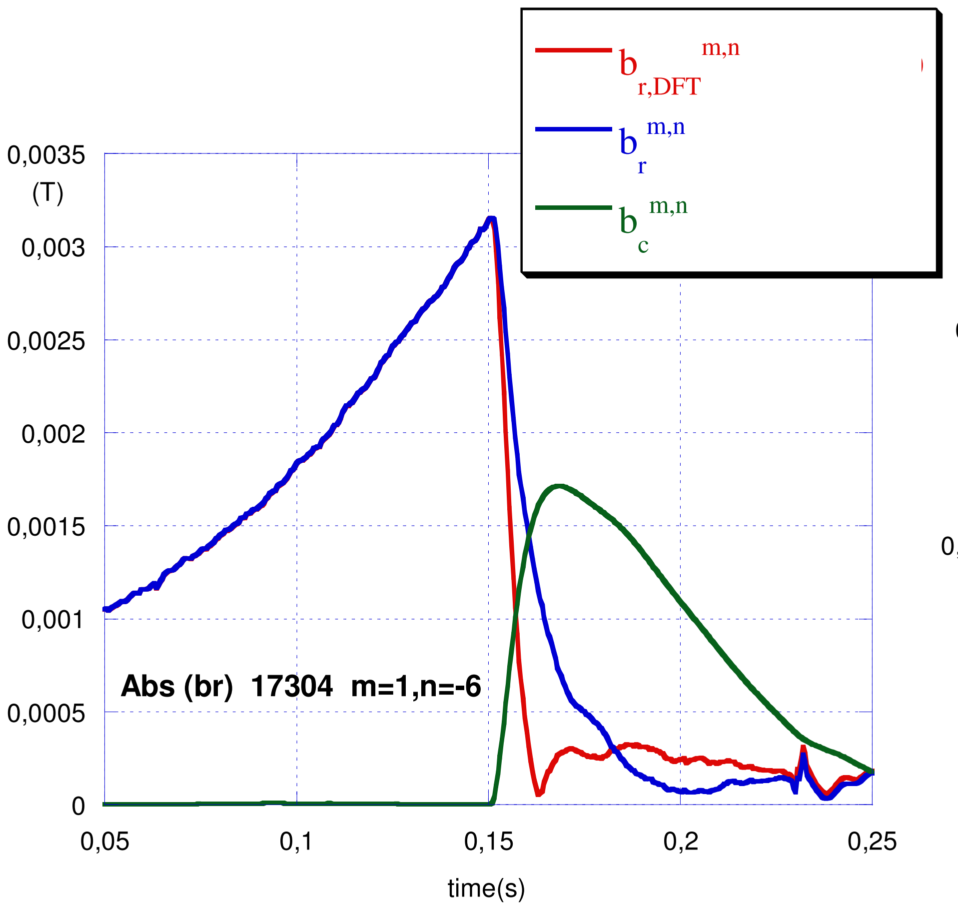
$$\boxed{b_n^{plasma}} - \boxed{b_n^{ext}} = 0$$

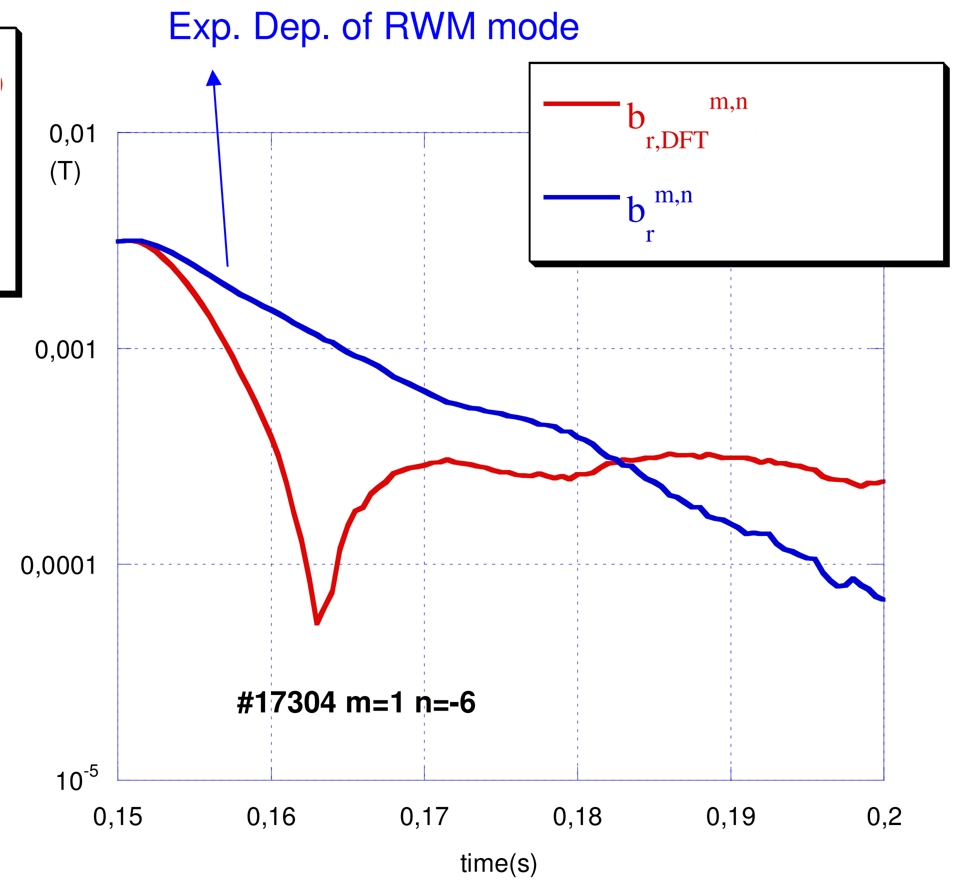
Fourier harmonics

- This issue may be in general relevant for fusion devices where it is suggested to use as more sensors as possible!

Comparison of Fourier and DFT harmonics

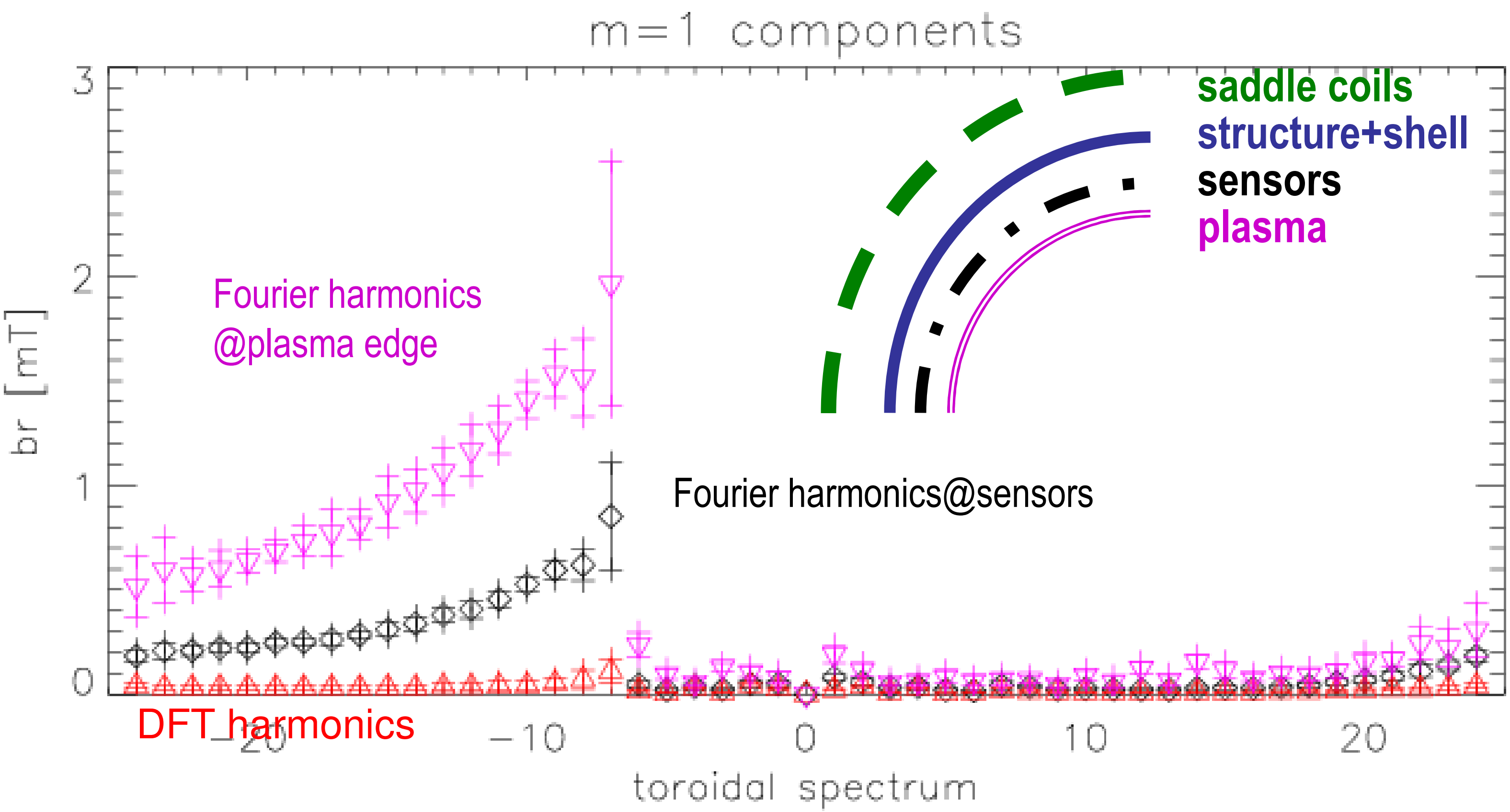
RWM stabilization: only the Fourier mode shows an exponential decrease





br@sensors ≠ br@plasma edge

- The radial distance of the sensors from the plasma edge is a another source of *systematic error*
- *the field at the plasma edge is obtained from radial and toroidal field harmonics at the sensors*



The Clean Mode Control requirements

- Both sidebands correction (Cleaning) and extrapolation to plasma radius need to be performed *in real time*

- Each mode needs a different PID controller

$$b_{m,n}^{coil}(t) = -K_P e_{m,n}(t) - K_I \int_0^t dt\, e_{m,n}(t) - K_D \frac{d}{dt} \Im\left(e_{m,n}(t), f_{cut}\right)$$

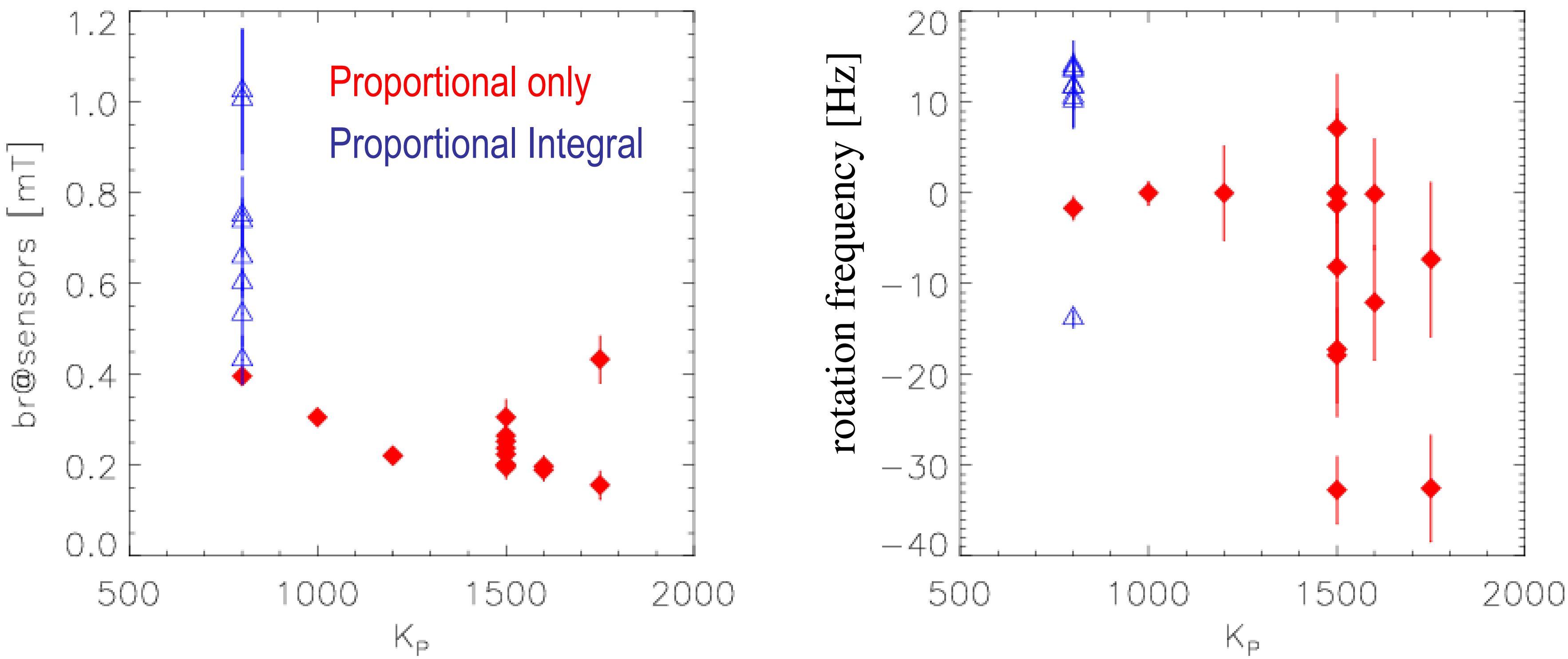
  – RWMs are stabilized by a **Proportional Integral** approach

  – Tearing Modes edge br cancellation requires a ***Proportional*** and ***Proportional Derivative*** approach

Effect of gains on individual TM

- An increase of proportional gain decreases the edge radial field amplitude

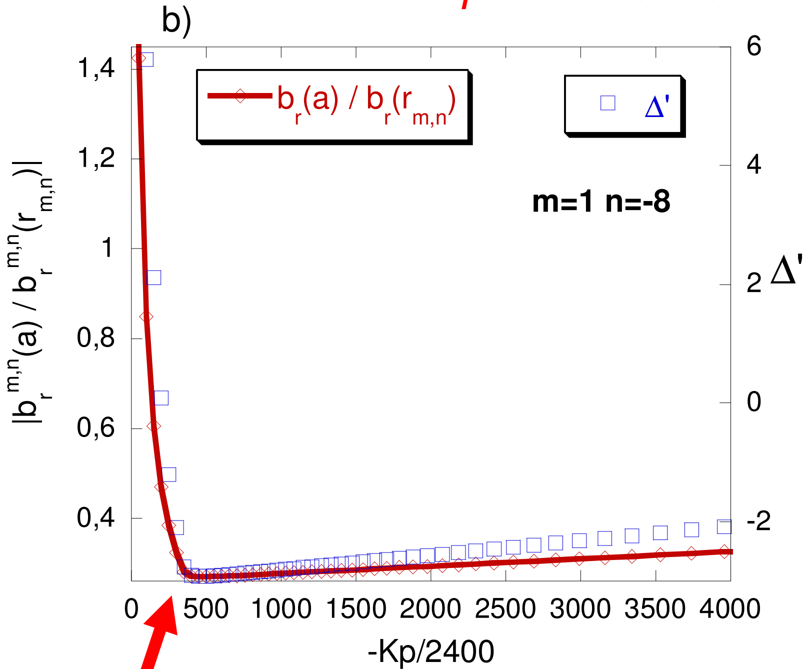
m=1,n=-7

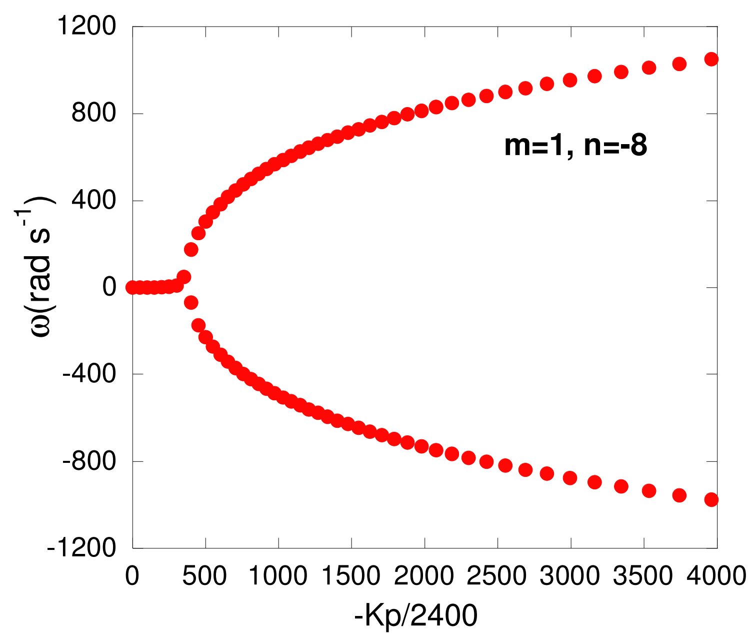


- At high gains, *mode rotations occur and amplitude does not decrease*
- Proportional Derivative *may speed up or brake rotation*.

Physics of individual TM control

- This behavior is consistent with the stationary solution of a single **Tearing Mode model** based on:
  - *Torque balance* *P.Zanca et al. ,Nucl. Fusion, 47 (2007) 1425*
    - EM torques due to feedback, eddy currents on passive structures and viscous torque
  - *Simplified power supply respose model*
  - *Newcomb's equation* for reconstructing the field inside the plasma





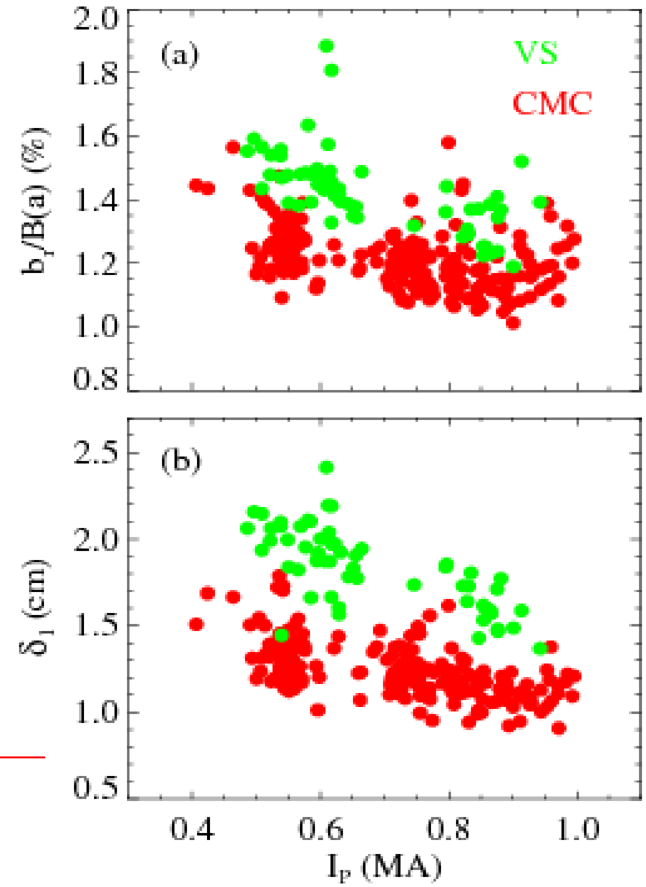
this minimum depends on passive structure and delays of the control system ...

Upgraded results in reducing plasma m=1 perturbations

a) RMS of the m=1 edge radial field, normalized to the poloidal field.

b) LCS shift δ vs plasma current for CMC (red cross) and VS (green diamonds)

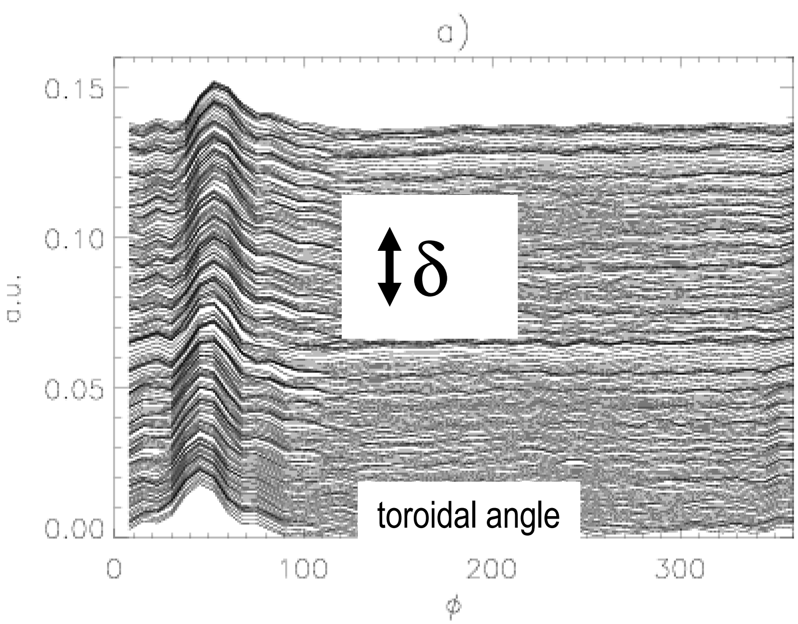
Depends also on phase locking partially weakened by CMC



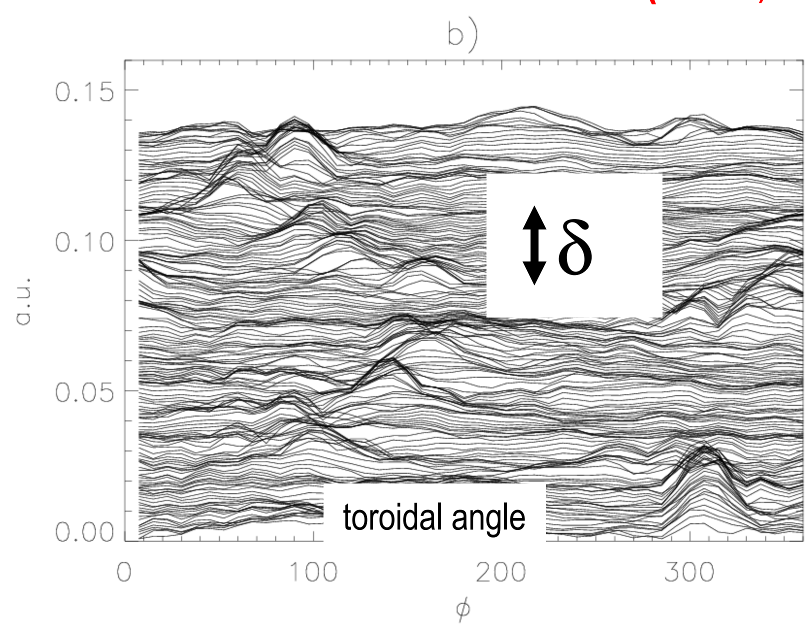
Multiple TM control: Phase unlocking

- With a proper choice of different proportional and derivative gains on the dominant tearing modes
  - Different mode frequencies can be selected for the modes
  - Partial phase and wall unlocking systematically occur

Virtual Shell (VS)



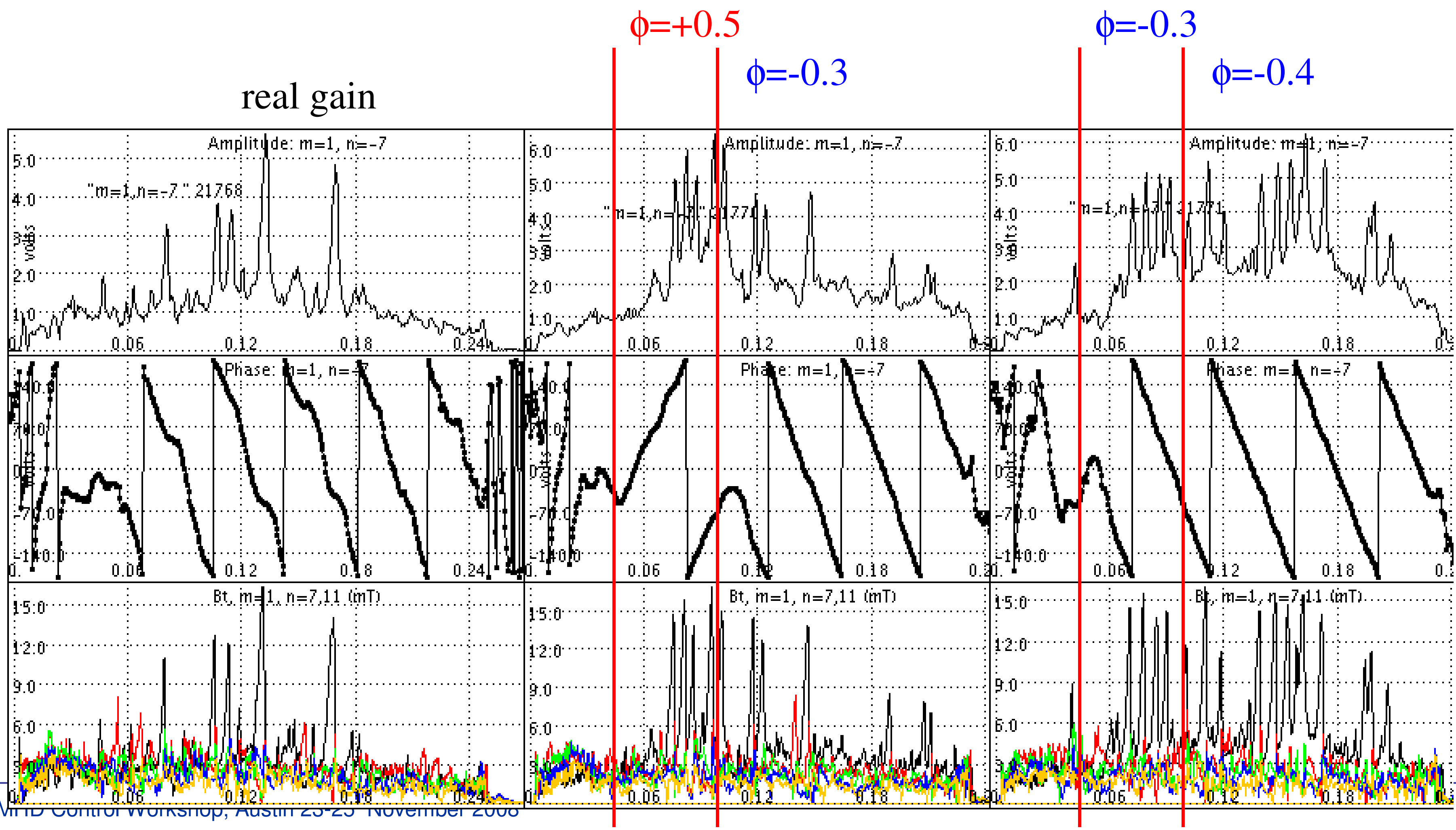
Clean Mode Control (CMC)



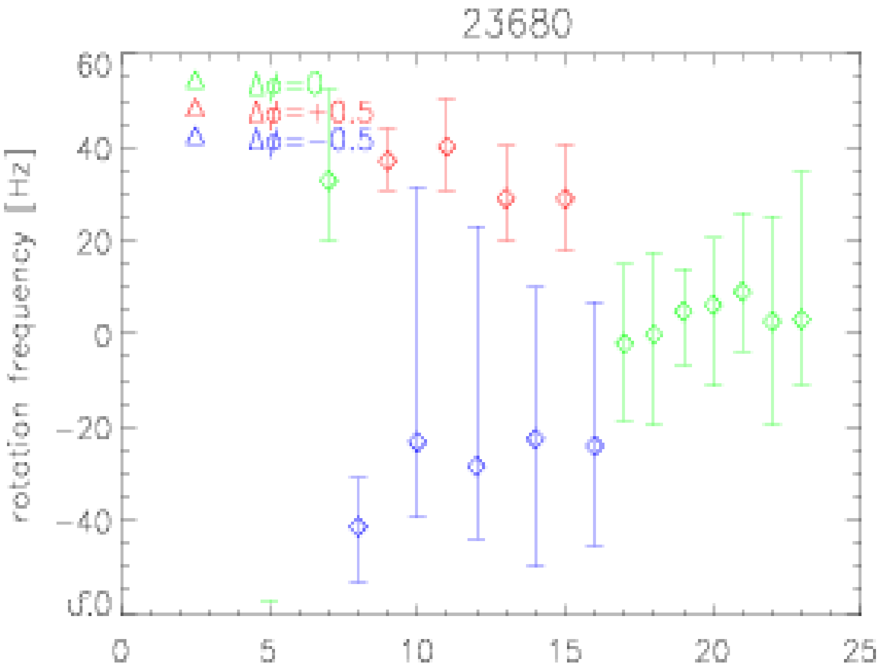
Complex gains

- A complex proportional gain determines the sign of the rotation frequency

$$b_{m,n}^{coil}(t) = -K_P e_{m,n}(t)$$

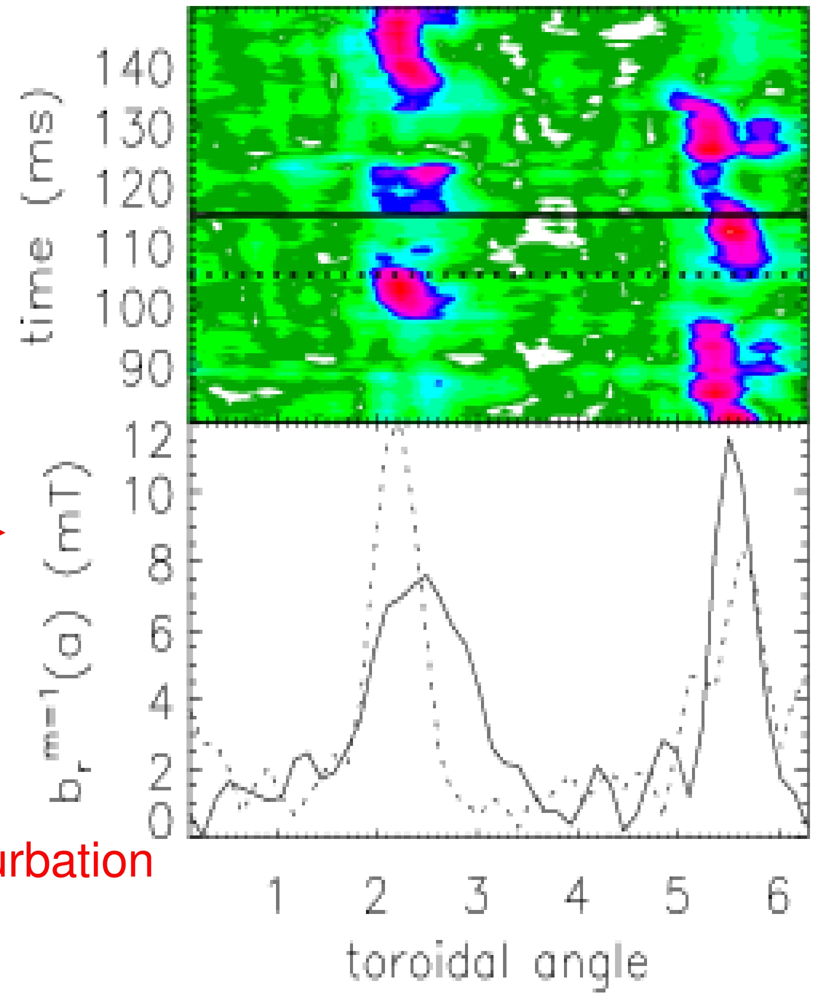


Complex gains



Compl. Gains on multiple tearings

time evolution of the m=1 deformation of the edge radial field

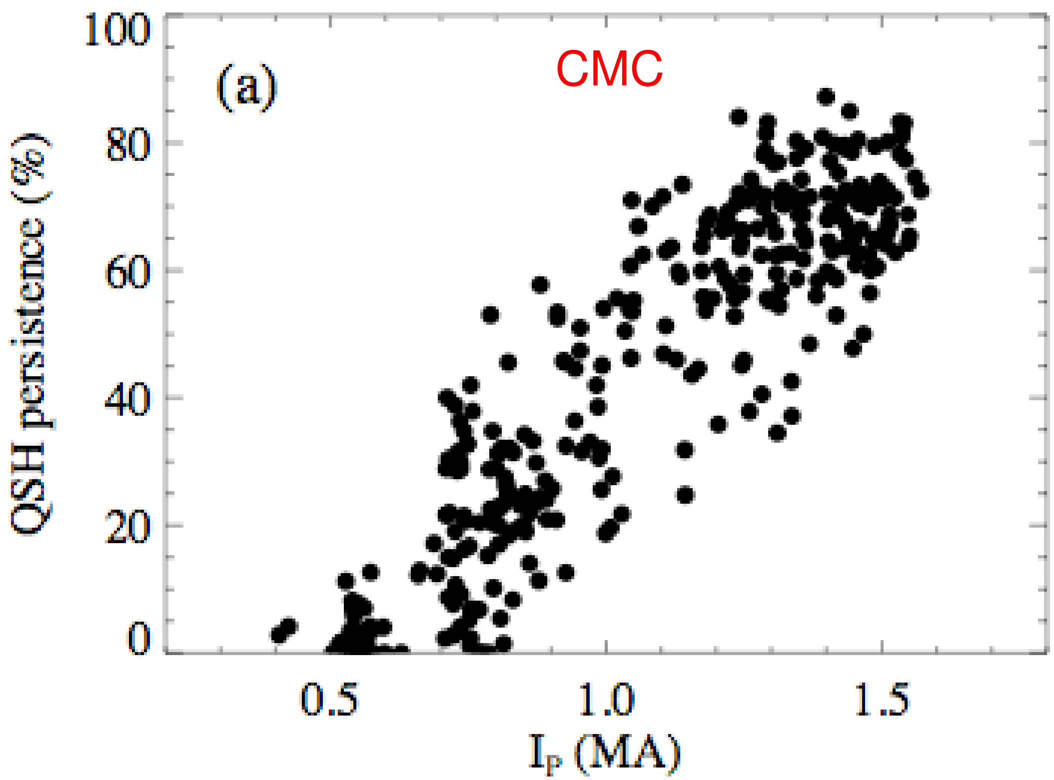


2 peaks in the m=1 total perturbation are sometime observed

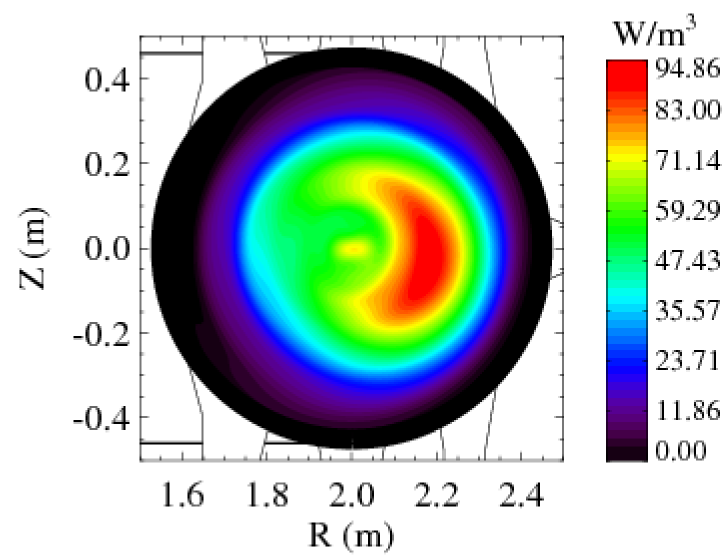
QSH is more frequent

- QSH appears more frequently during the discharge

  at high current
- Setting a non-zero reference on secondary modes inhibits QSH

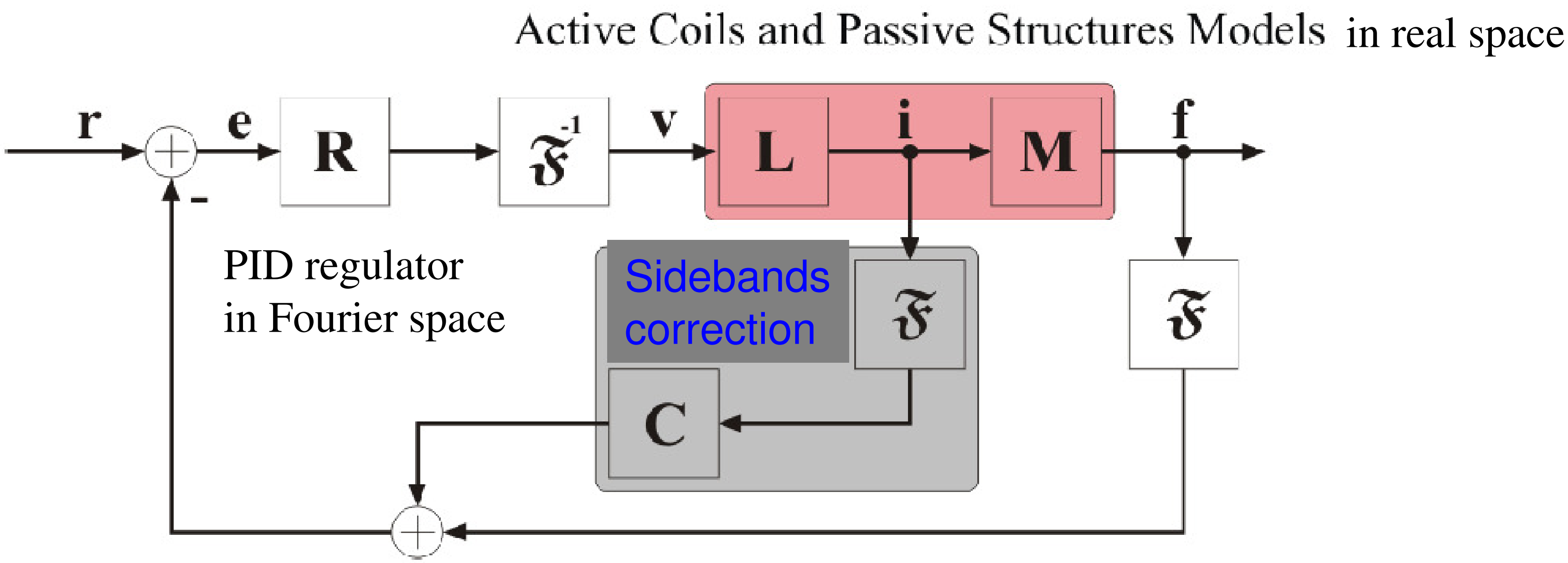


RFX-mod SXR Tomographic reconstruction



Model of the control system

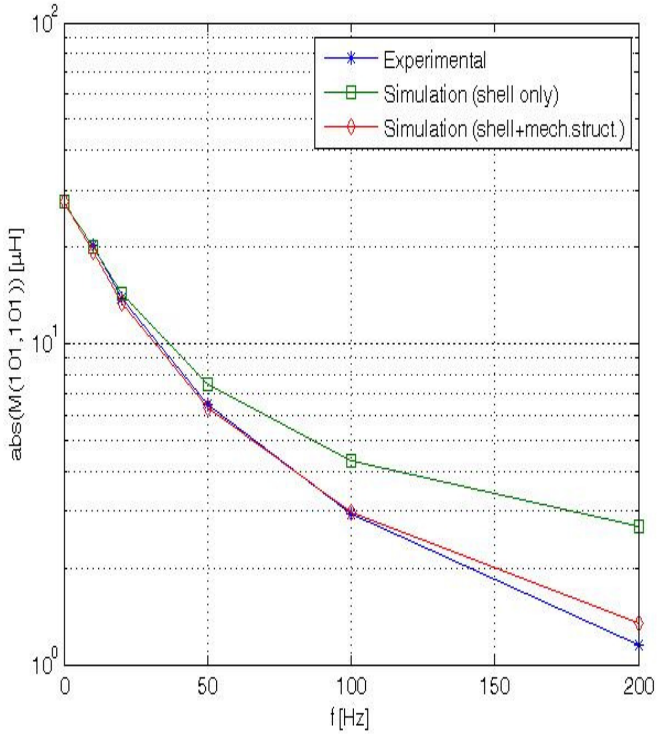
- *An electromagnetic model of the passive boundary and of the control system (not including plasma) is being developed*
  - *mutual inductances M have been experimentally determined and are being benchmarked against the CARIDDI code*

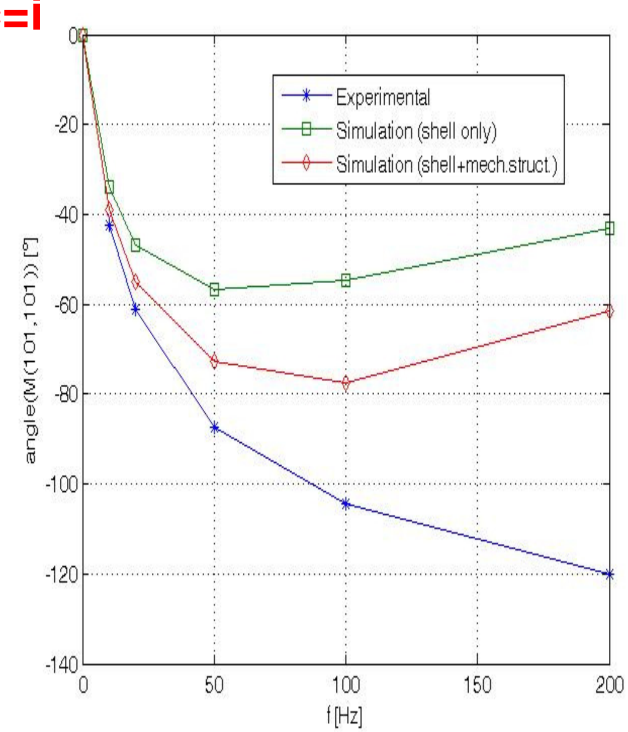


- L is the model of the active saddle coil system
- M is the model of the coupling between active coils and sensors

Comparison of experimental mutual inductances with Cariddi simulations

M s=i,c=i





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SUMMARY AND CONCLUSIONS

• An intrinsic limitation, due the *aliasing* of saddle coils sidebands, have been corrected in real time by using a model for the vacuum field

Such a limitation is important for error field cancellation, and may be relevant for other experiments

•Improvement of latency and phase delay results in a reduction of the minimum edge value of br for Tearing Modes

•Improved Tearing Modes control edge and core amplitude reduction of secondary modes phase and wall unlocking
development of QSH

• MIMO system under development for a better understanding of the system dynamics