CONSORZIO RFX
Ricerca Formazione Innovazione

# Progresses in resonant modes control in RFX-mod

L.Marrelli

F.Bonomo, P.Piovesan L.Piron,G.Spizzo, P.Zanca,
B.Zaniol

# Outline

- Background:
  - Resonant modes (a.k.a Tearing modes) in RFX-mod
- Non linear model of resonant modes dynamics with feedback
- Application of the model to find optimal control parameters
- Comparison with experiments
- Open issues

# Background

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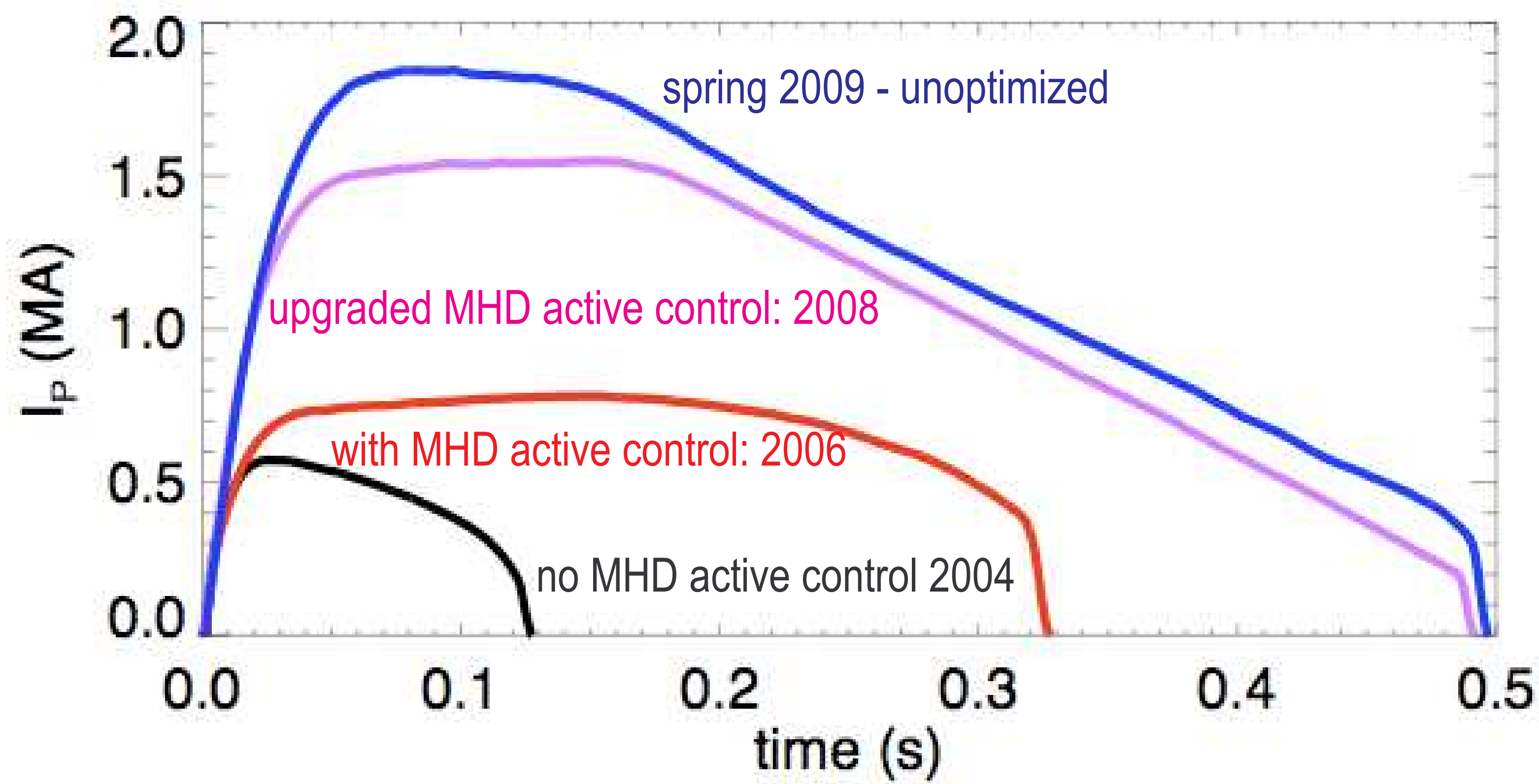
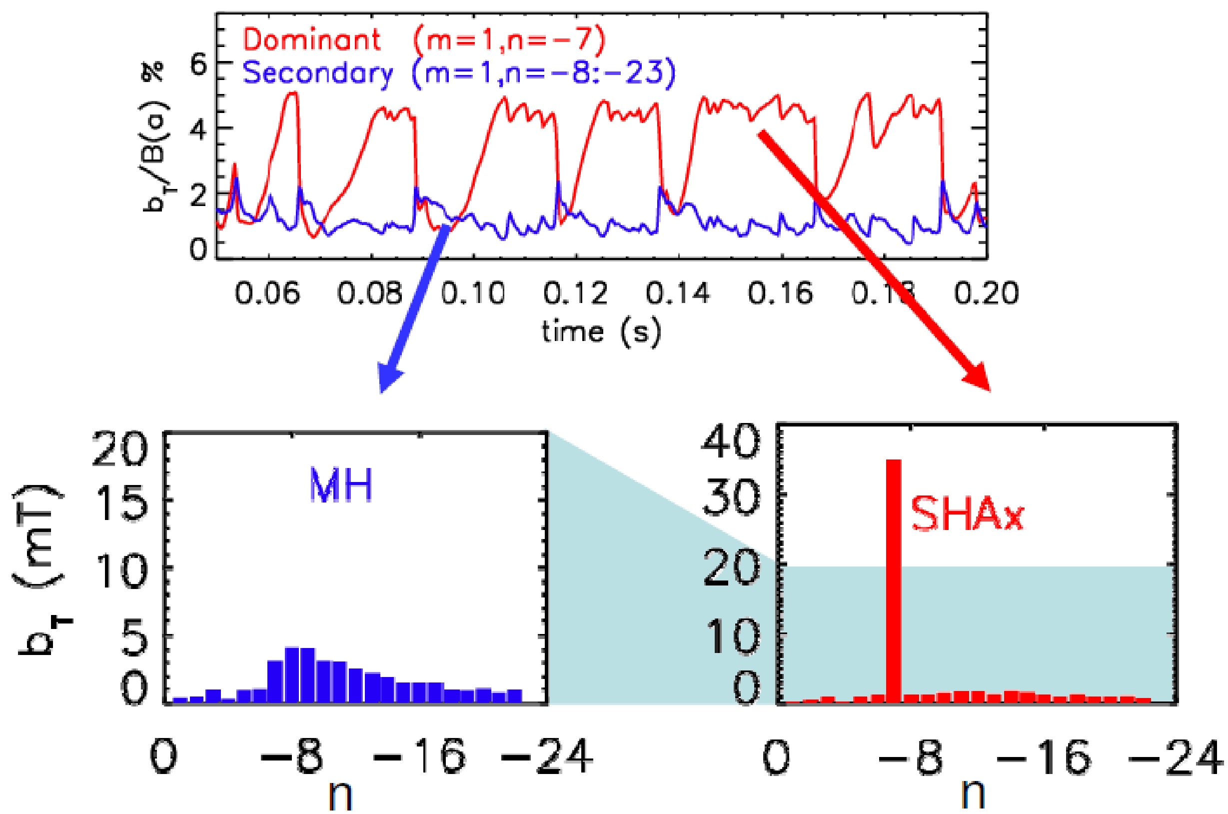
- The reduction of the non axisimmetric radial field at the edge of the plasma has been a key ingredient for the exploration of the high current regime (up to 1.8MA) in RFX-mod.

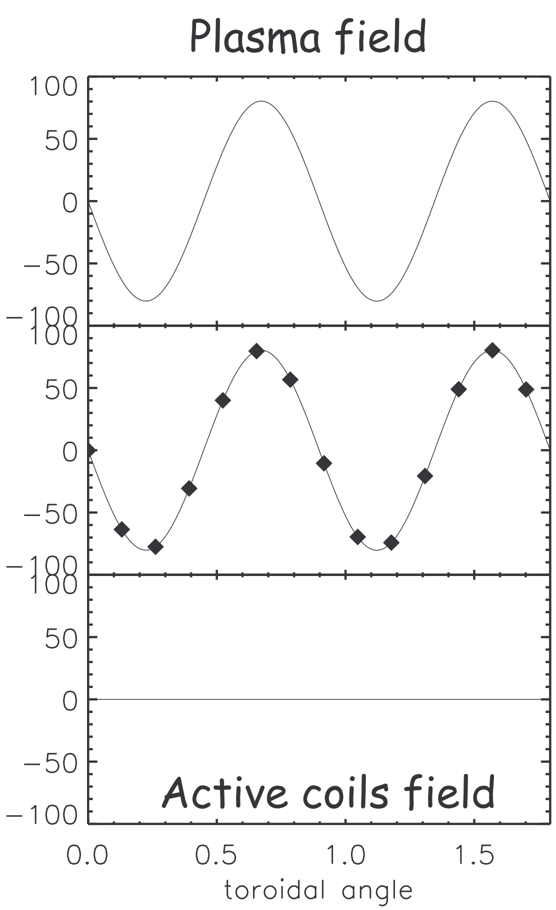


- The spectrum of the radial field measured at the edge is dominated by m=1,n harmonics which are resonant inside the plasma.
  - n>7 for the typical axisimmetric q profile of RFX-mod



# Active coils: sidebands aliasing

- A considerable reduction of the edge radial field has been obtained by identifying and correcting the aliasing of the sidebands produced by the active coils.




Field produced by the plasma at the sensor radius

Idealized sensors sampling the field

Field produced by the active coils

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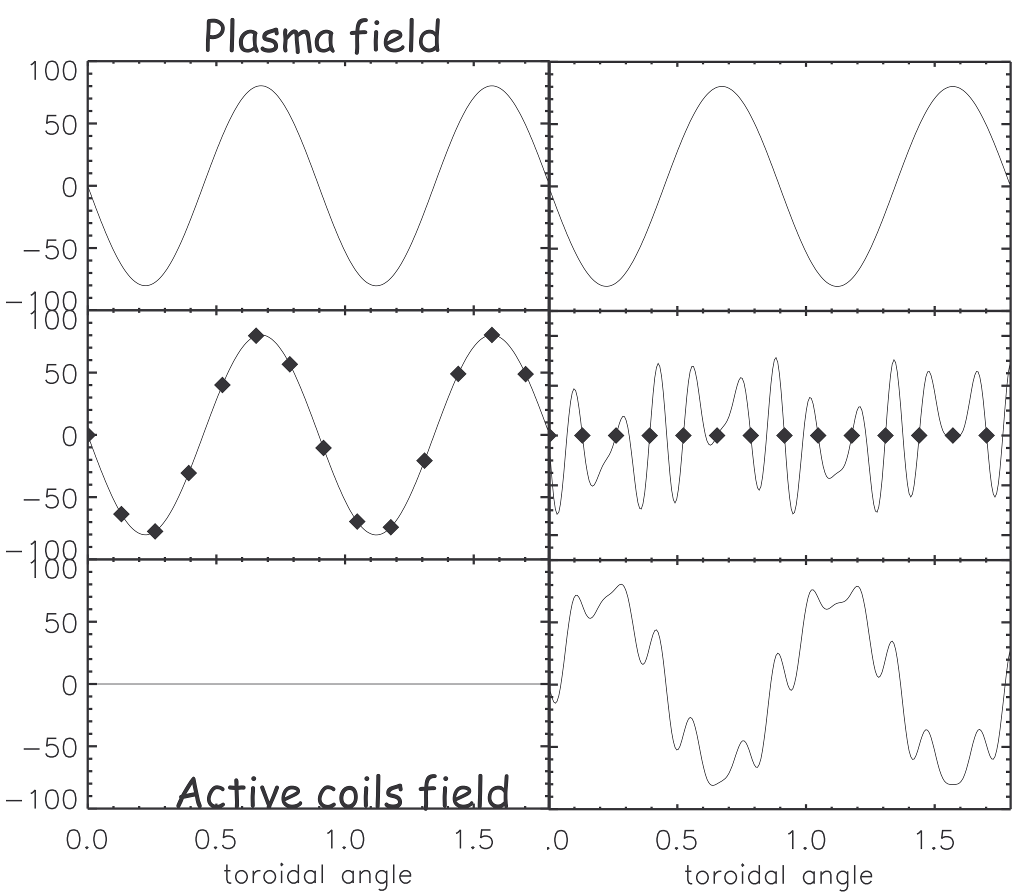


Given the measurements
the feedback law determines
currents in the saddle coils
aiming at generating a zero field

# Active coils: sidebands aliasing

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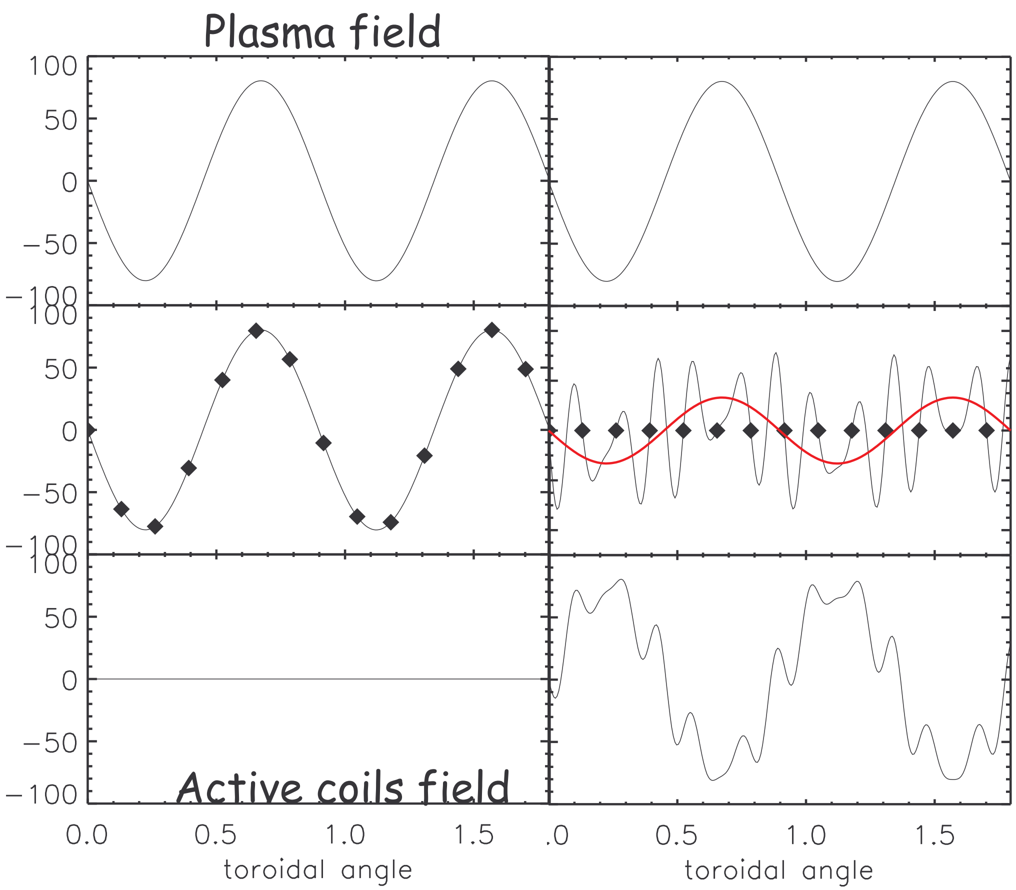


But, even though measurements are exactly zero, an average residual field with at the same spatial period of the plasma field remains to be compensated

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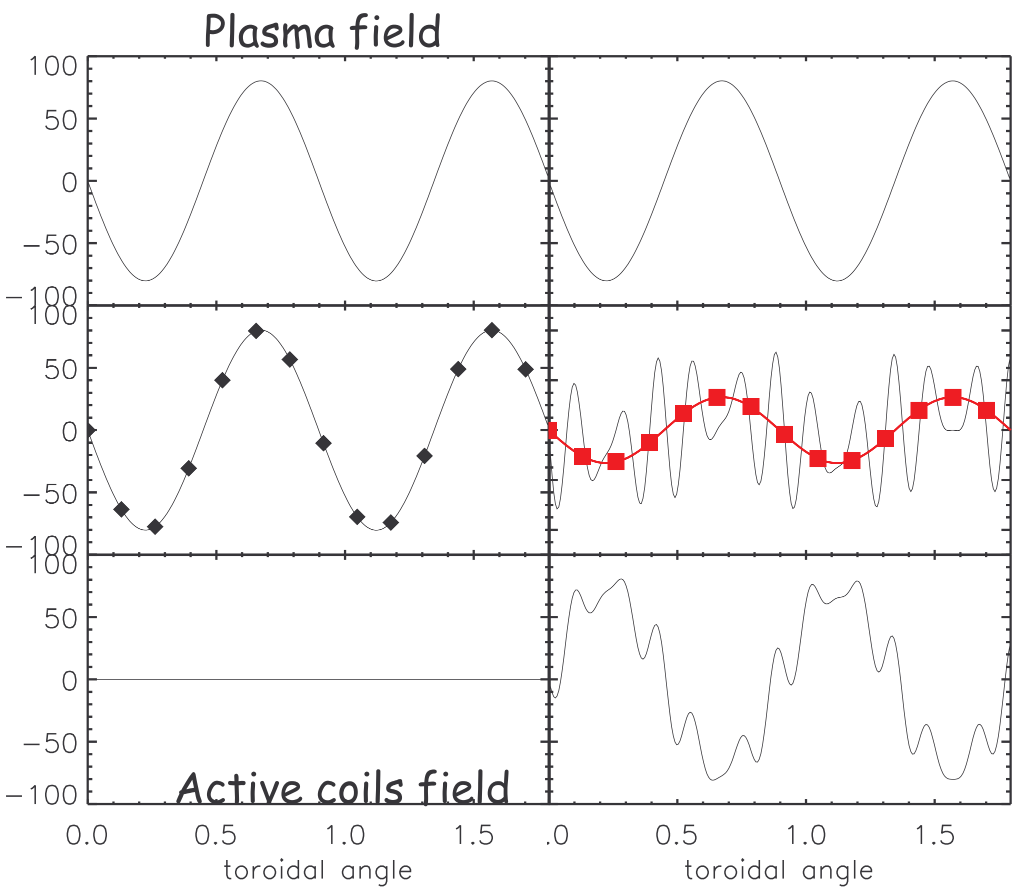


The first solution would be to increase the number of sensors (as HBT-EP : Maurer this morning)

The solution chosen in RFX-mod is to remove the aliasing from the sensors signals ( ▪ ):
"cleaning" in RFX-mod jargon

# Active coils: sidebands aliasing

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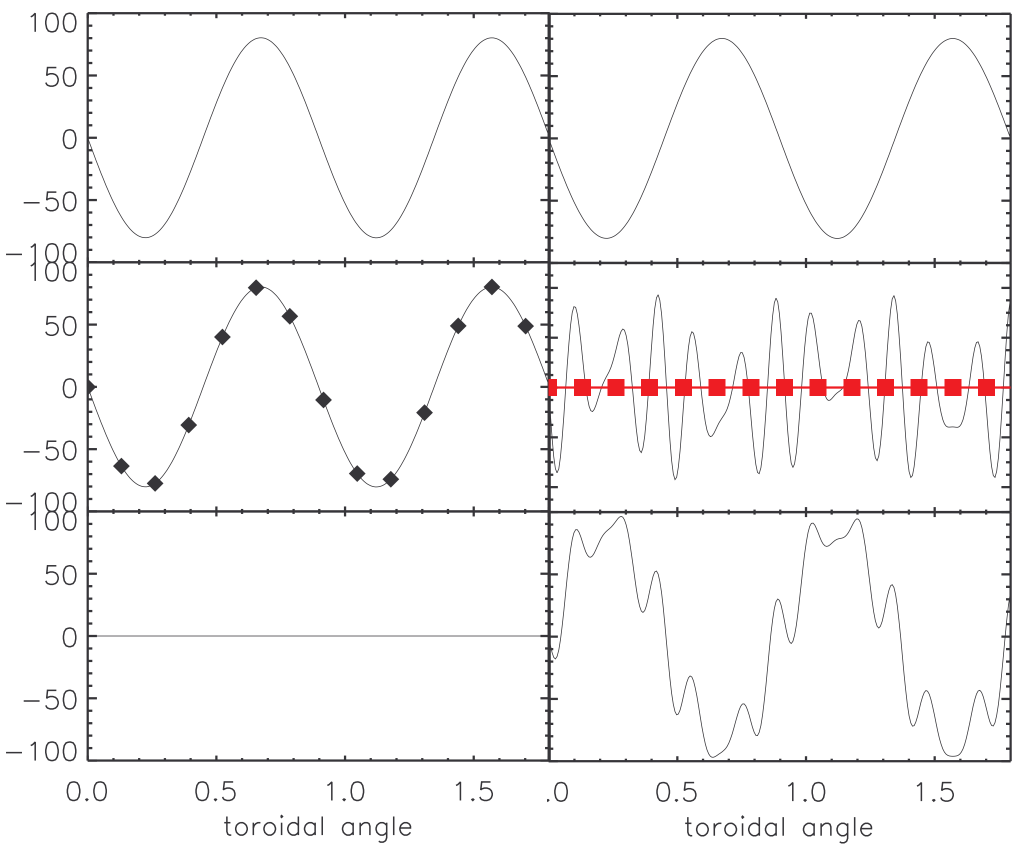
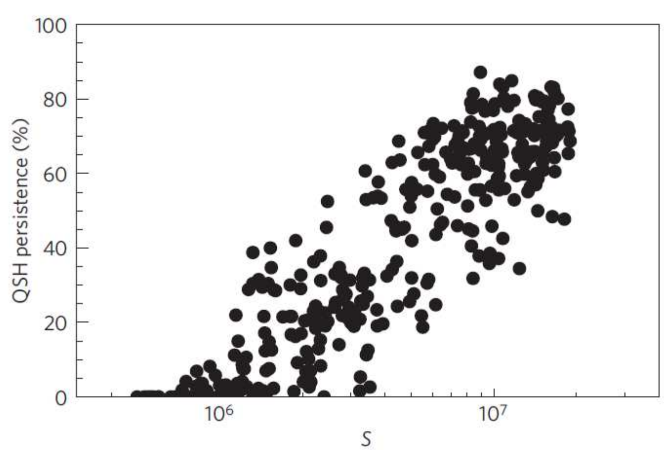



Clean Mode Control feedback law corresponds to zeroing the clean signals (▪)

More current needs to be driven into the saddle coils and more sidebands are produced

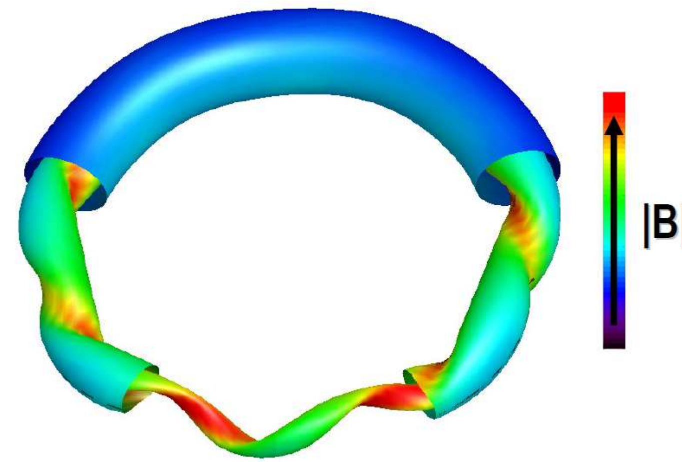
# Transition to QSH/SHAx states

- In the high current regime, frequent transitions to helical states are observed.
  - The dominant mode grows…

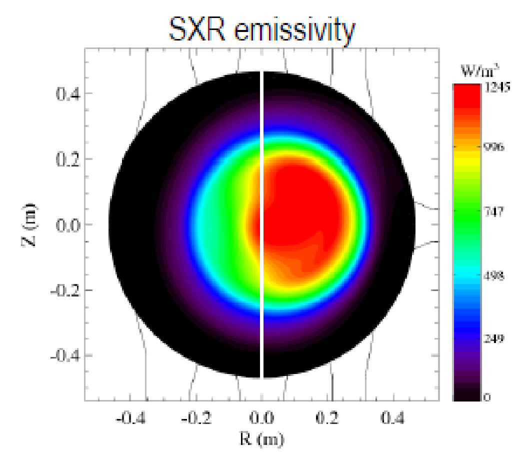



  - … while the secondary ones decrease

- … the internal topology of the magnetic field becomes helical…

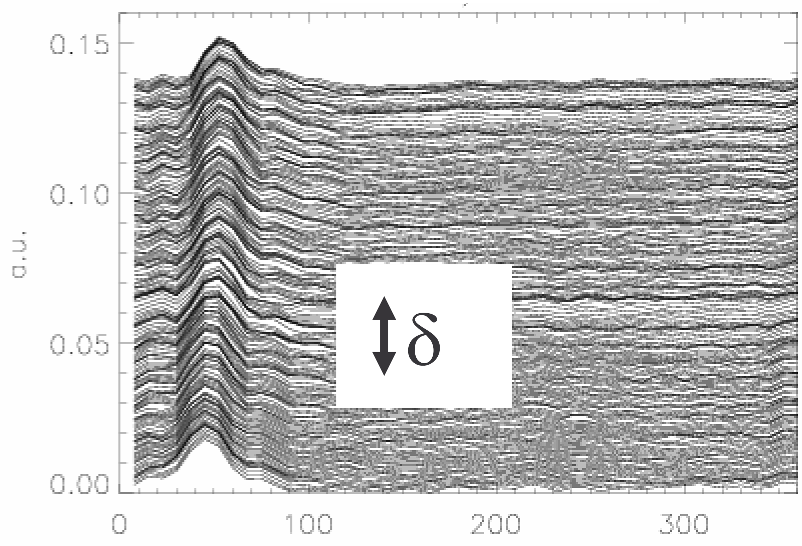



- … and the thermal content too



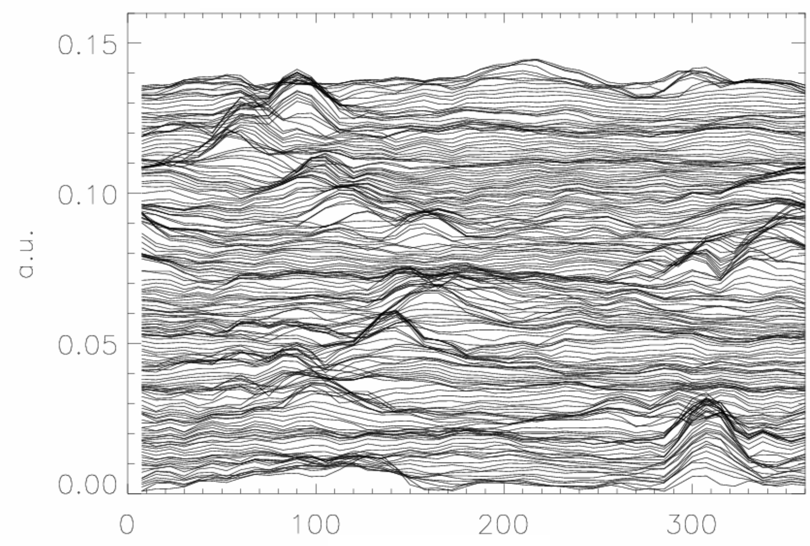
- Secondary modes are phase locked and produce a residual localized bulging of the Last Closed Magnetic Surface…

Virtual Shell (VS)



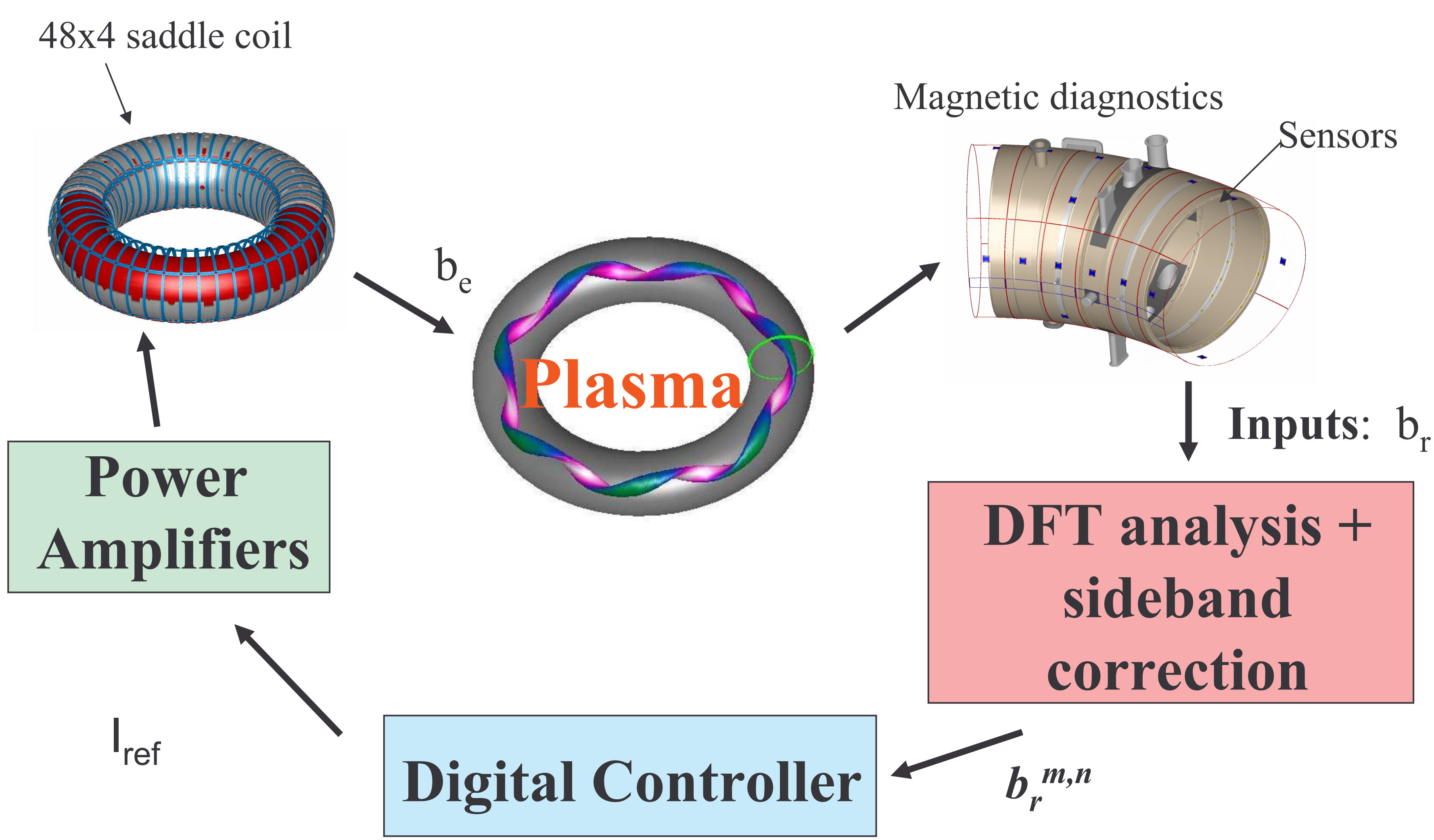

- But by proper tuning of the feedback logic, wall unlocking and partial phase unlocking is routinely obtained

**Clean Mode Control (CMC)**



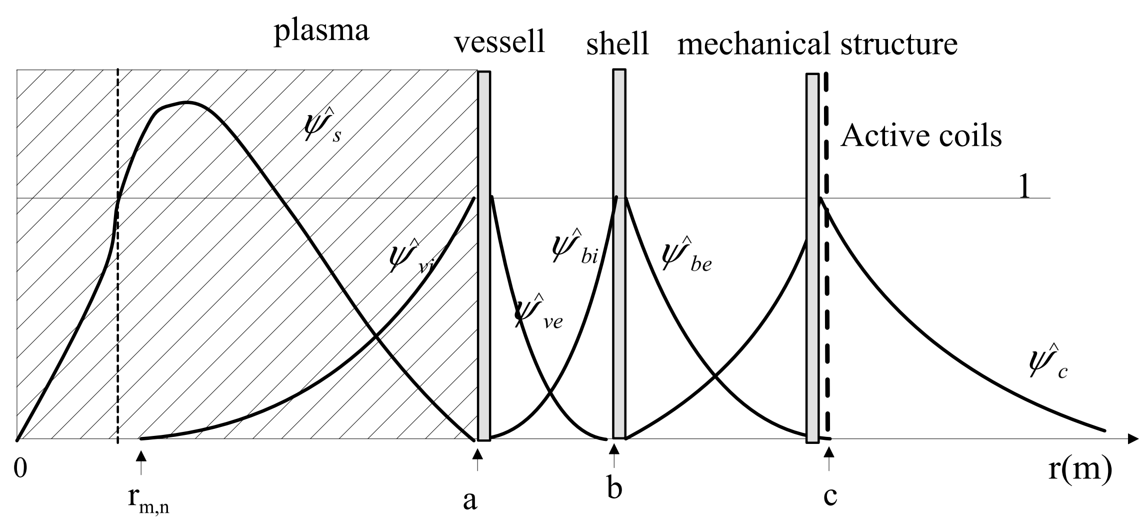

- The deformation of the last closed surface is not stationary and is reduced

# The RFX-mod feedback architecture



# The dynamical model of TM control

- The limits to the reduction of edge radial field can be described by a model of Tearing Modes physics [1]: *RFXlocking code*
- The model assumes
  - Force-free cylindrical axisimmetric equilibrium magnetic field
  - Perturbative approach for TM radial profiles:
    - Linearized ideal-MHD force balance: Newcomb equation
    - The amplitude of TMs at the resonant surface is given
  - 3 uniform thin shells (vacuum vessel, copper shell, mechanical structure)






[1] P. Zanca, Plasma Phys. Control. Fusion 51, 015006 (2009)

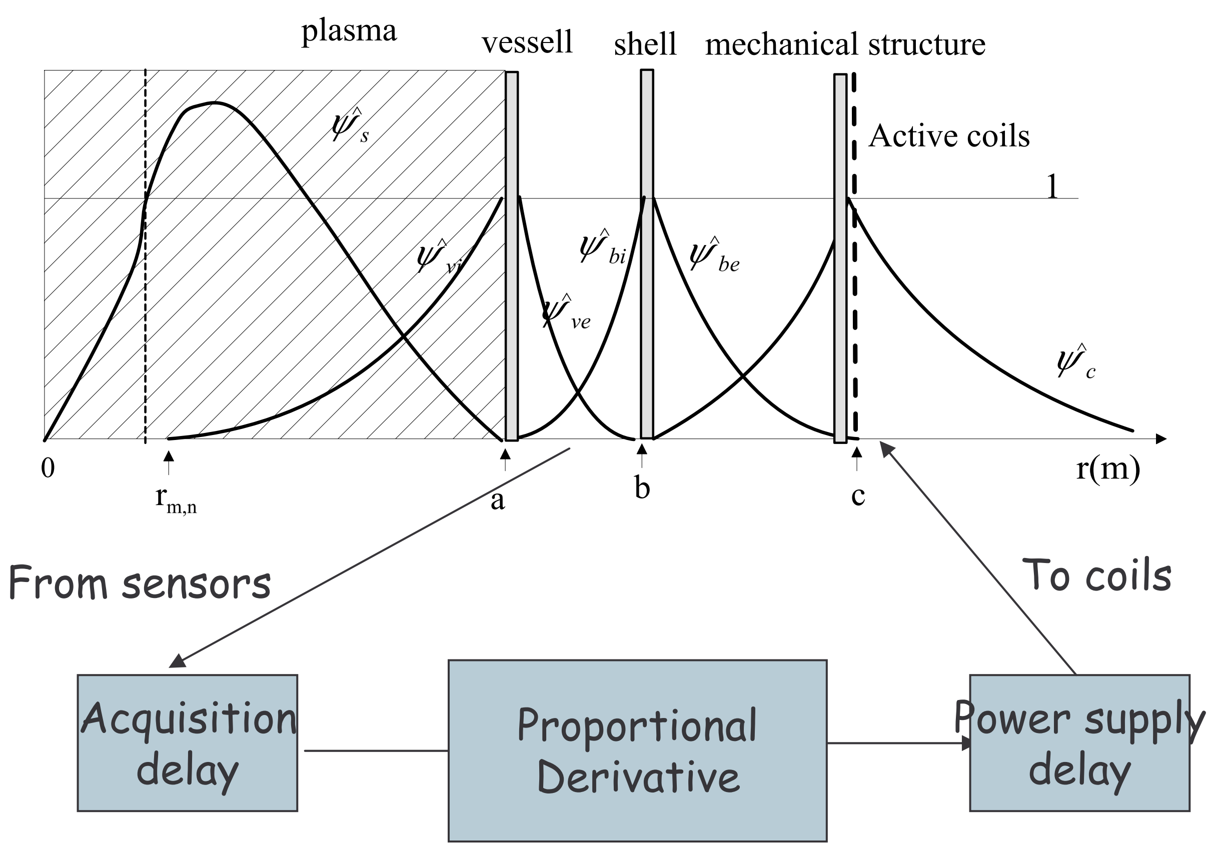
# TM phase evolution

- The phases of TMs at the resonant surface co-rotate with the plasma fluid: *no-slip condition*

$$\frac{d\varphi^{m,n}}{dt} = n\Omega_\phi(r_{m,n}, t) - m\Omega_\theta(r_{m,n}, t)$$

- The (flux surface averaged) fluid motion is determined by the balance between
  - Phenomenological momentum source densities
  - Viscous torque
    - Estimated from flow passive spectroscopic measurements
  - Electromagnetic torques acting on resonant surfaces
    - Quasi Linear approach: non linear terms evaluated by using the linear Newcomb solutions
    - Torque between the mode and the eddy currents
      - » (present also in single mode simulations: wall locking)
    - –Torque exerted by modes $(m_1,n_1)$ and $(m_2,n_2)$ such that $m=m_1+m_2$, $n=n_1+n_2$
      - » Present in multi-mode simulations: phase locking
    - –Feedback generated torque

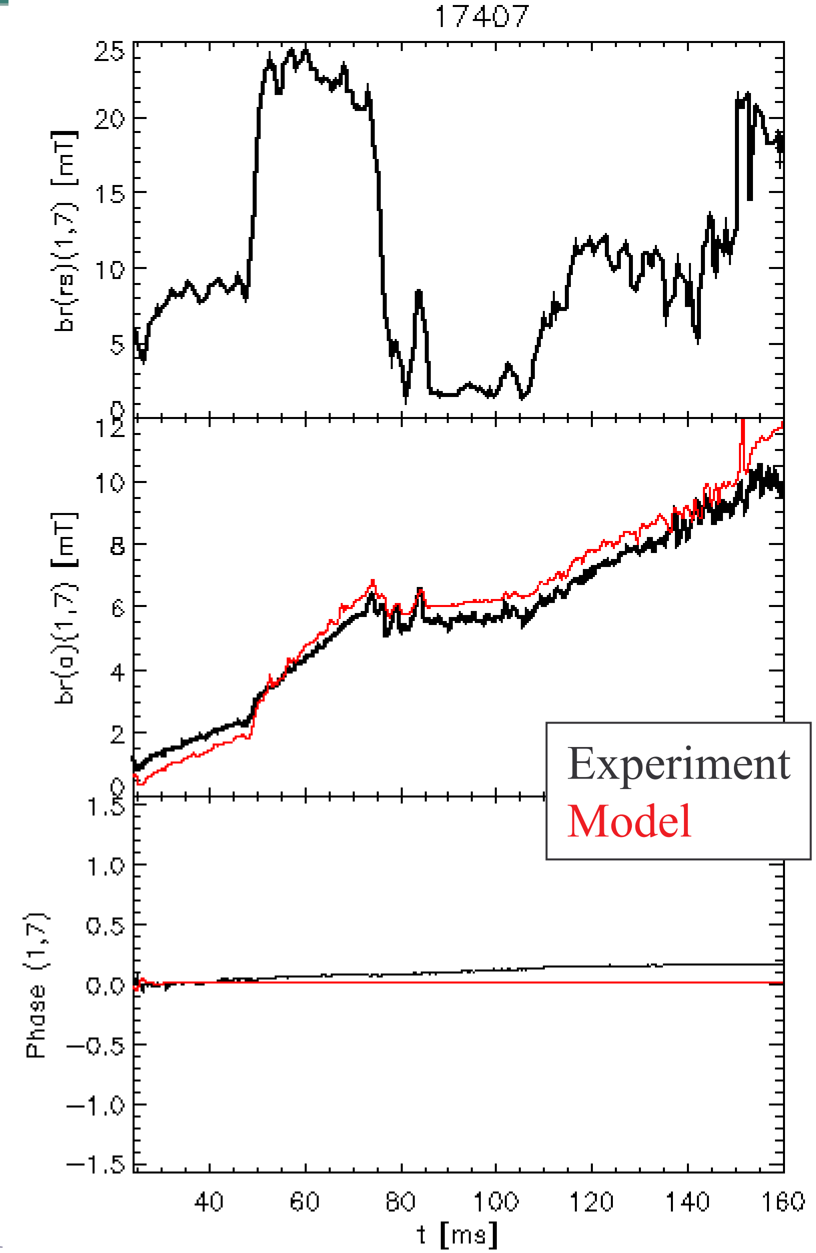
- The reference (command) for currents harmonics in the active coils is obtained by prescribing a PD feedback law
- Delays due to digital acquisition and non-ideal power supplies are modeled by a 1 pole filter $\tau_d$ = 1.5ms



# Single mode simulations: no feedback

- The dynamic model can be applied to simulate the feedback behavior during a discharge

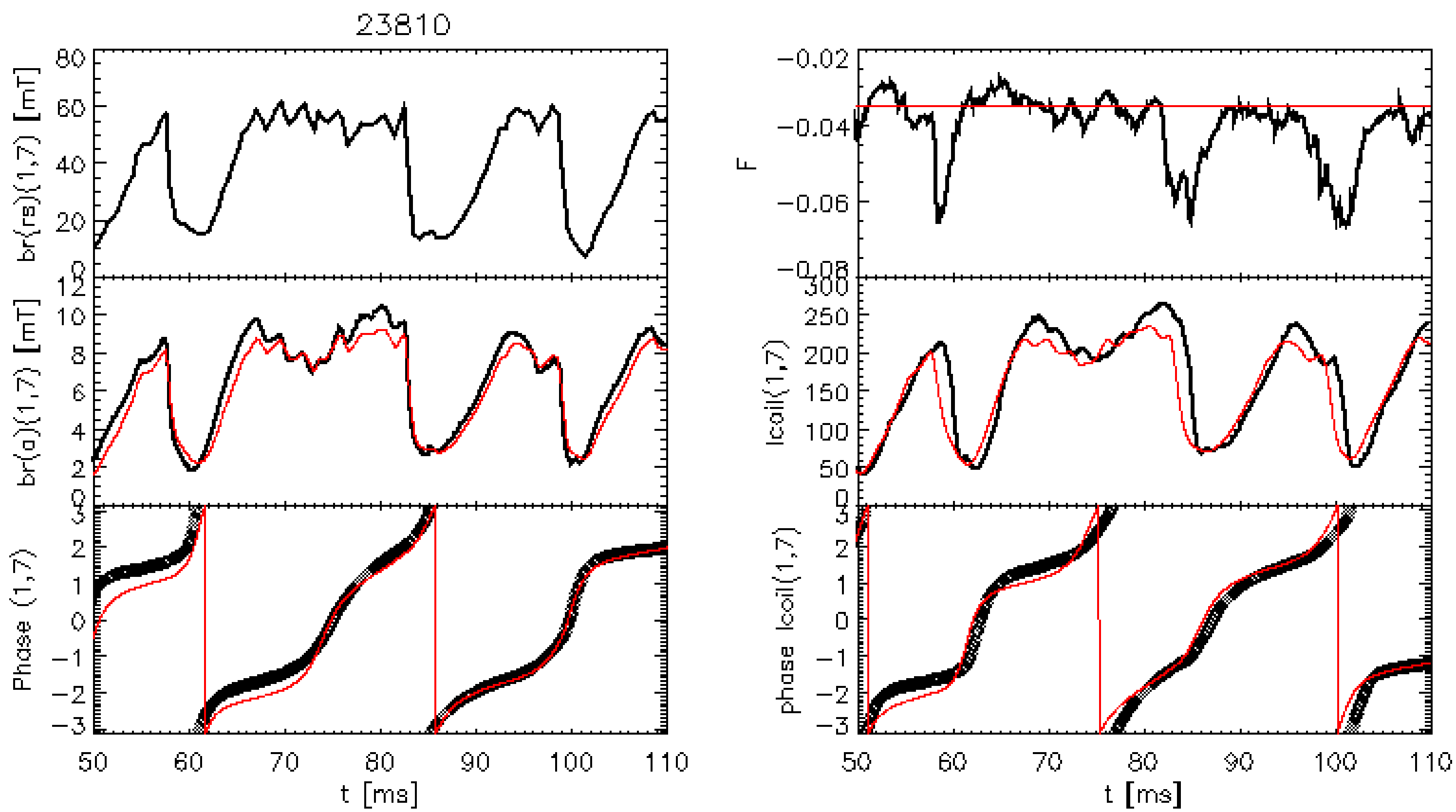
- Without feedback the radial field at the edge grows on walls time scale
  - (Feedback law is Selective Virtual Shell: Kp=0 on m=1,n=-7 only)



# Single mode simulations: feedback case

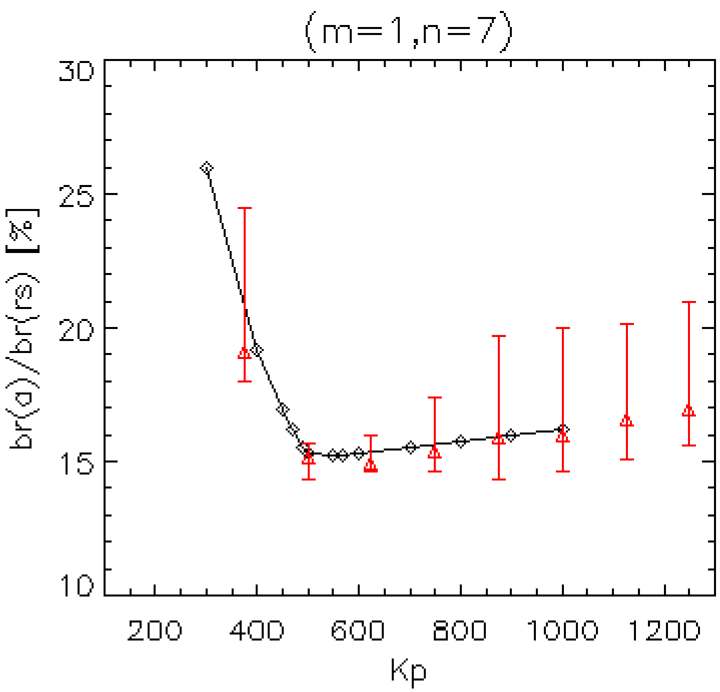
- High current (1.4MA) QSH discharge
  - Purely proportional gain

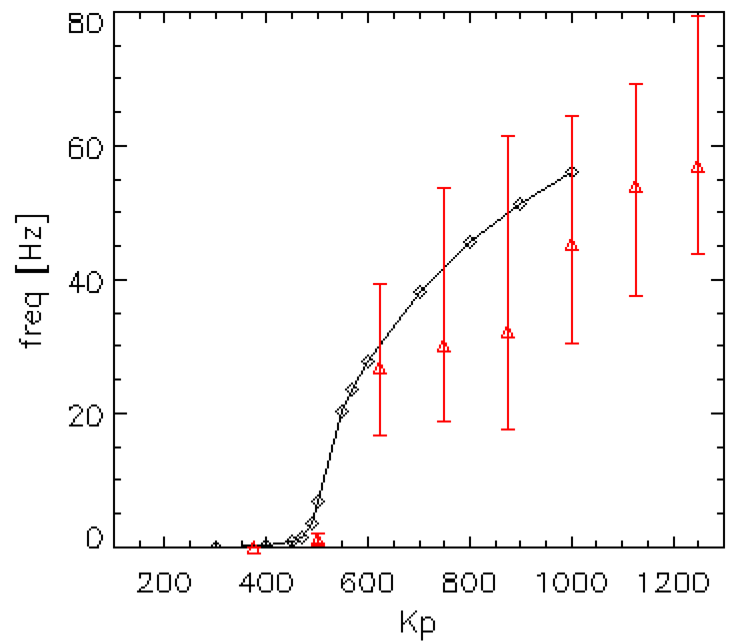
Simulation
Experimental data



# Single mode: Proportional gain dependence

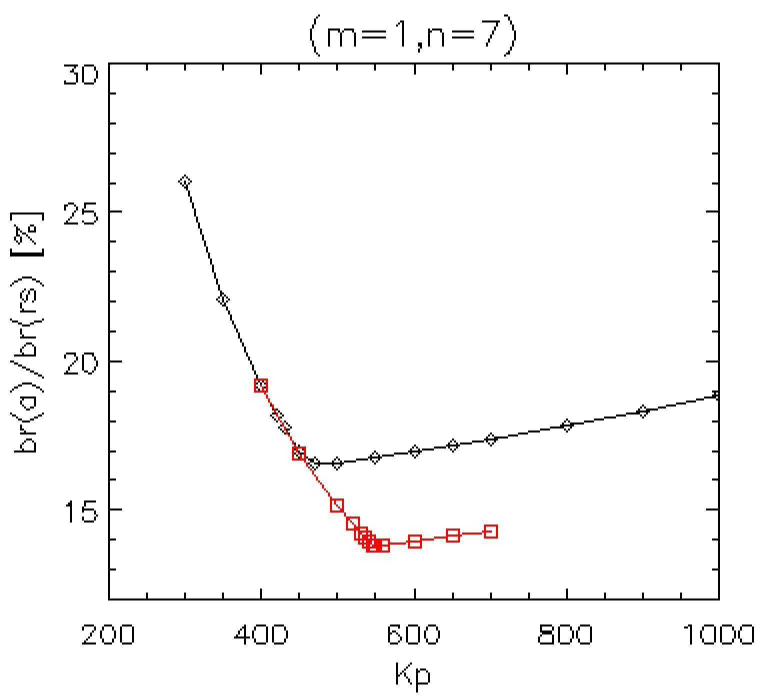
- Dynamic simulations with time varying amplitude of the dominant mode (as in the previous slide) confirm previous findings obtained with the stationary model
  - Dynamic model results are important for time scales < $\tau_b$

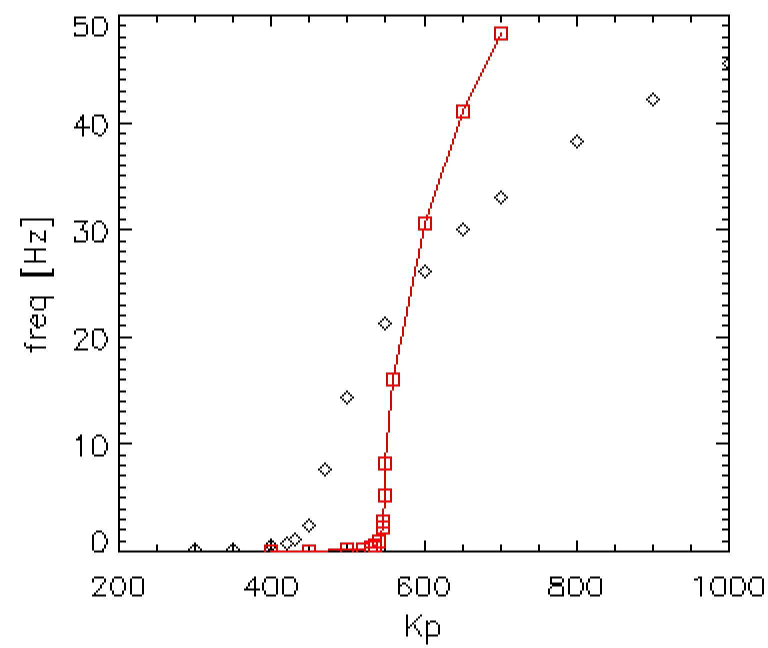


# Derivative gain: single mode

- Within the framework of the model, the main role of the derivative gain is to compensate for the delays in the data acquisition and power supplies.



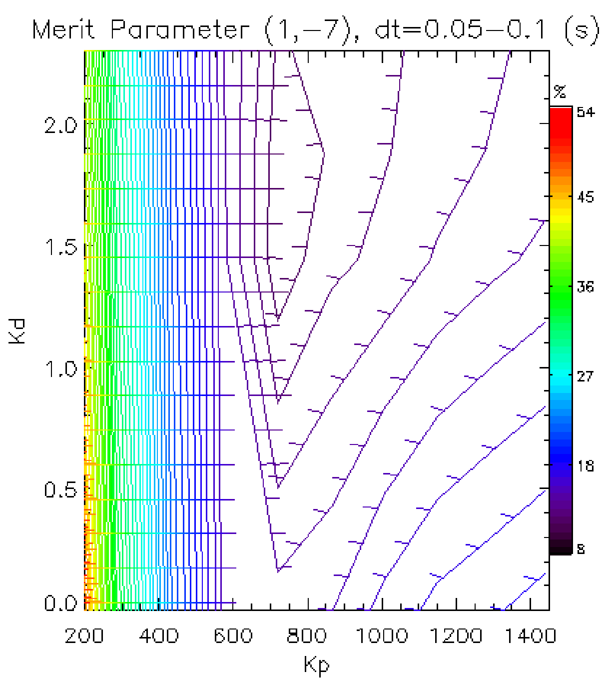

Kd =0

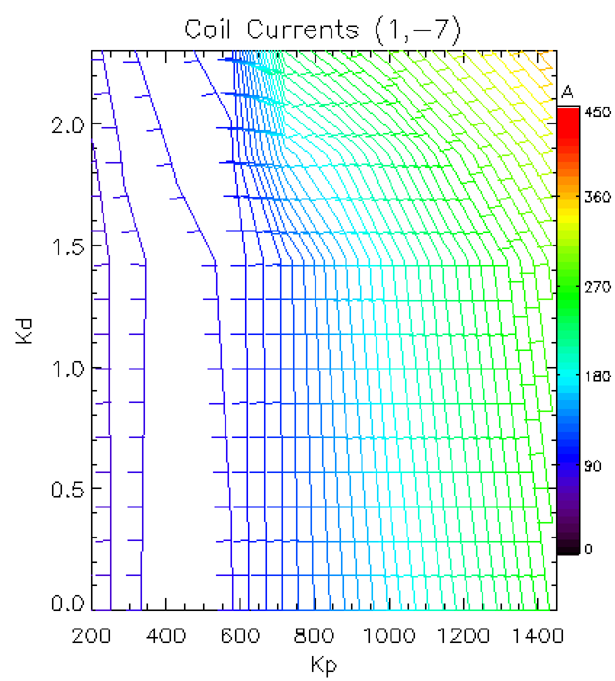
Kd/Kp= 2 ms

# Optimization strategy /1

- Single mode simulations with experimentally measured time evolution of the radial field at the resonance have been performed for a set of Kp and Kd values.
  - The gain couple for the minimum br(a)/br(s) for each mode is determined

Derivative gain, $K_p$

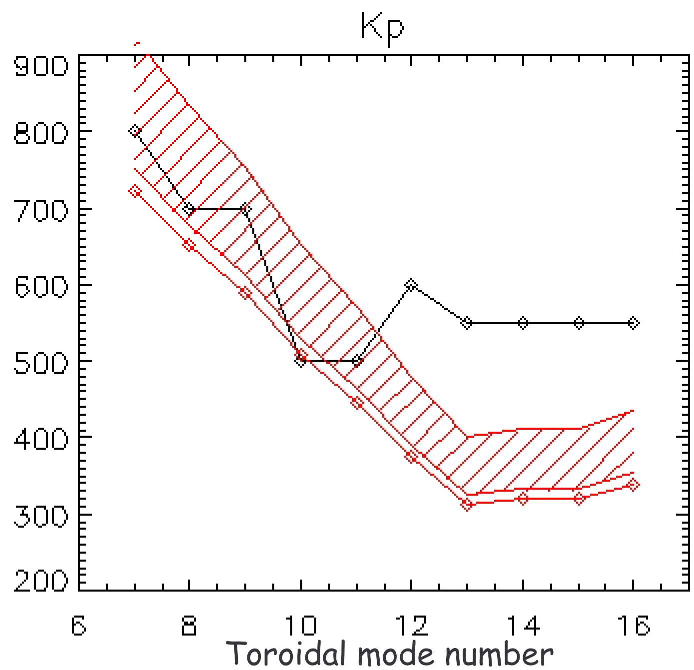


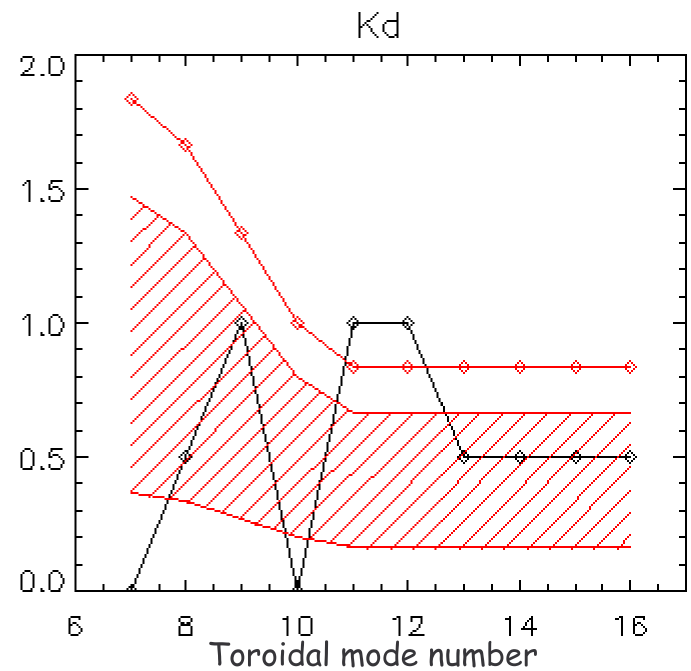




Proportional gain, $K_d$

# Optimization strategy /2

- The "optimum gains" for the dominant modes are
  - (black: empirical gains of 2008 campaigns)



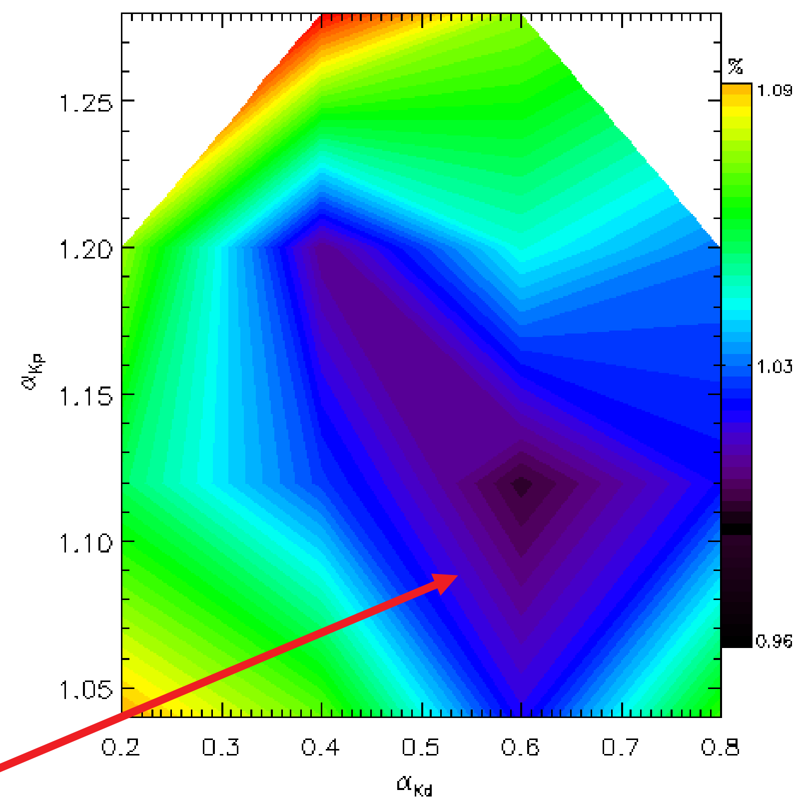

- A smaller gain scan is performed on the experiment.
  - All proportional gains are multiplied by $a_{kp} \approx 1.0\text{-}1.3$
  - All derivative gains are multiplied by $a_{kd} \approx 0.2\text{-}0.8$
  - (explored ranges are shown in the red shaded region)

# Experimental results /1

- Each gain set has been tested at least twice at comparable plasma current and electron density.
  - $I_p$=0.8 - 1.1 MA
  - F=-0.05 - -0.02

- The minimum is rather broad

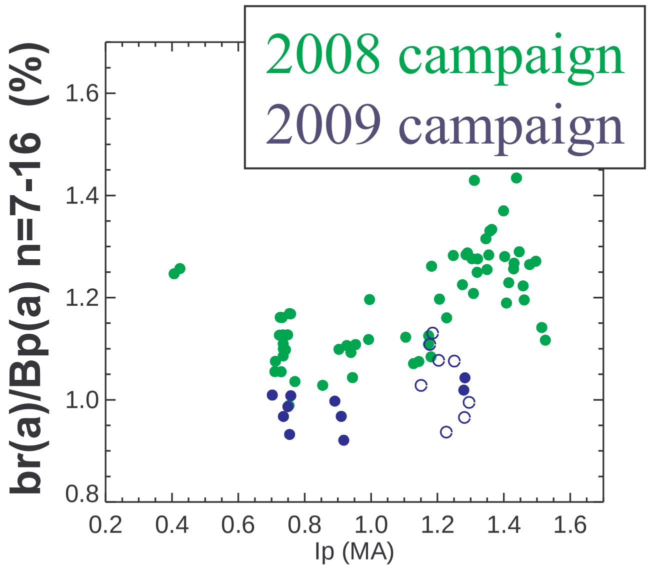
$$b^{tot} = \frac{\sqrt{\sum_{n=-16}^{-7} \left(b_r^n(a)\right)^2}}{B_p(a)}$$

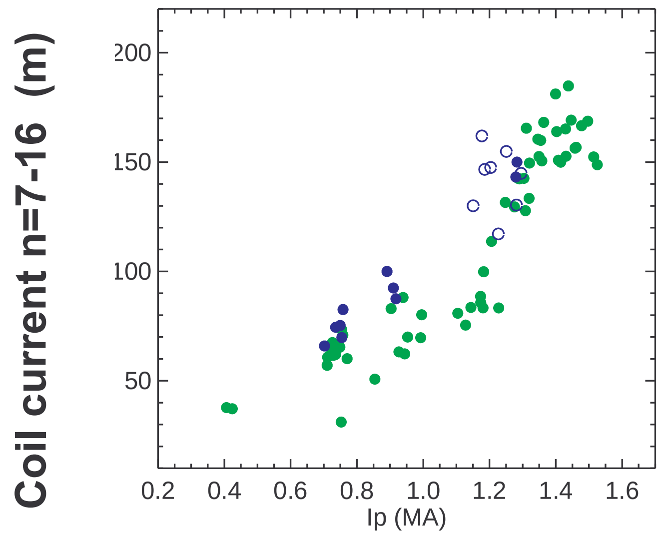



•The experimentally found minimum has been selected for the 2009 campaign

# Experimental results /2

- The selected gains set systematically give lower values of the edge radial field compared to the 2008 gain set…

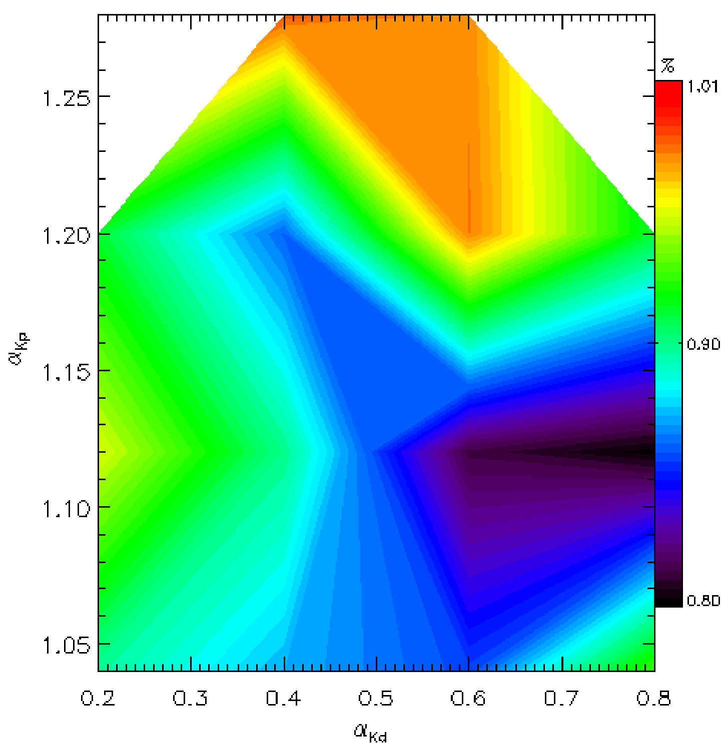



- … with coil currents 20% greater than the 2008 campaign

# Multi mode simulations

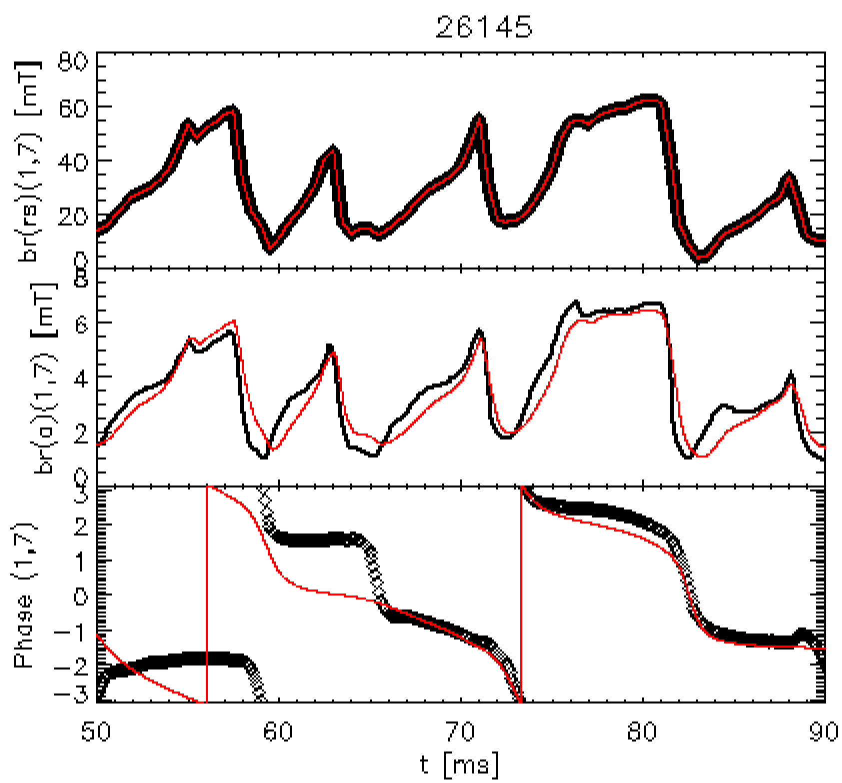
- Multi-mode simulations have been performed based on experimentally estimated fields at the resonances:
  - In multi-mode simulations the minimum corresponds to the experimentally found one

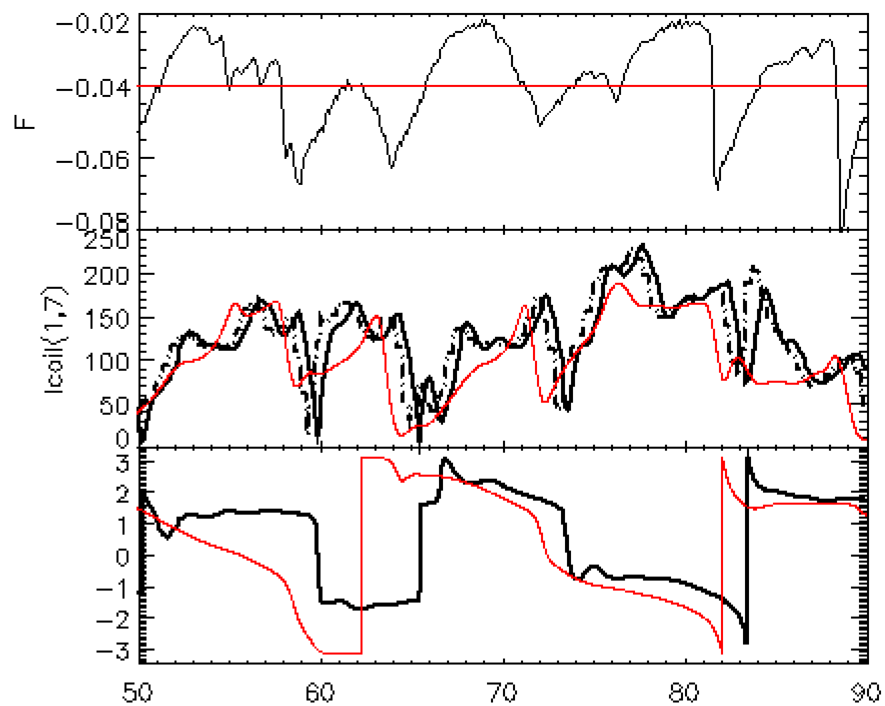



*The minimum occur at a slightly greater derivative value in the model: the modeling of delays may need to be improved.*

# Derivative gain: single mode dynamical simulations

- The agreement between the model and the experiment is slightly less satisfactory when the derivative gain is considered




  - The equilibrium is not constant
  - The presence of the toroidal gap may be important, especially during fast transitions
  - The representation of all delays with a single pole filter may be inadequate

# Conclusions



- The RFXlocking code has been used to determine the optimal gains for obtaining the minimum edge radial field due to resonant modes (Tearing Modes)
  - A lower radial field has been systematically obtained

- Experimental data are better represented by multi-mode simulations:
  - Electromagnetic torque between modes is an important ingredient

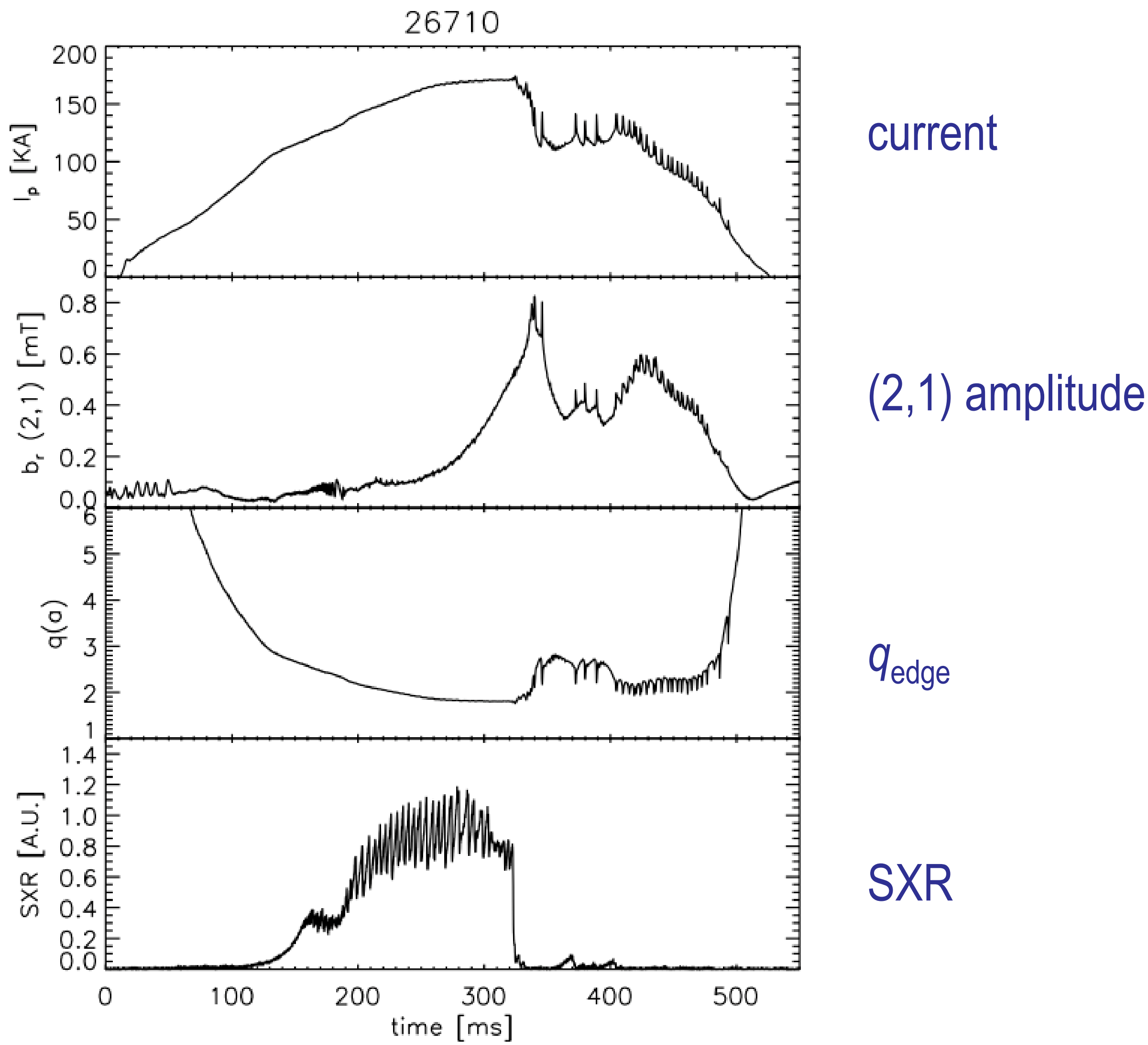
- Possible improvements
  - Better modeling of delays
  - Investigate toroidal effects / effect of gaps
    - Modal decoupling (see talk by P.Piovesan)

# Active control of a (2,1) mode in a ramped tokamak with $q_{edge} \approx 2$

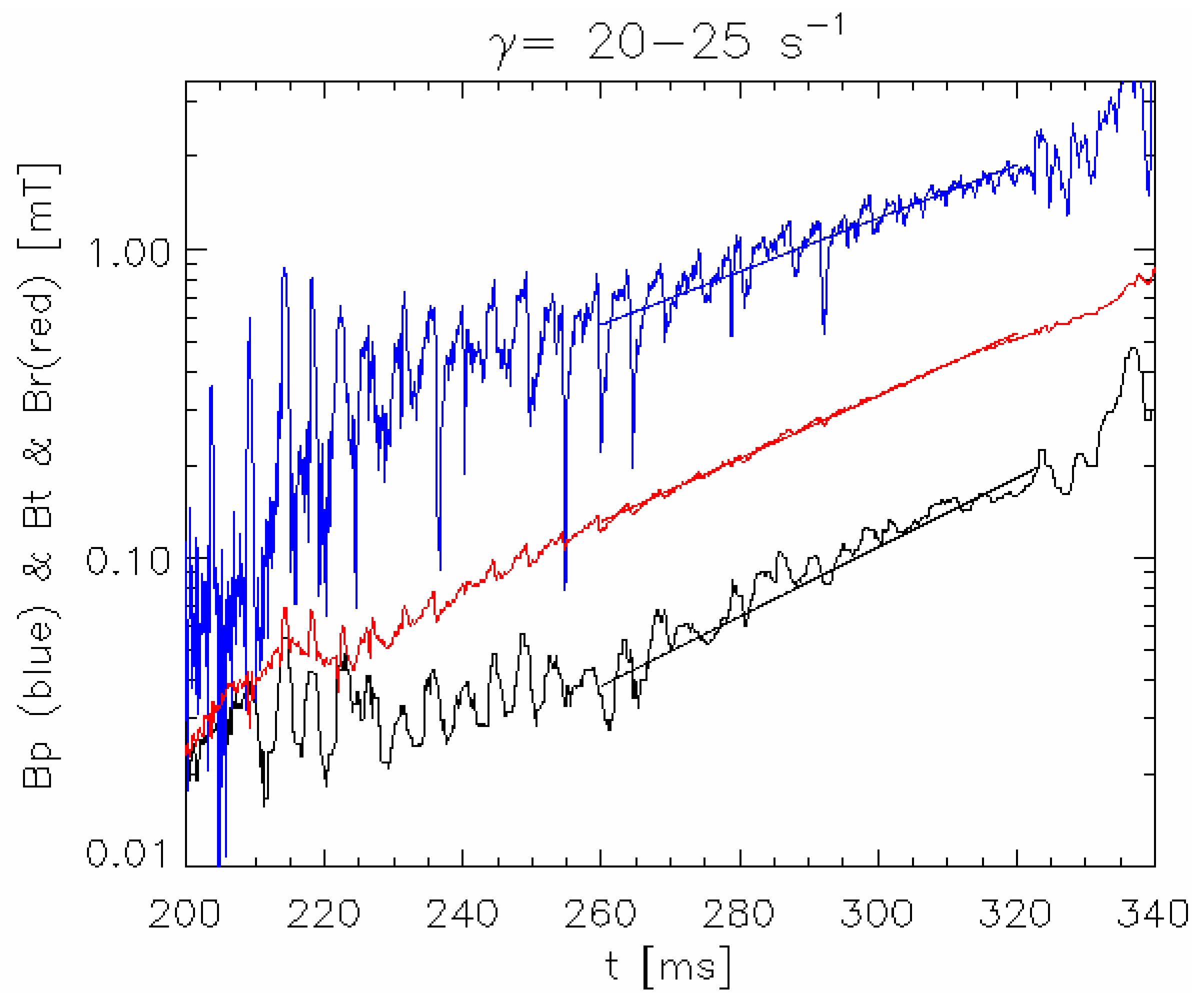
Follows an idea realized in **DIII-D** on a proposal by **In, Okabayashi, et al** (with RFX participation)

Okabayashi et al., paper EX/P9-5 2008 IAEA FEC, Geneva

w/o active control



- All components of the magnetic field grow on a time scale comparable to the shell penetration time

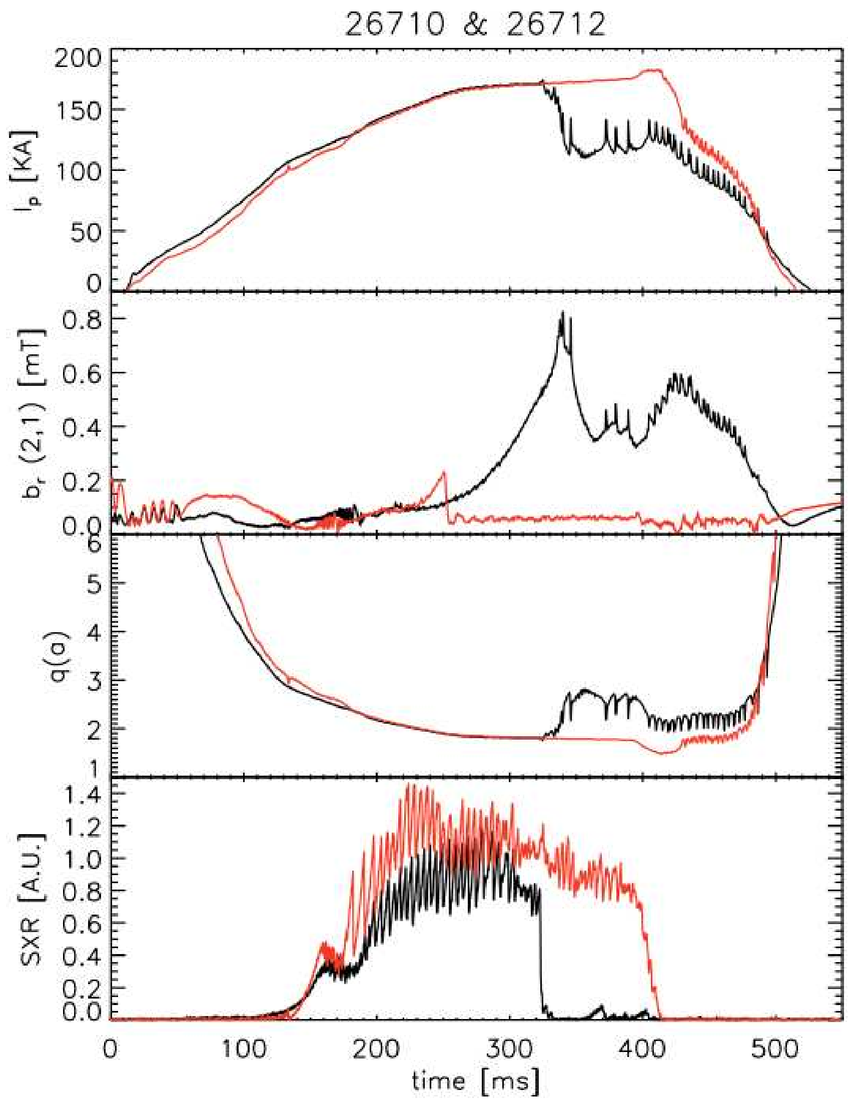


# Active control of a (2,1) mode in a ramped tokamak with $q_{edge} \approx 2$

Setting feedback parameters similarly to DIII-D (zeroing offset DURING discharge) the (2,1) mode is kept at a low level for the whole discharge.

w/o active control

w/ active control




current

(2,1) amplitude

$q_{edge}$

SXR