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Beyond the Intelligent-Shell concept:

the clean-mode-control

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Outline

- **Introduction**
- **The sideband effect**
- **The clean-mode-control (CMC)**
- **Experimental results on RFX-mod**
- **MHD modeling of CMC**
- **Conclusions**

Introduction

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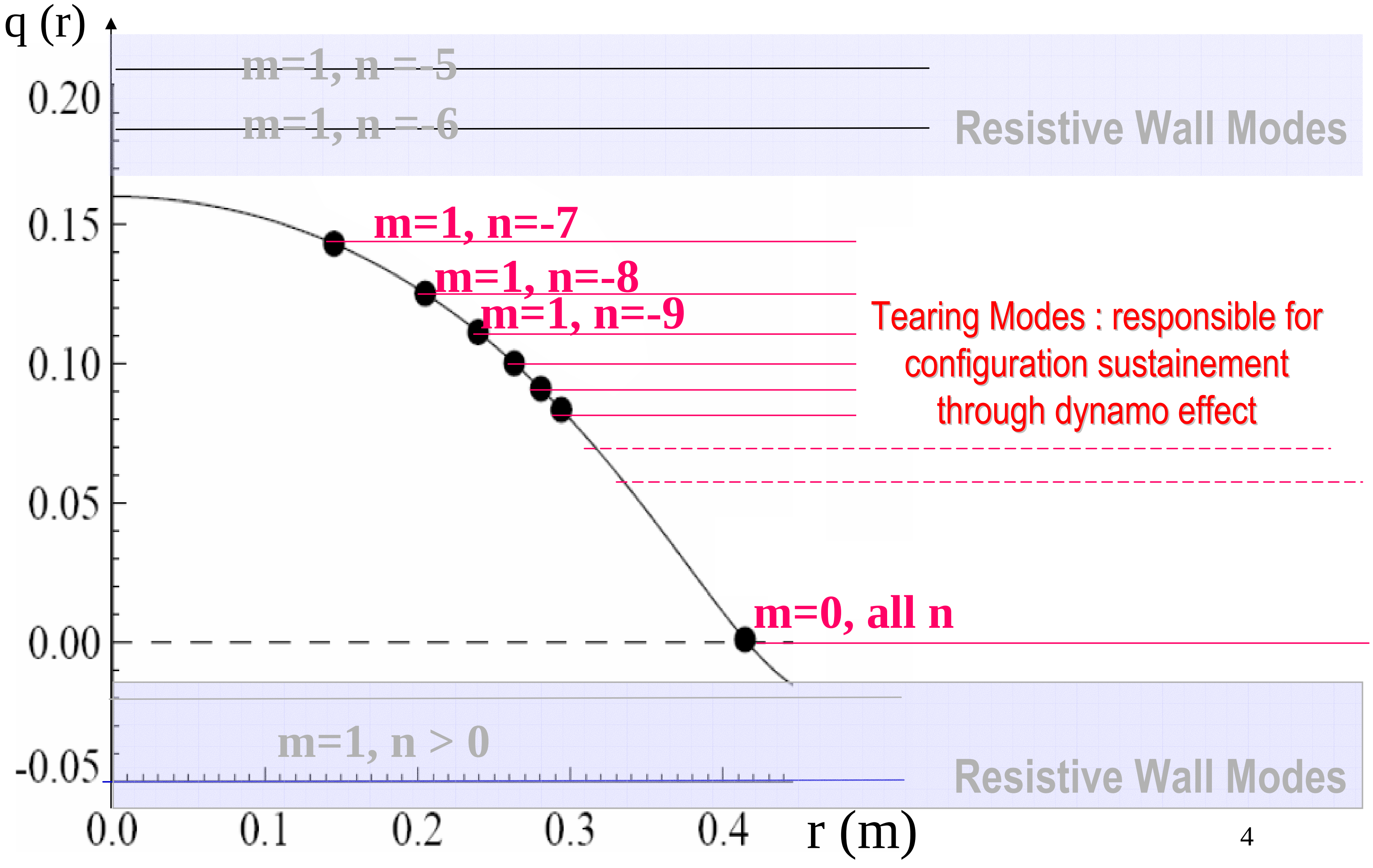
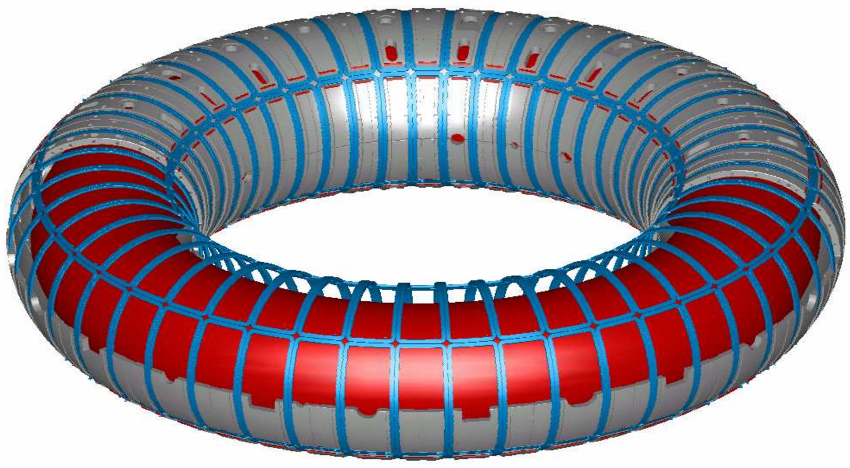
RFX-mod spectrum



Virtual-Shell (VS) scheme

- In the Intelligent-Shell scheme a grid of active coils counteract in a feedback scheme the radial field measured by an **identical** grid of radial field sensor loops [C. M. Bishop, *Plasma Phys. Control. Fusion* **31** (1989) 1179] .

- **RFX-mod Virtual-Shell (VS):**
  4x48 I_{coil} , $c=0.5815m$ fully covering the torus
  Resistive shell $\tau_b=100ms$, $b=0.5125m$
  4x48 radial (toroidal) sensors $r_s=0.507m$
  Vacuum vessel $\tau_v=3ms$, $r_v=0.49m$
  Plasma surface $a=0.459m$, $R_0=2m$



$\rightarrow$ *T.Bolzonella, A.Soppelsa talks*

Tearing modes (TMs) control

- The VS is able to **stabilize completely** the RWMs (*m*=1, $n \geq -6$) and to **mitigate considerably** the dynamo TMs (*m*=1 $n \leq -7$, *m*=0, $n \geq 1$).
  [R.Paccagnella *et al, Phys. Rev. Lett* 97, 075001 (2006); S. Ortolani *et al, Plasma Phys. Control. Fusion* **48** (2006) B371-B381].

- The dynamo TMs, which are non-linear instabilities, cannot be suppressed: the best that the active control can do is to control their amplitudes by reducing their edge ($r=a$?) pedestal.

- Concerning TMs or error fields VS reveals an intrinsic limitation: the origin of the problem is the unavoidable **sideband harmonics** generation of any discrete coils system.

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The sideband effect

Vacuum cylindrical formulas

Consider a rectangular ($\Delta\theta \times \Delta\phi$) coils grid ($M \times N$).

$$I_{DFT}^{m,n} \equiv \frac{1}{M\ N} \sum_{i,j} I_{i,j}\, e^{-i\left(m\theta_i + n\phi_j\right)}$$

Vacuum cylindrical formulas

Consider a rectangular ($\Delta\theta \times \Delta\phi$) coils grid ($M \times N$).

$$b_{r,c}^{p,q}(r,t) = \mu_0 K'_p\left(\frac{|q|c}{R_0}\right) I'_p\left(\frac{|q|r}{R_0}\right) \frac{q^2 c}{R_0^2} f(p,q) A^{p,q} \int_{t_0}^{t} e^{A^{p,q}(t-\xi)} I_{DFT}^{m,n}(\xi)\, d\xi, \qquad r \le b$$

$$p = m + l\,M,\;\; q = n + k\,N,\;\; l,k \in Z$$

$$I_{DFT}^{m,n} \equiv \frac{1}{M\,N} \sum_{i,j} I_{i,j}\, e^{-i\left(m\theta_i + n\phi_j\right)}$$

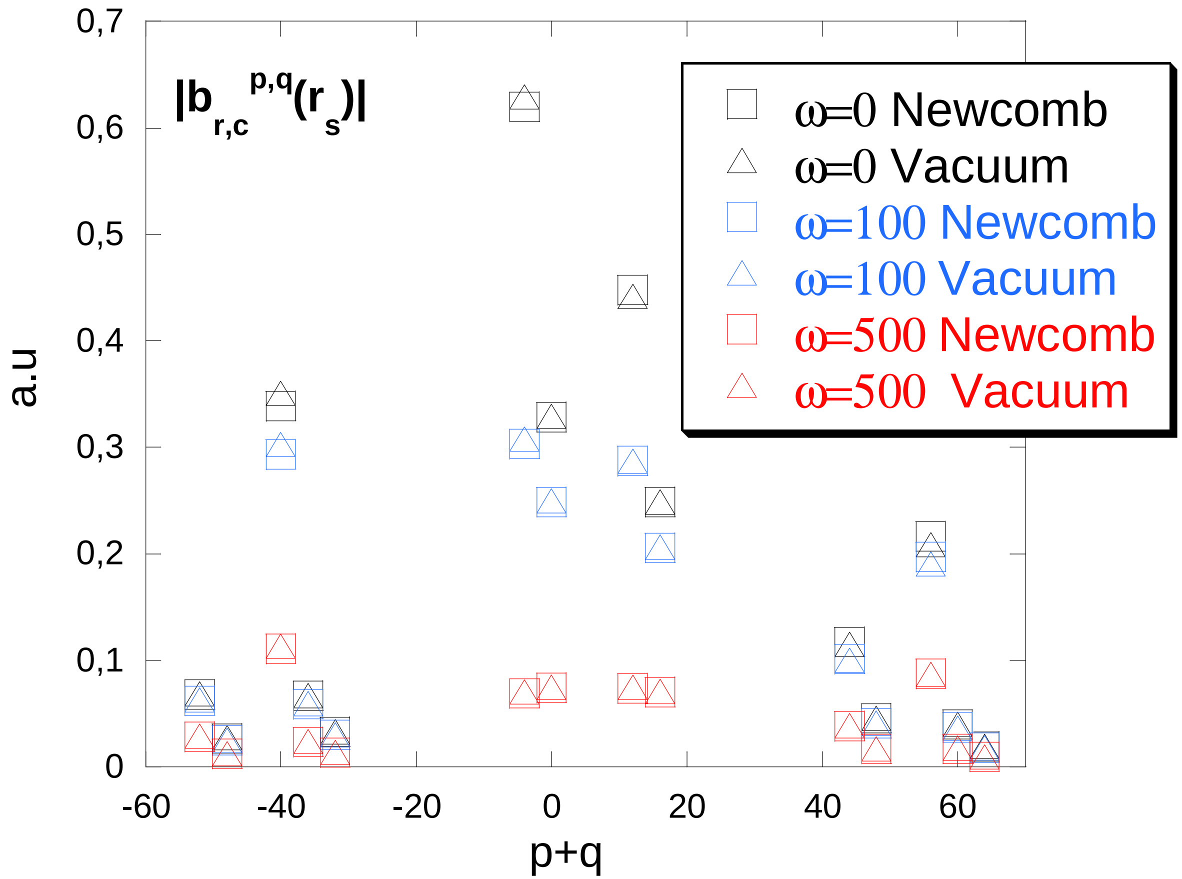
$$A^{p,q} = \frac{1}{\tau_b} \frac{1 + \left(\frac{p R_0}{q b}\right)^2}{K'_p\left(\frac{|q|b}{R_0}\right) I'_p\left(\frac{|q|b}{R_0}\right)}$$

$$f(p,q) = \frac{\sin\left(q\frac{\Delta\phi}{2}\right)}{q\frac{\Delta\phi}{2}} \frac{\sin\left(p\frac{\Delta\theta}{2}\right)}{p\frac{\Delta\theta}{2}};$$

Comparison with Newcomb's solution

- They do not correspond to any unstable plasma mode if *M,N* large enough (M=4, N=48 in RFX-mod). The vacuum formulas are a good approximation also in the presence of plasma, since the Newcomb's equation solution for the sideband is similar to the vacuum solution.

m=1,n=-7



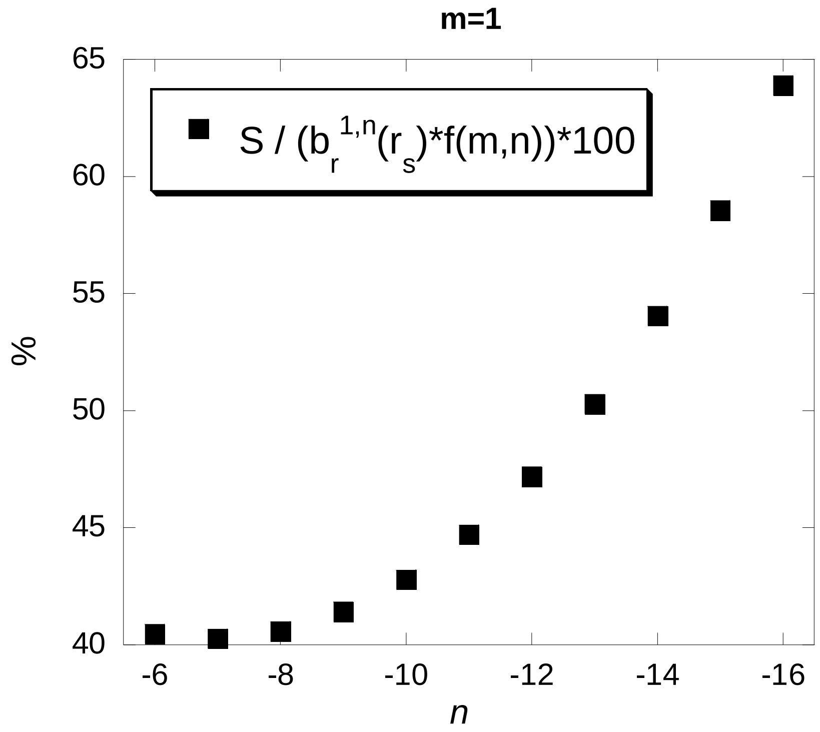
Effect on the measurements

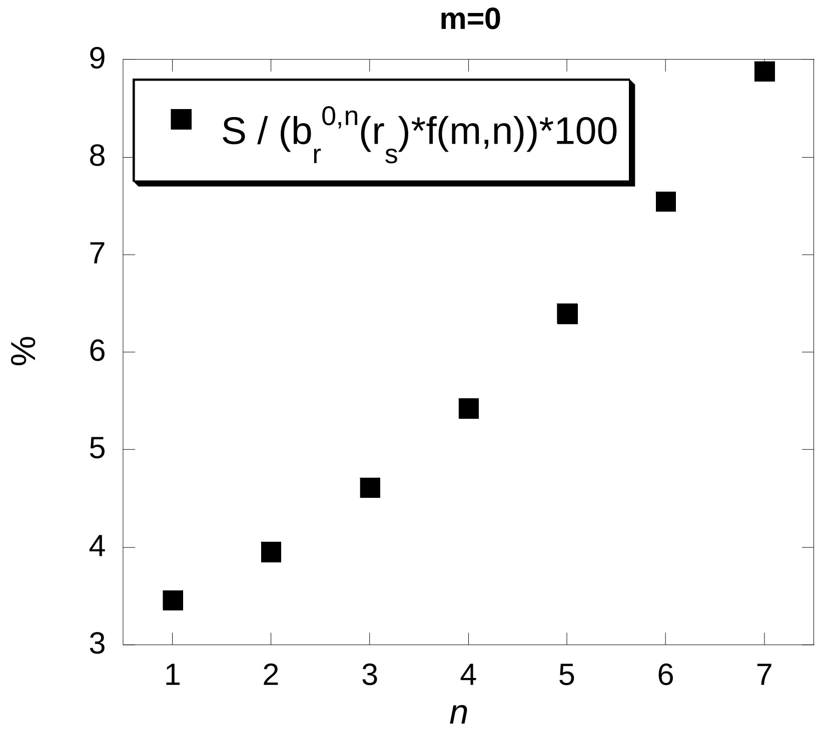
Since the sensor and coil grids are **identical** the coil produced sidebands are the **same** that enter in the measurement by aliasing:

$$b_{r,DFT}^{m,n} \equiv \frac{1}{M\,N} \sum_{i,j} b_{i,j}^{r} e^{-i\left(m\theta_i + n\phi_j\right)} = b_r^{m,n}(r_s)\, f(m,n) + \sum_{\substack{p=m+lM,\, q=n+kN \\ \{l,k\}\in Z^2 - \mathbf{0}}} b_{r,c}^{p,q}(r_s)\, f(p,q)$$

Sideband series (II)

For m=0 modes the sideband effect is less important





ω=0

Sideband effect on VS (I)

$$b^{m,n}_{r,DFT} \equiv \frac{1}{M\,N}\sum_{i,j} b^{r}_{i,j}\, e^{-i\left(m\theta_i + n\phi_j\right)} = b_r^{m,n}(r_s)\, f(m,n) + \sum_{\substack{p=m+lM,\,q=n+kN \\ \{l,k\}\in Z^2-\mathbf{0}}} b^{p,q}_{r,c}(r_s)\, f(p,q)$$

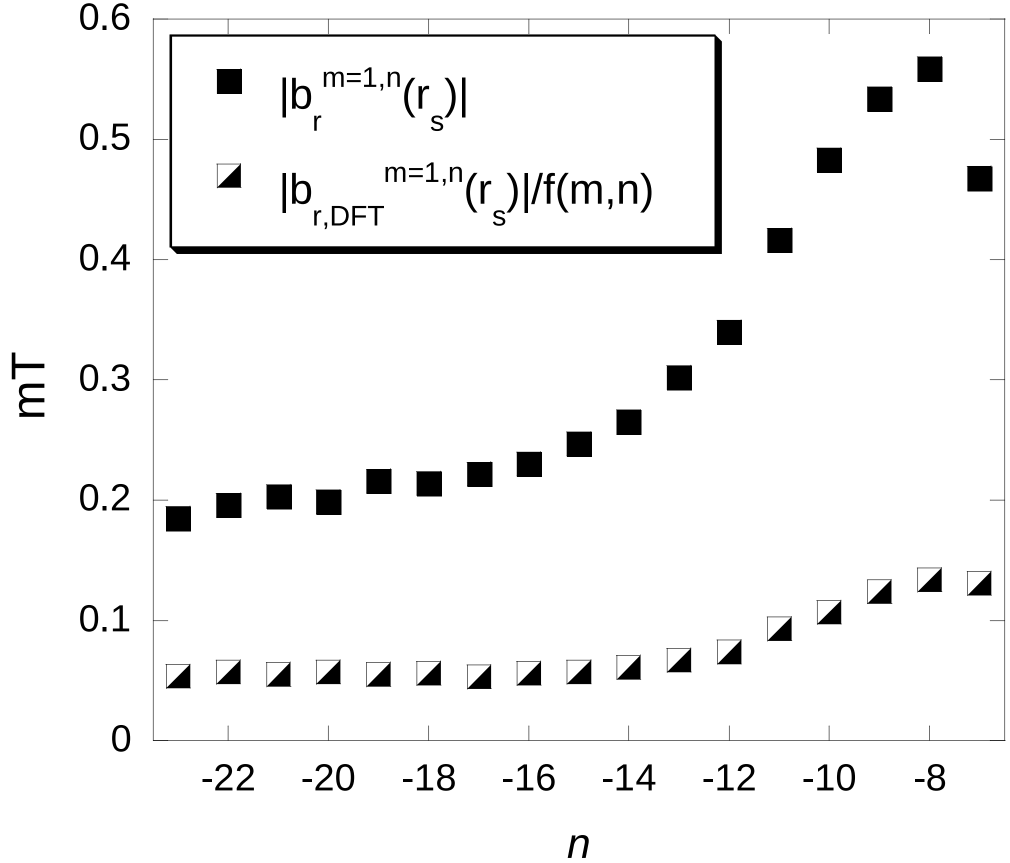
$b^{m,n}_{r,DFT} \rightarrow 0$, $\quad b^{r}_{i,j} \rightarrow 0$

$$b_r^{m,n}(r_s) = -\frac{1}{f(m,n)} \sum_{\{l,k\}\in Z^2-\mathbf{0}} b^{p,q}_{r,c}(r_s)\, f(p,q)$$

This does not prevent the suppression of a linear instability such as the RWMs [R. Paccagnella, D. Gregoratto, A. Bondeson, Nucl. Fusion **42** (2002) 1102; R. Fitzpatrick, E. P. Yu, *Phys. of Plasmas* **6** (1999) 3536].

Sideband effect on VS (II)

- Nevertheless it decrease the efficiency in the edge pedestal reduction of the saturated amplitude TMs or error fields



Ip=600kA F>-0.1

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The clean-mode-control (CMC)

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CMC feedback signal

$$\boxed{b_r^{m,n}(r_s)} = f(m,n)^{-1} \cdot \left[b_{r,DFT}^{m,n} - \sum_{\{l,k\} \in Z^2 - \mathbf{0}} b_{r,c}^{p,q}(r_s) f(p,q) \right]$$

$\downarrow$

0

Since the control act on the Fourier modes and not simply on the measurements, it can be extrapolated in vacuum region $a \le r \le b$.

$$b_r^{m,n}(a) \quad \leftarrow \quad b_r^{m,n}(r_s), b_\phi^{m,n}(r_s)$$

4×48 signals b_r, b_ϕ, I_{coils} $\rightarrow$ latency time (<500μs) greater than VS (<333μs)

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Experimental results on RFX-mod

Summary (I)

- Test of CMC on selected group of modes (the dominat TMs m=1, -12≤n≤-7) leaving the others controlled in VS

- **PID feedback controller** → mainly K_p, K_d with K_p>> K_d

- **TMs rotations up to 100Hz**

- Reduction of b_r amplitude (at most 40%) with respect to VS

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Summary (II)

- Mitigation of the phase and wall-locking:

  reduction of the global plasma geometrical distortion due to *m=1* Locked Mode (about 40%)

  Locked Mode movement in toroidal direction

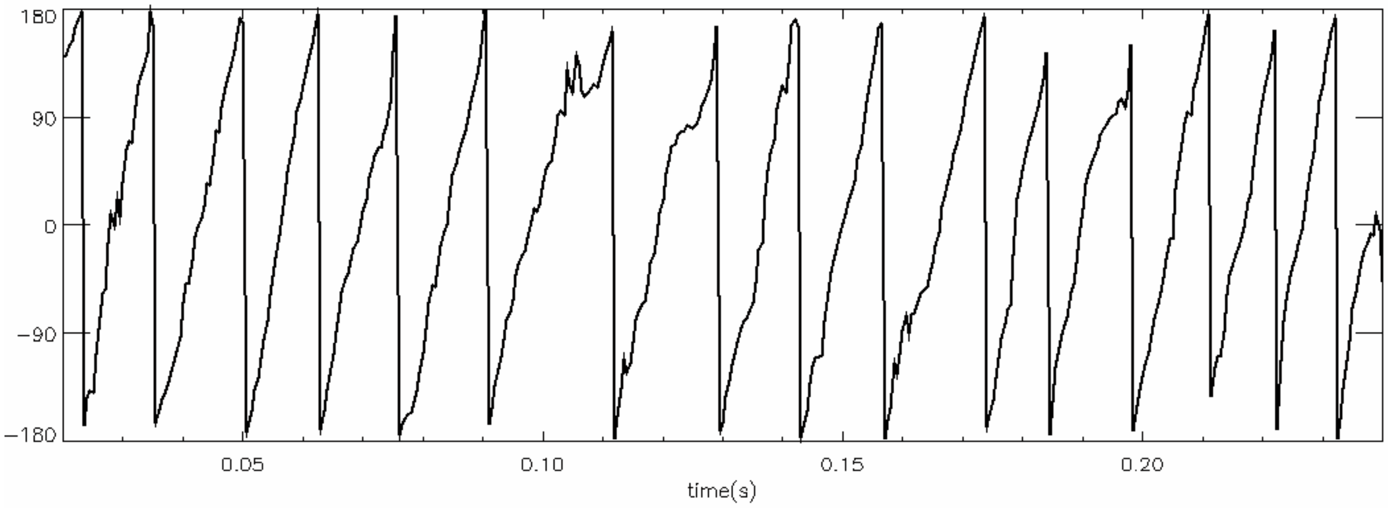
- Mitigation of the plasma wall-interaction

- Possibility of raise the plasma current up to 1.5MA (operation at shallow reversal $-0.1<F<0$)

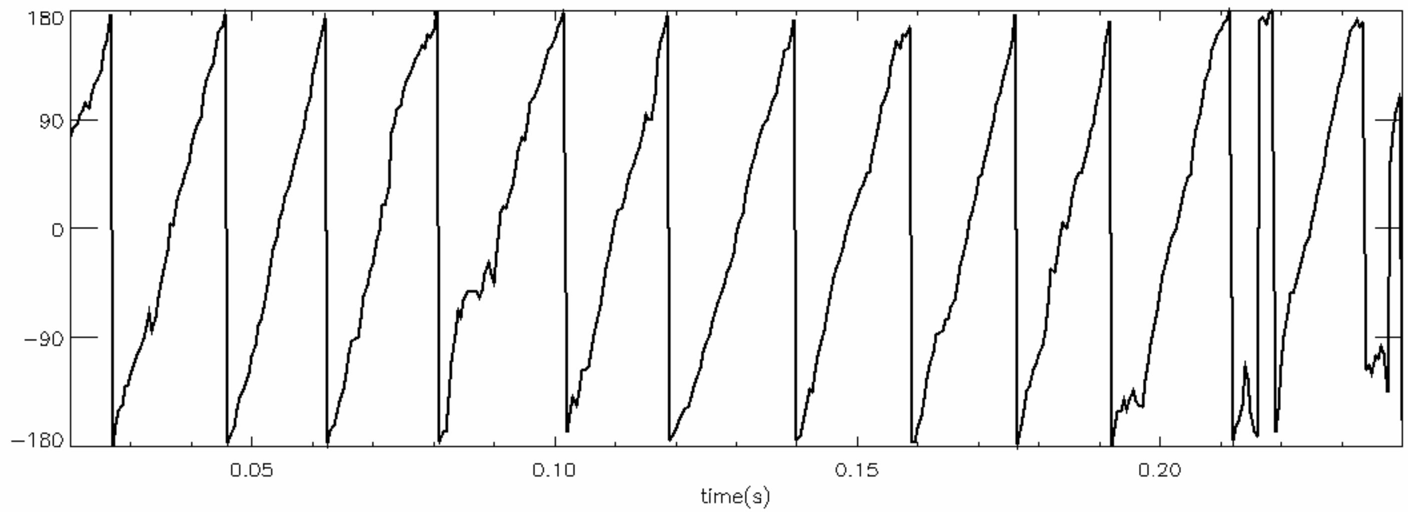
- Appearance of QSH

TMs rotations

#21468 CMC;   arg[b_r(a)]

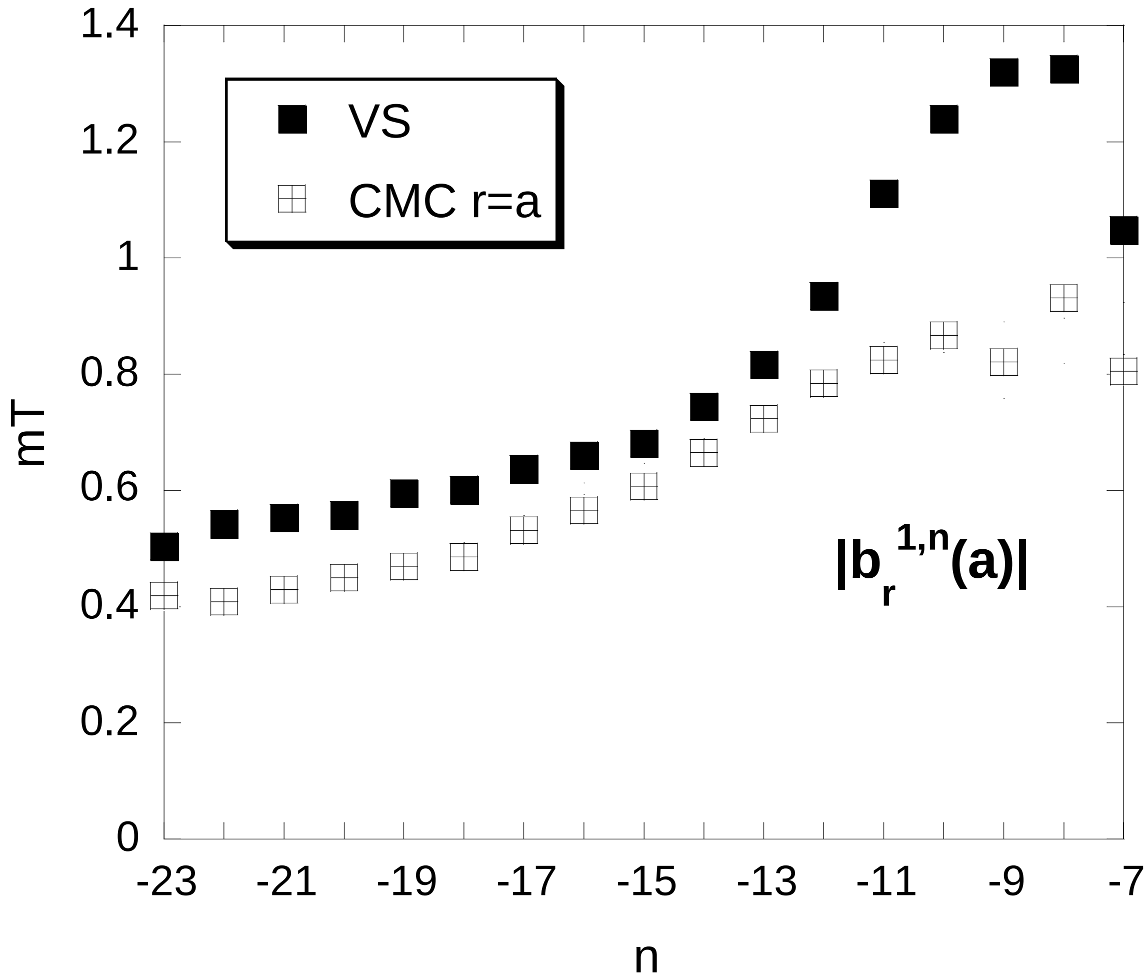


m=1, n=-7



m=1, n=-8

b_r amplitude reduction (m=1 TMs)



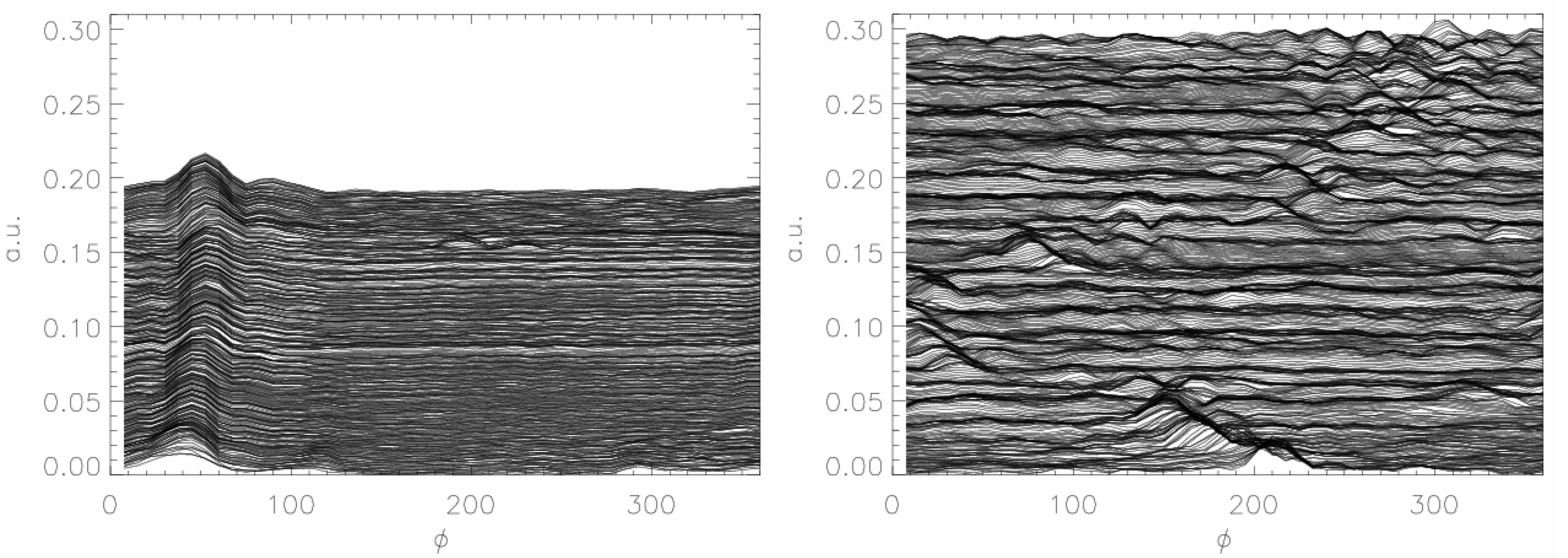
Ip=600kA F>-0.1

Mitigation of m=1 plasma surface distortion

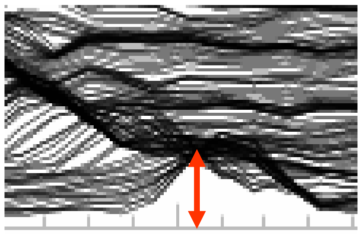
$$\xi_r^{m=1}(\phi, t)$$

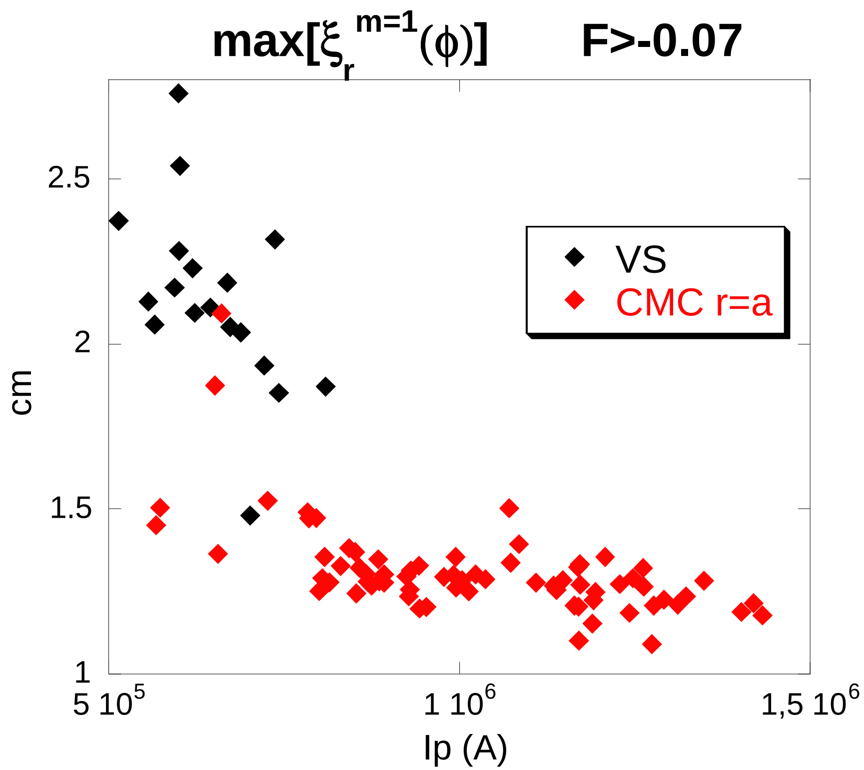
#18942 VS

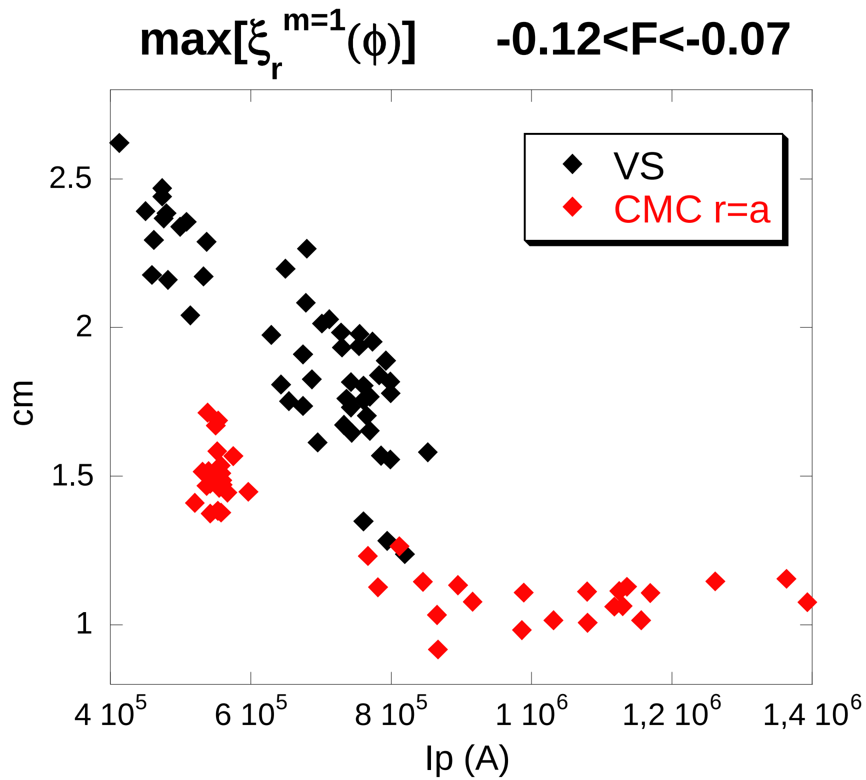
#22805 CMC



Maximum m=1 distortion



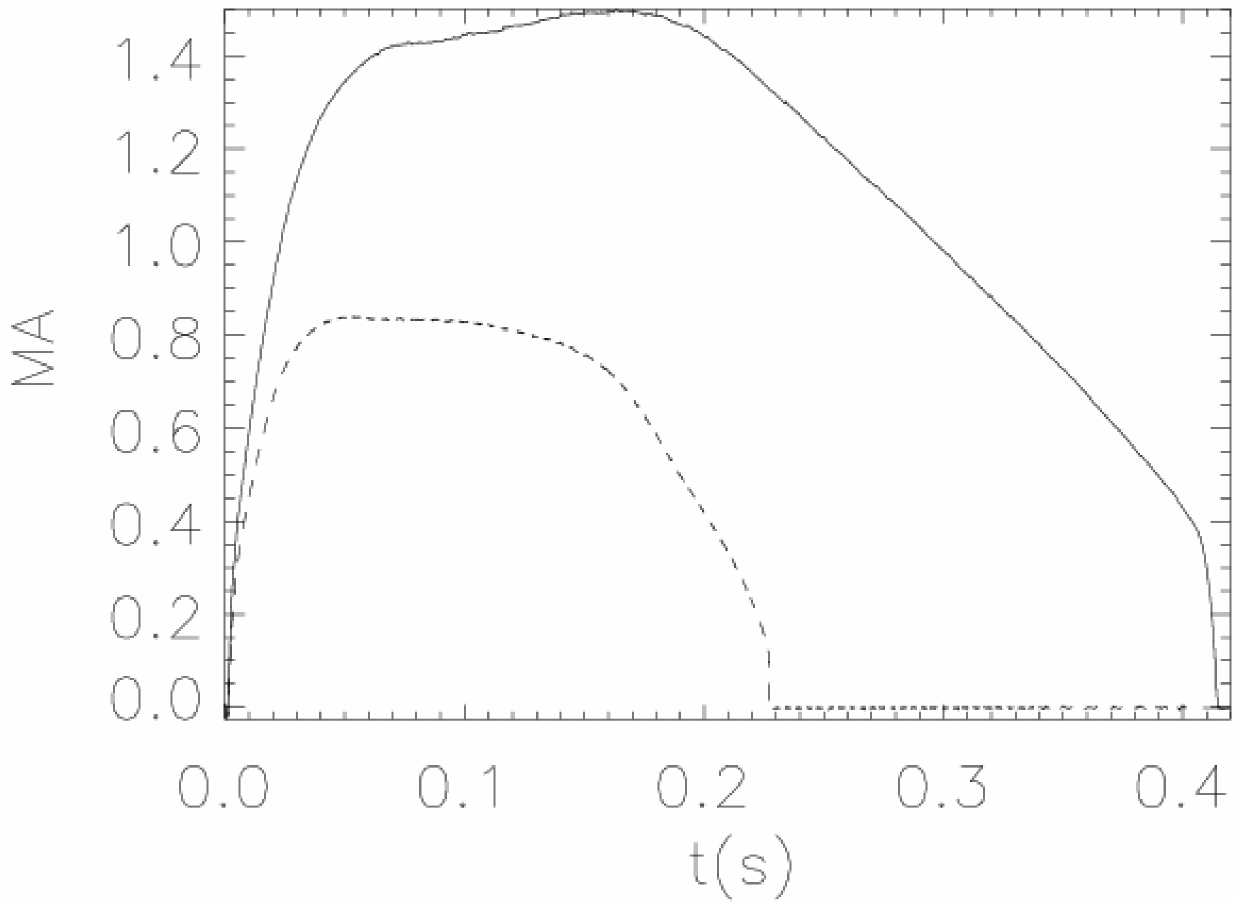




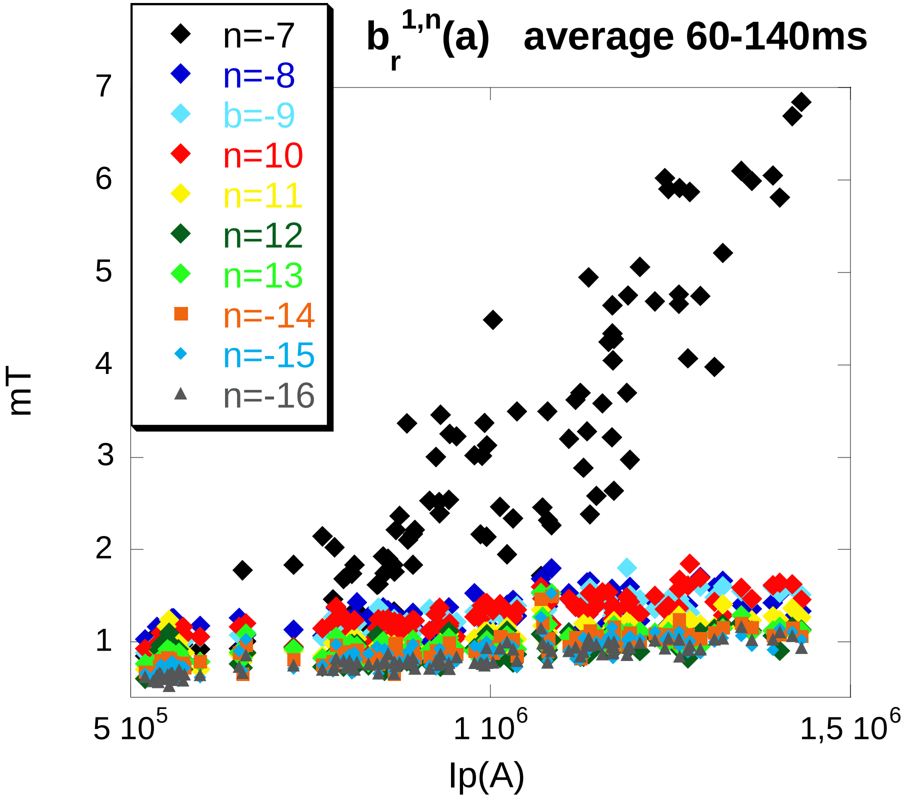
High current shots

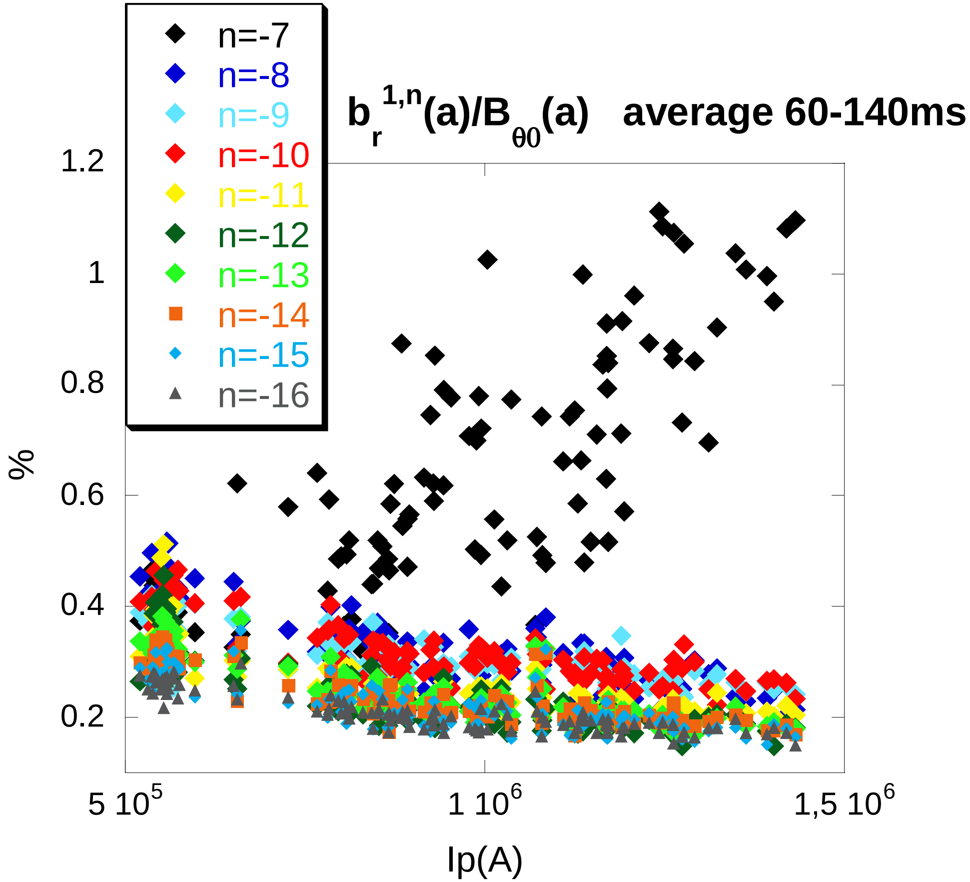
#22805 CMC

#18942 VS -----



QSH with CMC (II)





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MHD modeling of CMC

Single mode stationary model

• Saturated amplitude TM, rotating with frequency ω (following R.Fitzpatrick, S.Guo, et al, Physics of Plasmas (1999) **6** 3878)

• Newcomb equation solution and thin shell dispersion relation for shell and vessel

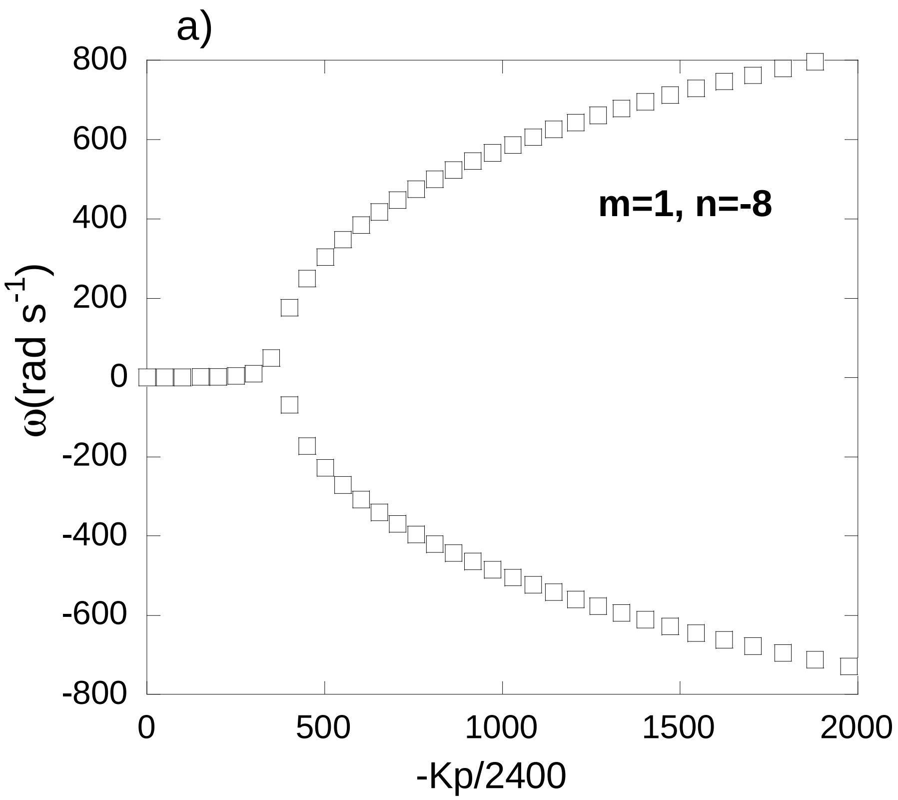
• The amplitude at the resonant surface is fixed

$\rightarrow$ merit parameter: $|\mathbf{b_r(a)/\ br(r_{m,n})}|$

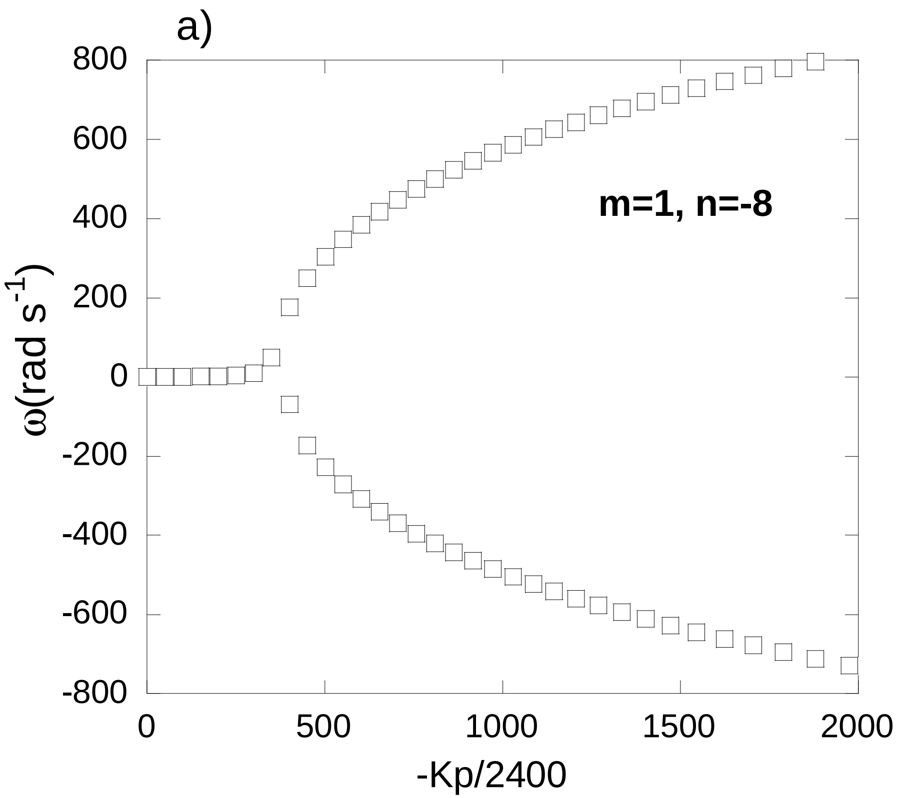
• CMC model:

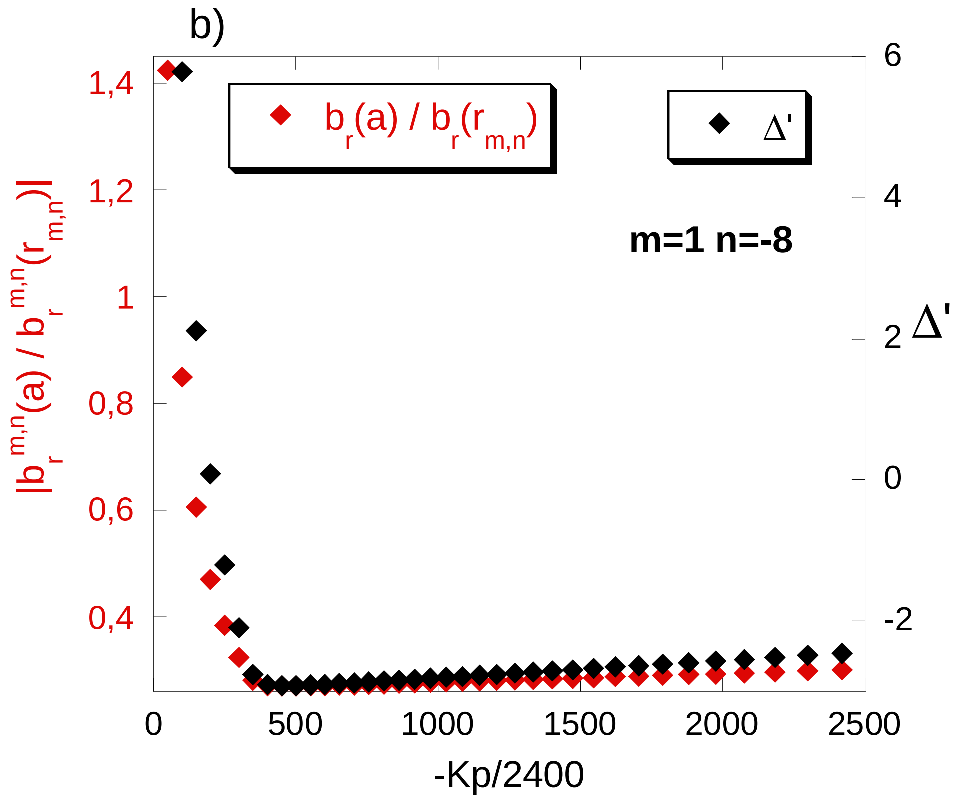
$$I_{DFT}^{m,n}(t) = \frac{1}{1+i\omega\Delta t} Kp\ b_r^{m,n}(a,t)$$

Efficiency limits



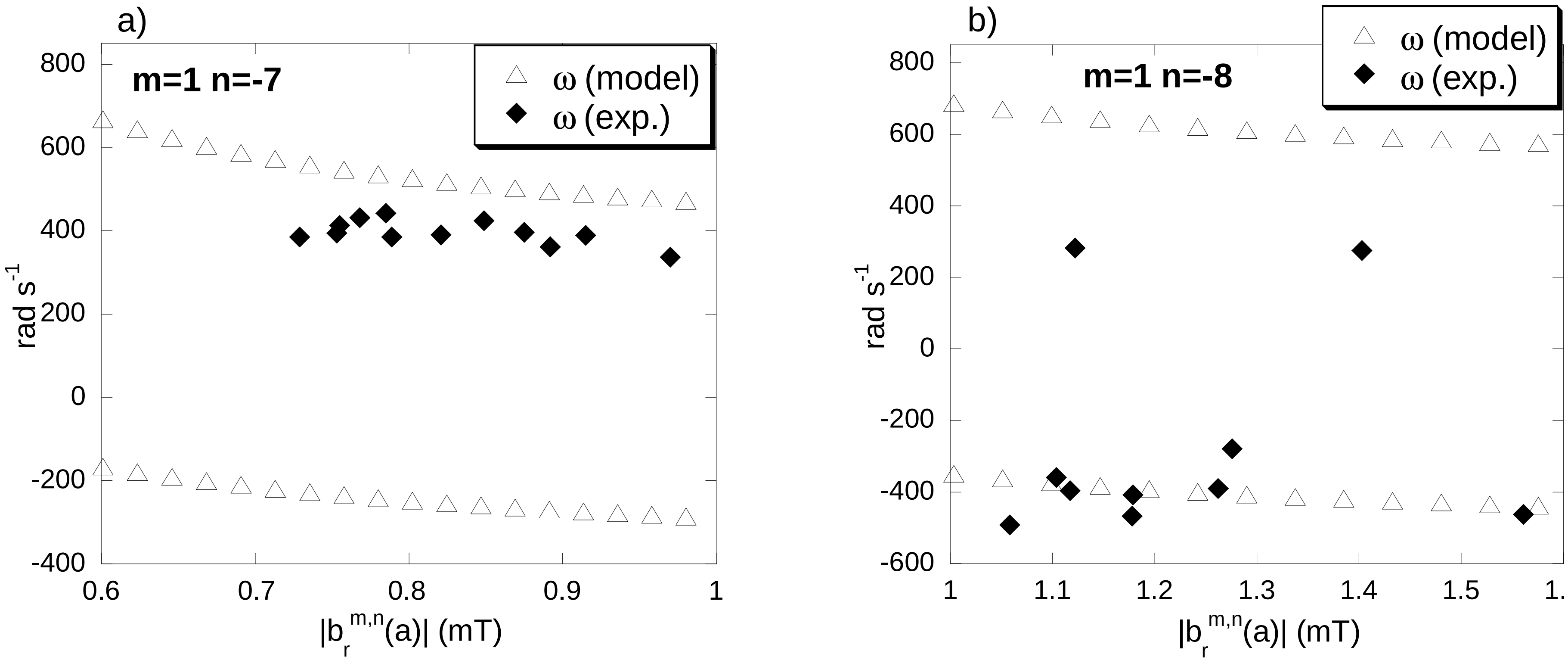
Efficiency limits





$$\min\left[\left|b_r^{1,-8}(a)/b_r^{1,-8}(r_{1,-8})\right|\right] \approx 0.26$$

Comparison with the experiment



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Multimode dynamical model

- Generalization of the mode locking code developed by R. Fitzpatrick (Phys. of Plasmas **9** (2002) 2707) in order to include the passive structures of RFX-mod and the CMC feedback

- PID feedback controller

- Non linear interaction of TMs taken into account

- Plasma velocity profile evolved self-consistently

- TMs amplitudes at the resonant surfaces imposed

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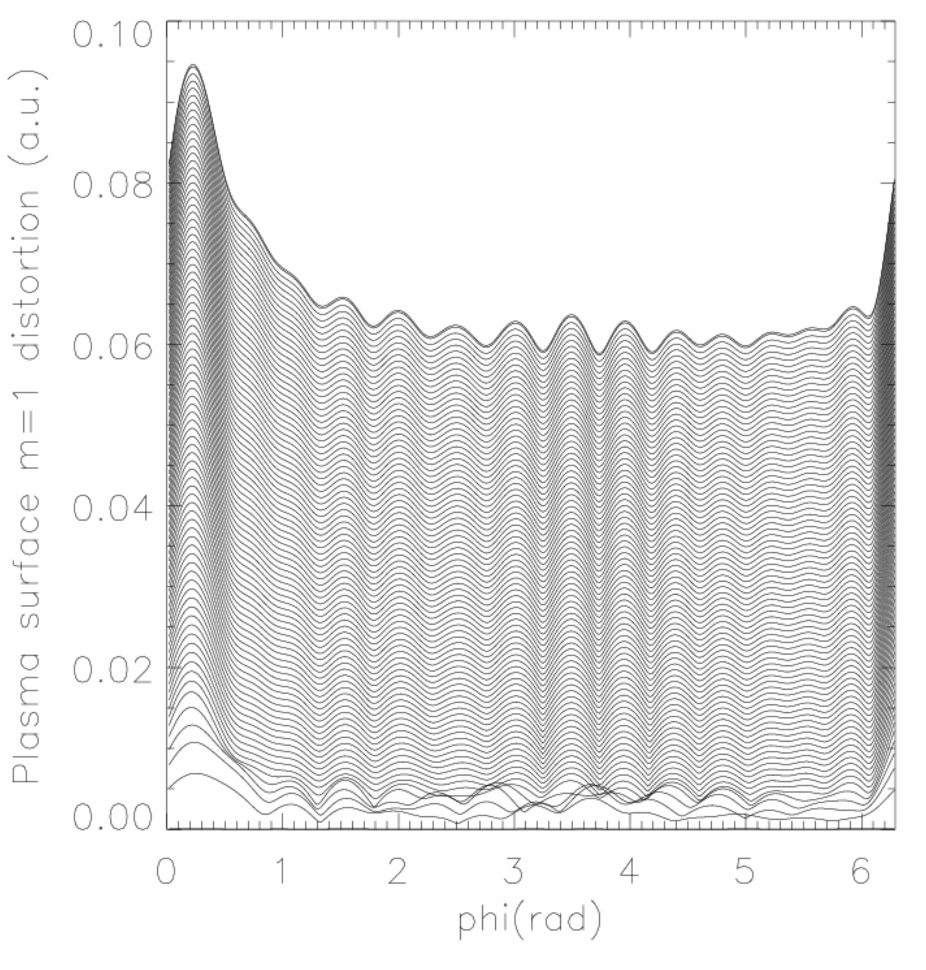
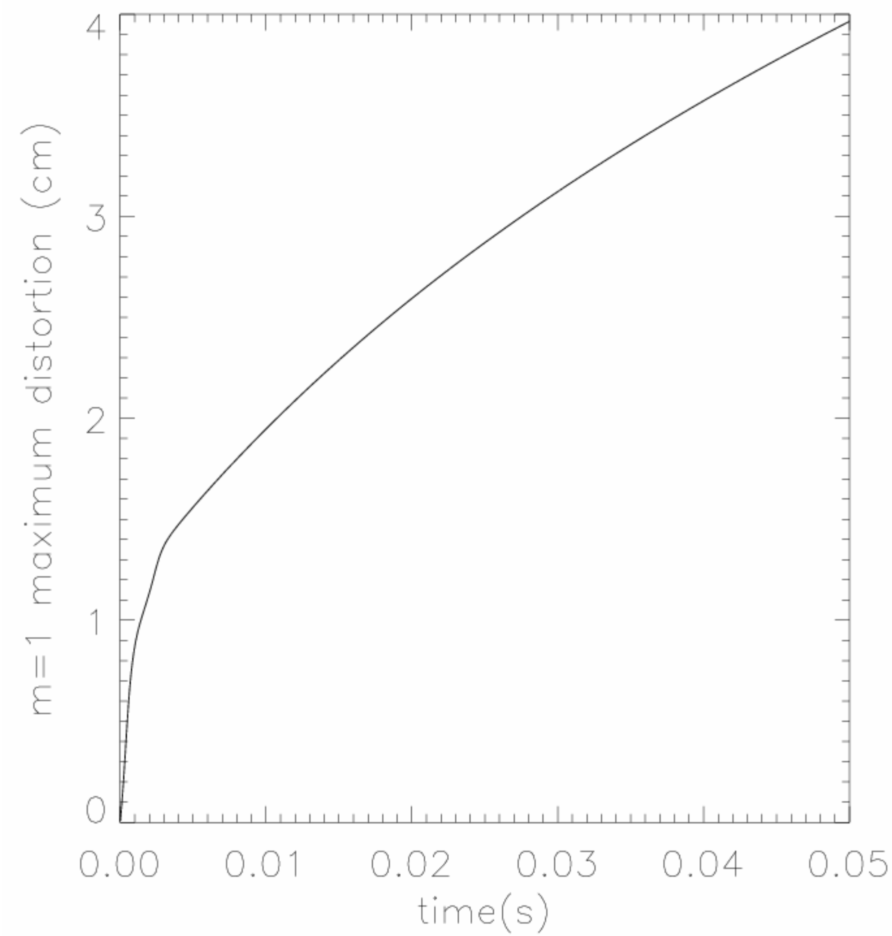
No-control case: strong phase and wall locking

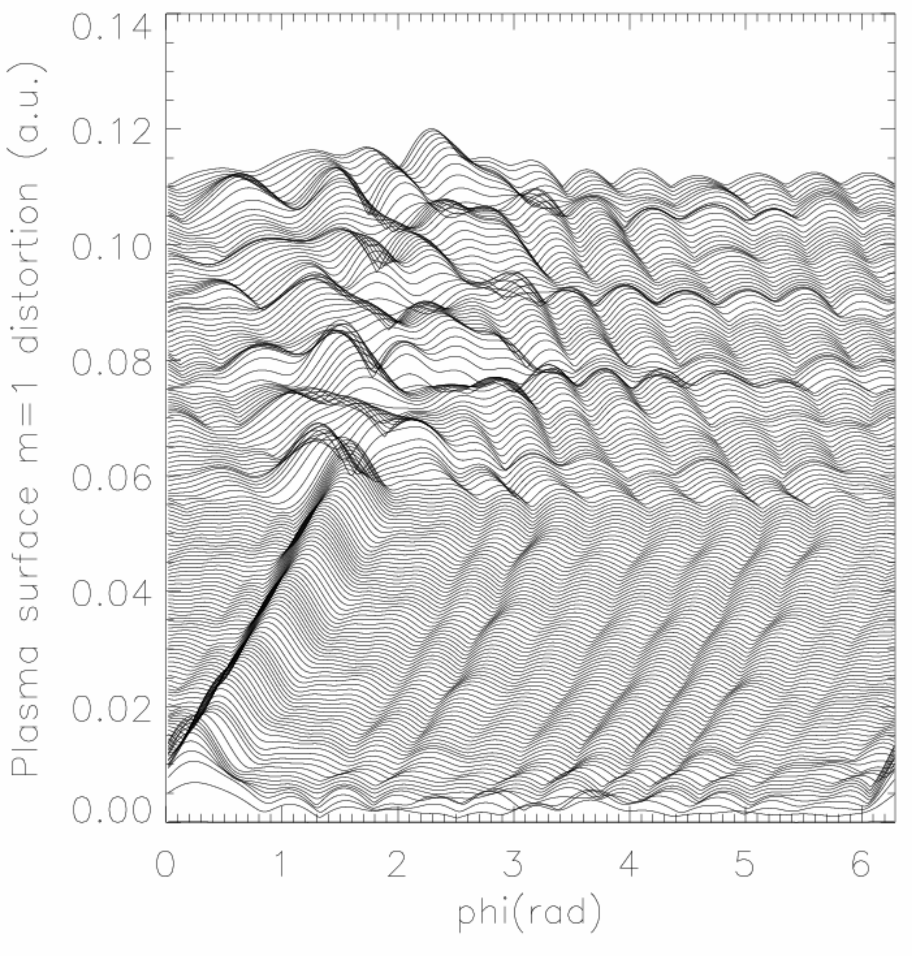
m=1, -22≤n≤-7; m=0, 1≤n≤15. Amplitudes $b_r^{m,n}(r_{m,n})$ from #21808 (800KA)



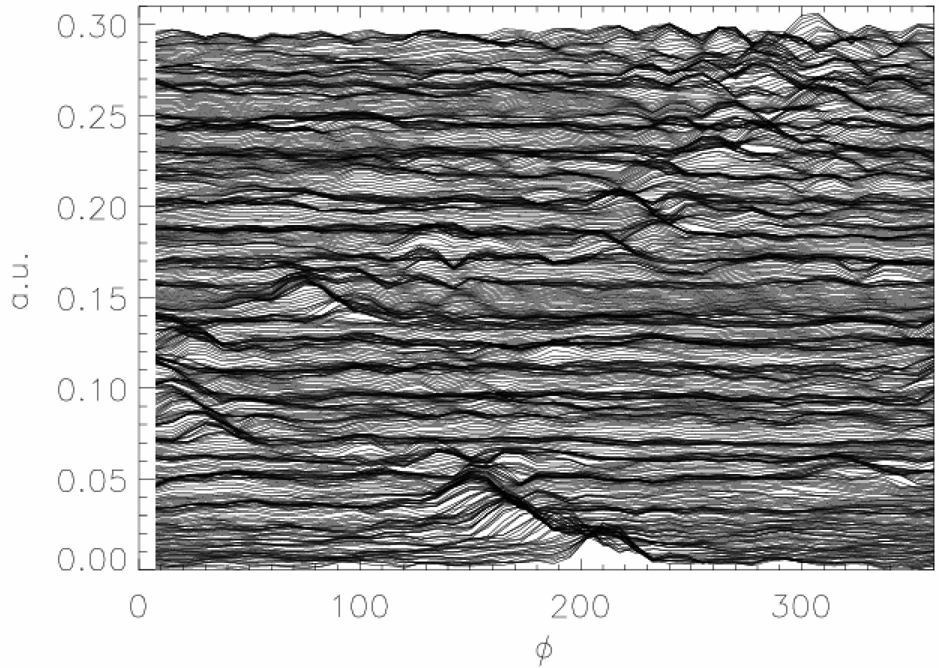


CMC: mitigation of phase and wall locking (I)

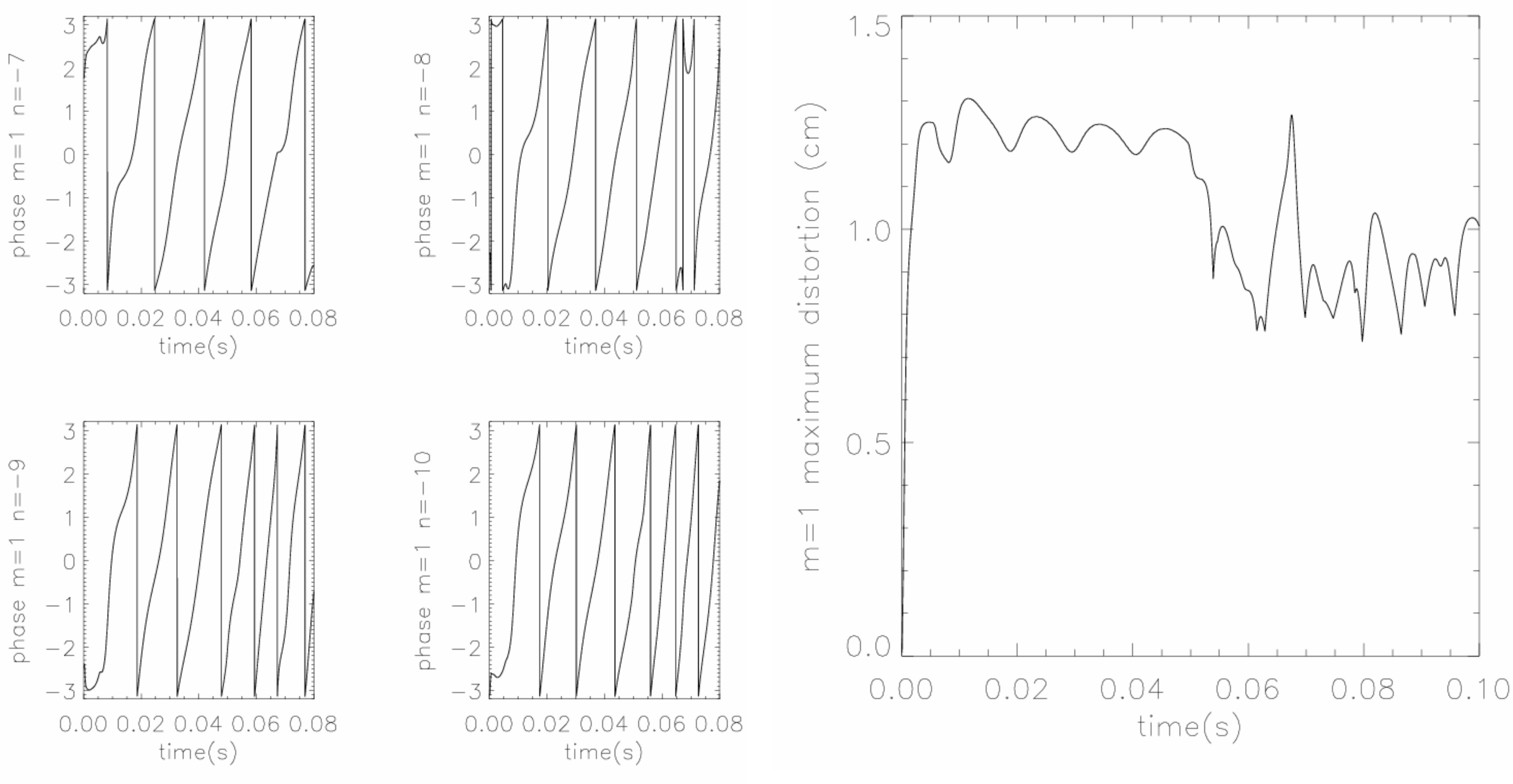
Simulation



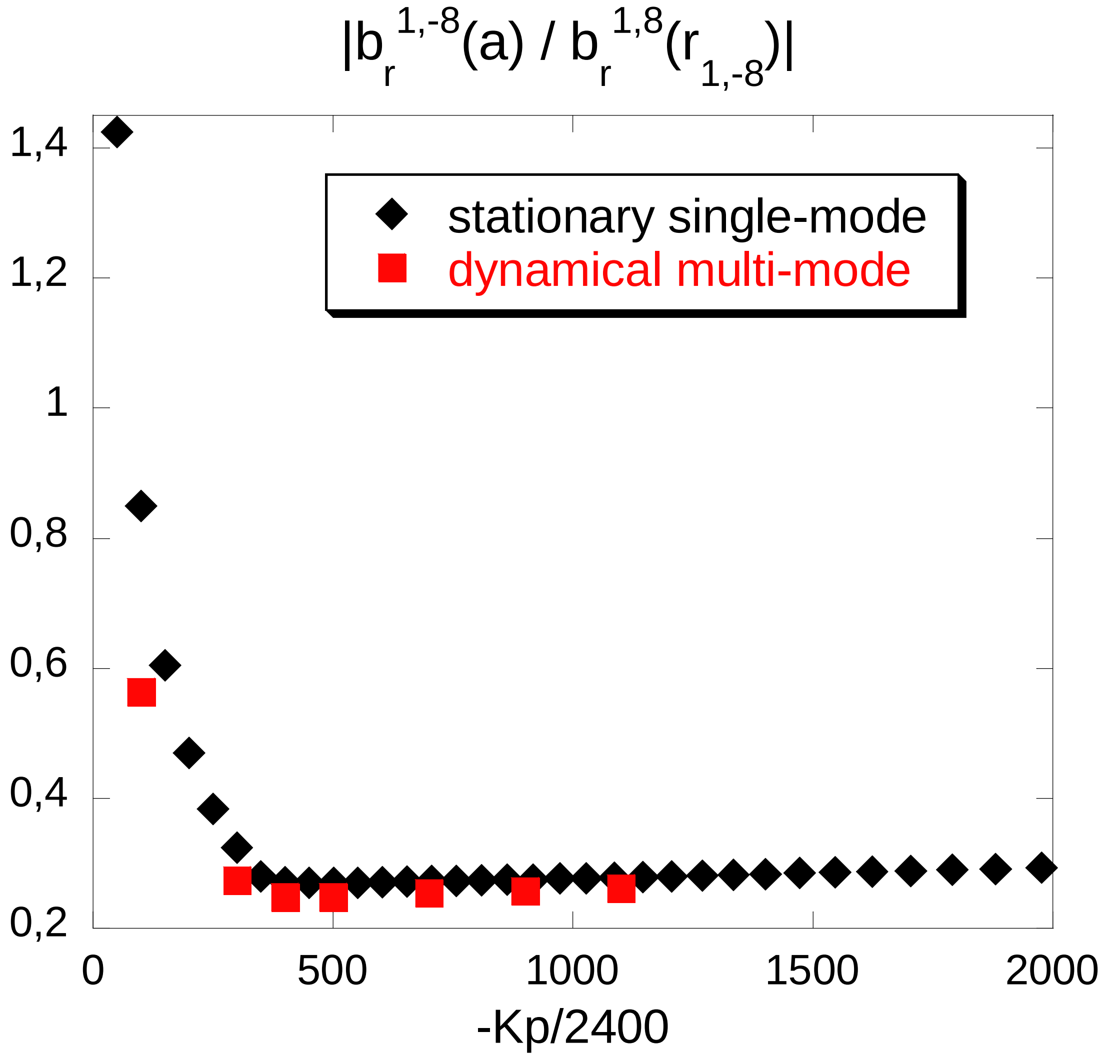
Experiment



CMC: mitigation of phase and wall locking (II)



Efficiency limits



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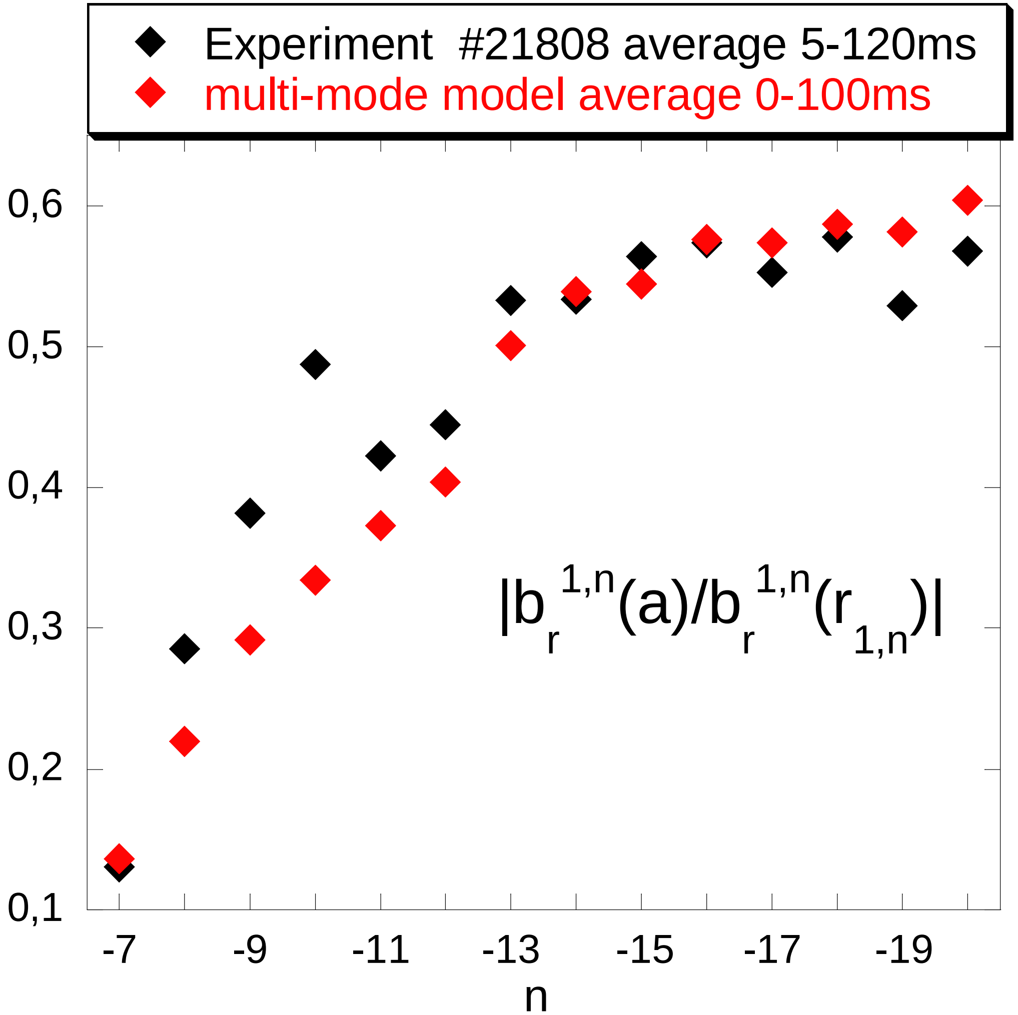
Comparison with the experiment



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Conclusions

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- Improvement in the feedback control of m=1 dynamo TMs by subtracting from the measurements the aliasing produced by the coils sidebands

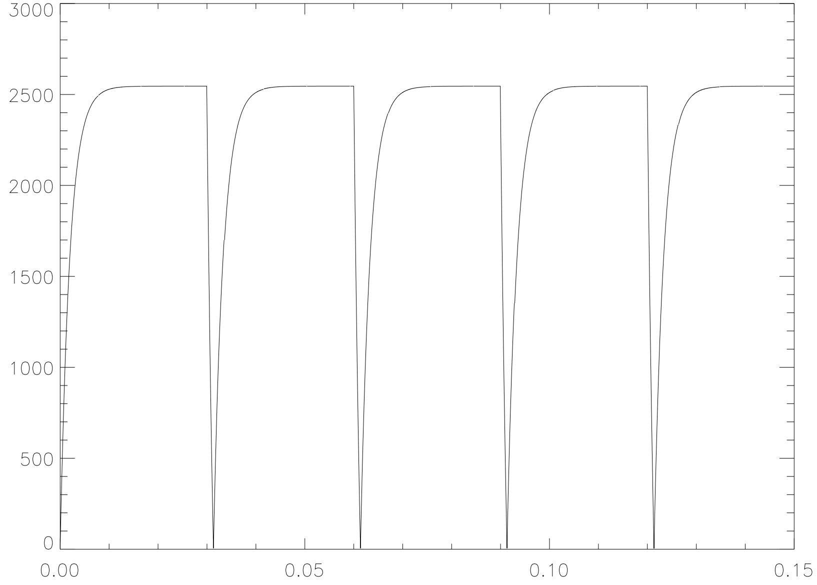
- Improvement of the global discharge performaces

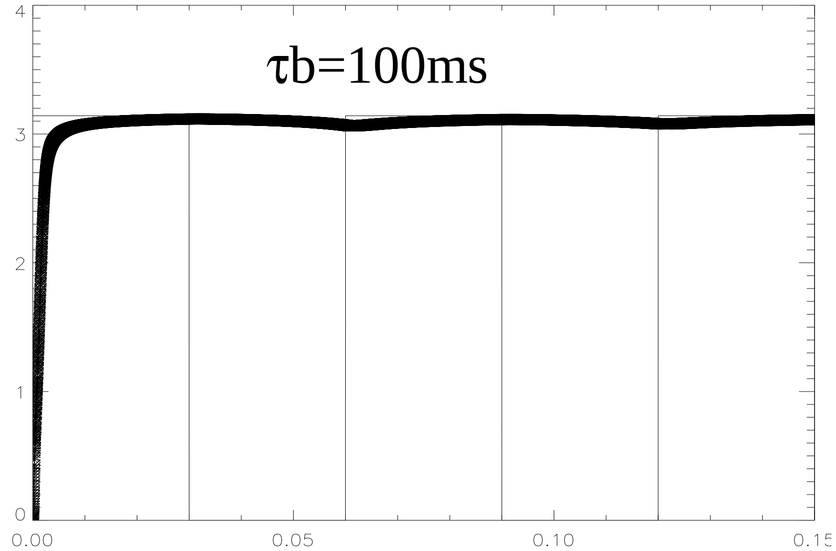
- Existence of a limit of the CMC efficiency with the PID controller (both in the experiment and in the MHD models) $\rightarrow$ $b_r(a)\neq 0$

- Studies of a model based controller for CMC are in progress

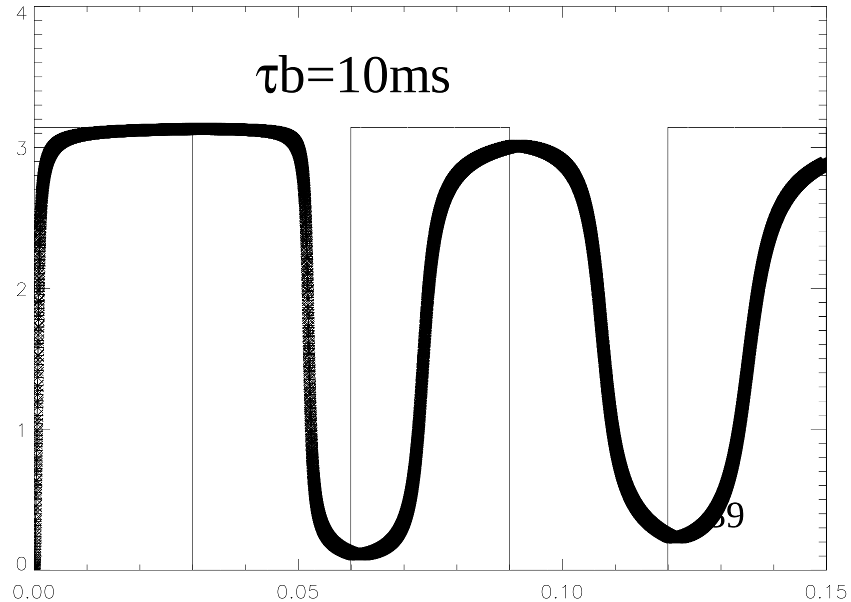
Open-loop simulation for m=1, n=-8

$|I^{1,-8}|$

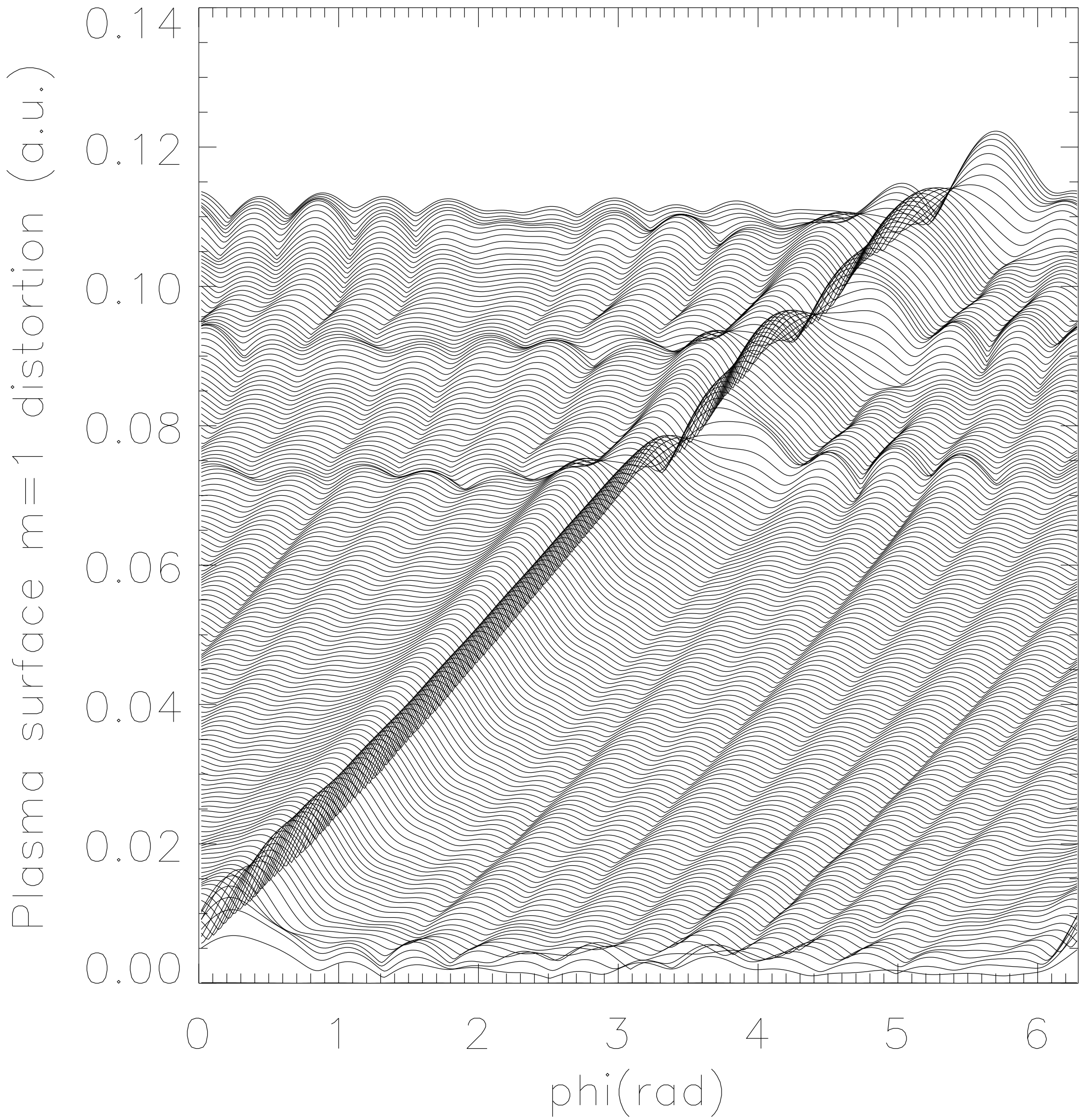




$\mathrm{Arg}(br^{1,-8})$

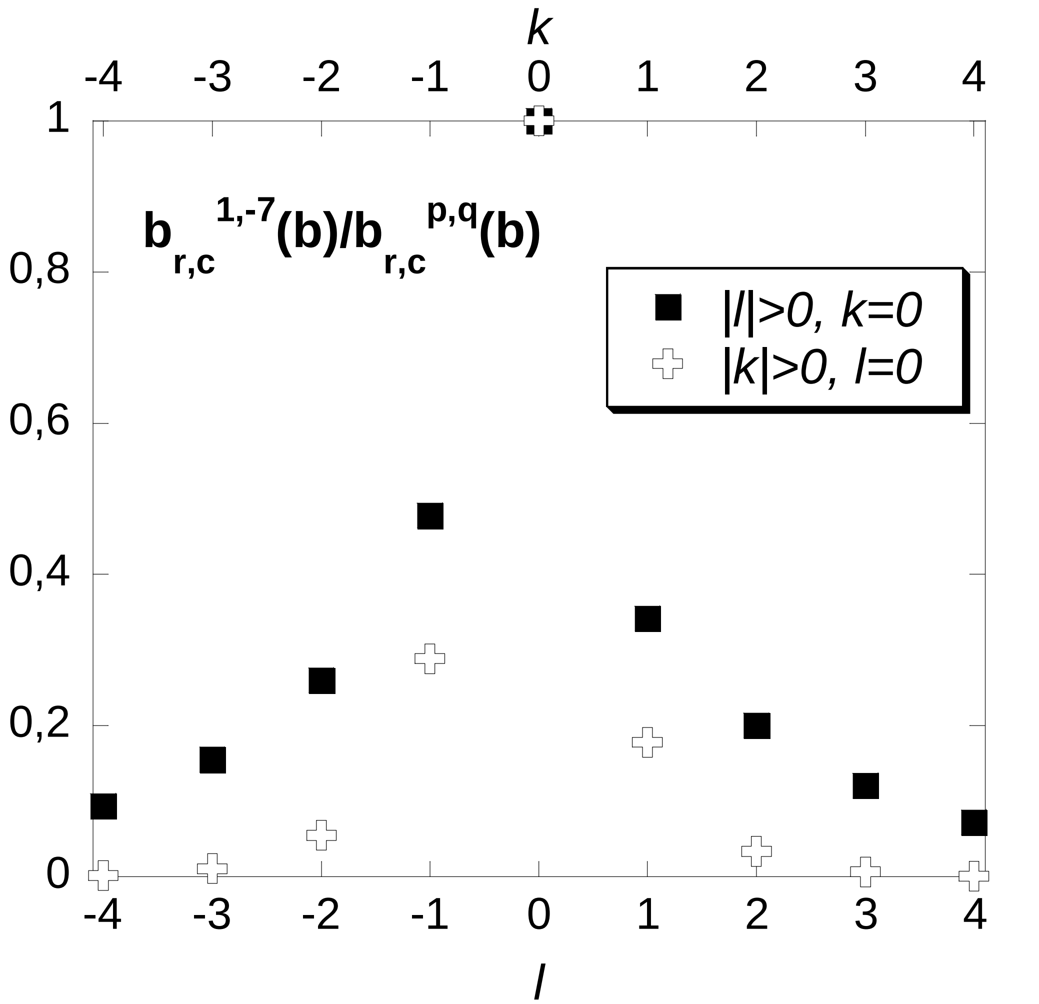


Gain increase on the low-n m=0 modes



Sideband amplitude

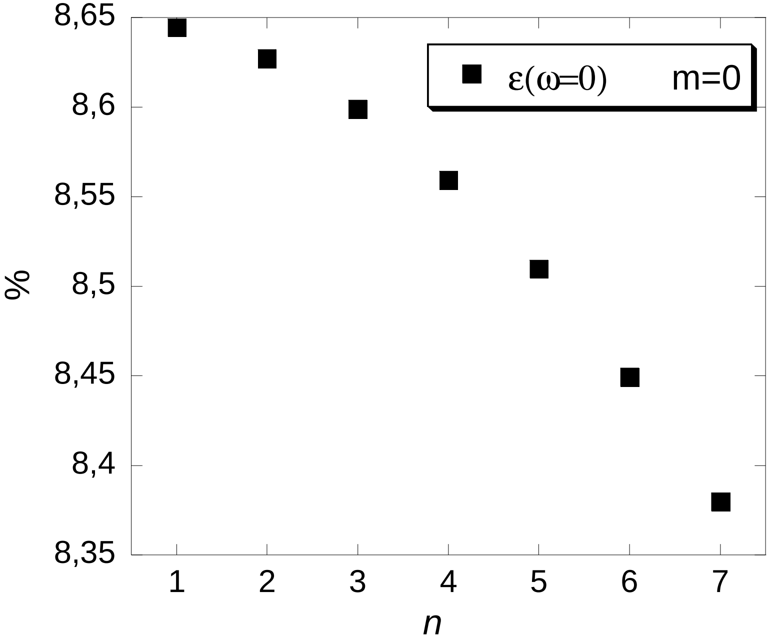
They are a not negligible fraction of the dominant harmonic. M=4, N=48 in RFXmod

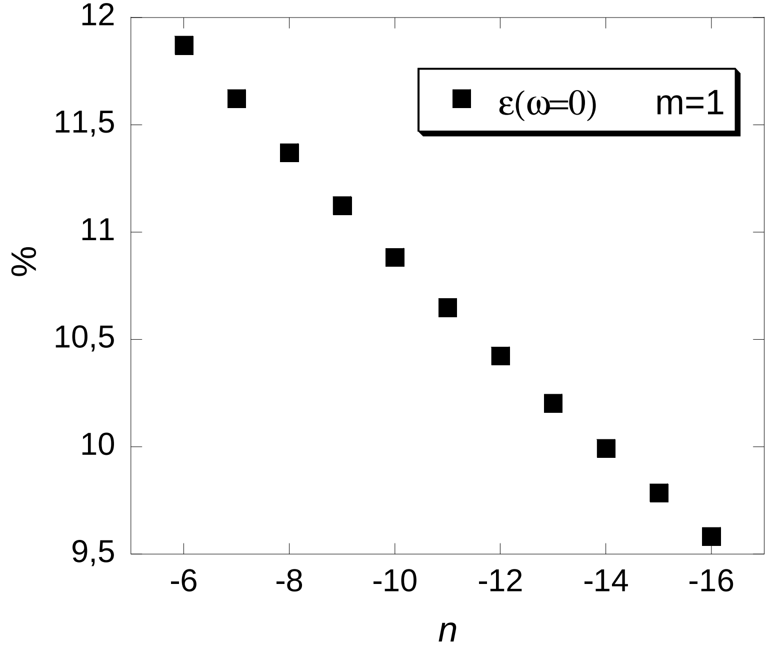


ω=0

Sideband series (I)

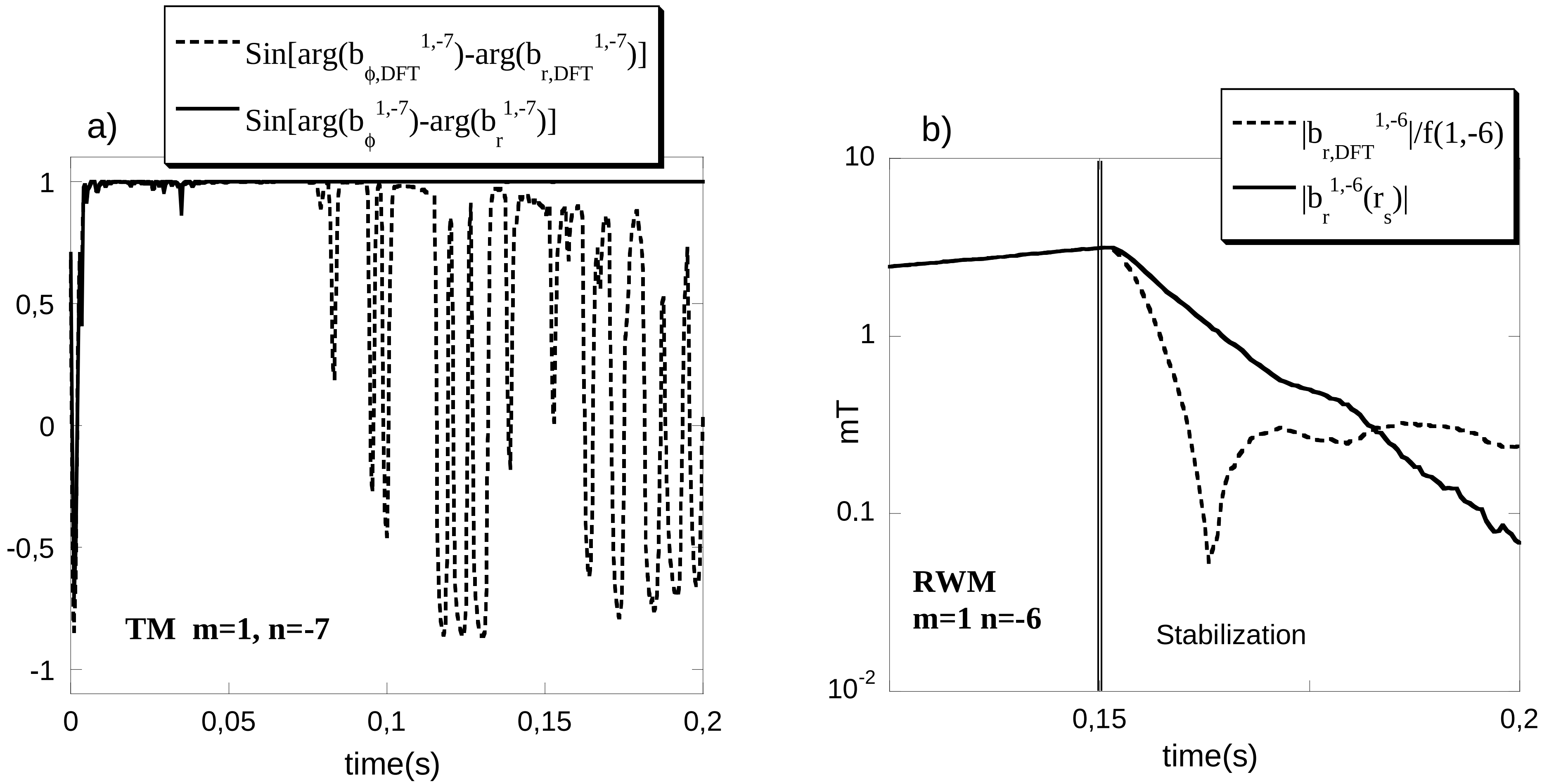
$$S = \sum_{\substack{p=m+lM,\,q=n+kN \\ \{l,k\}\in Z^2-\mathbf{0}}} b_{r,c}^{p,q}(r_s)\,f(p,q);\qquad \varepsilon = \left(1 - \sum_{\substack{p=m+lM,\,q=n+kN \\ l=0,\pm1,\pm2;\;k=0,\pm1;\;\{l,k\}\neq\mathbf{0}}} b_{r,c}^{p,q}(r_s)\,f(p,q) \Big/ S\right)\cdot 100$$





ω=0

Clean Fourier analysis



Extrapolation

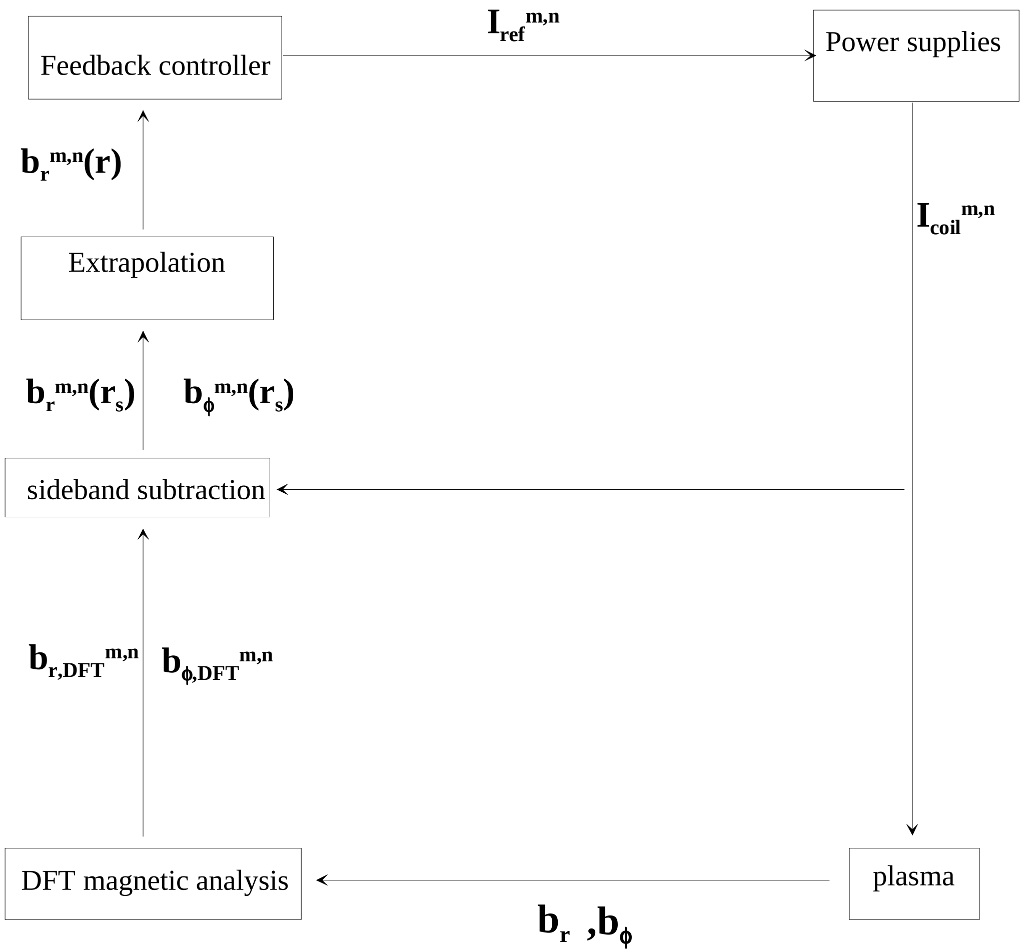
$$b_r^{m,n}(r) = \alpha^{m,n} I'_m\left(\frac{|n| r}{R_0}\right) + \beta^{m,n} K'_m\left(\frac{|n| r}{R_0}\right)$$

$$\alpha^{m,n} = \frac{-i\,\mathrm{sgn}(n) b_\phi^{m,n}(r_s) K'_m(z_s) - b_r^{m,n}(r_s) K_m(z_s)}{K'_m(z_s) I_m(z_s) - I'_m(z_s) K_m(z_s)};$$

$$z_s = \frac{|n| r_s}{R_0}$$

$$\beta^{m,n} = \frac{i\,\mathrm{sgn}(n) b_\phi^{m,n}(r_s) I'_m(z_s) + b_r^{m,n}(r_s) I_m(z_s)}{K'_m(z_s) I_m(z_s) - I'_m(z_s) K_m(z_s)};$$

CMC scheme

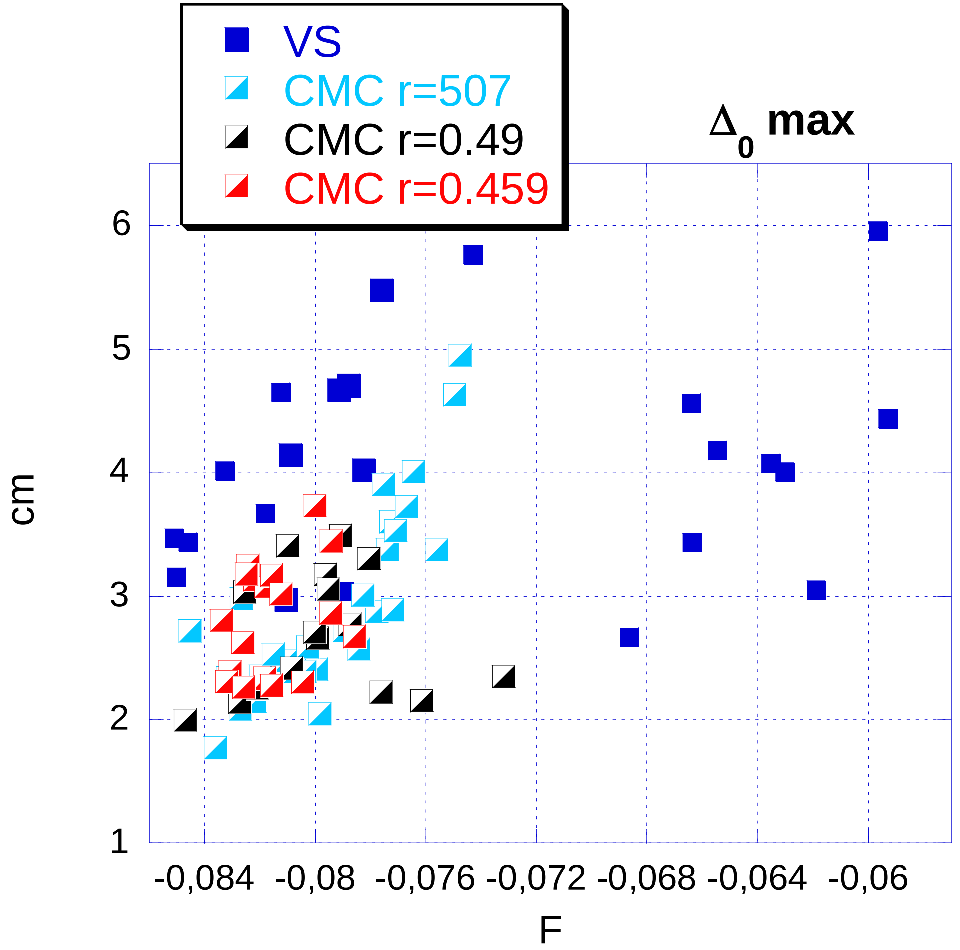


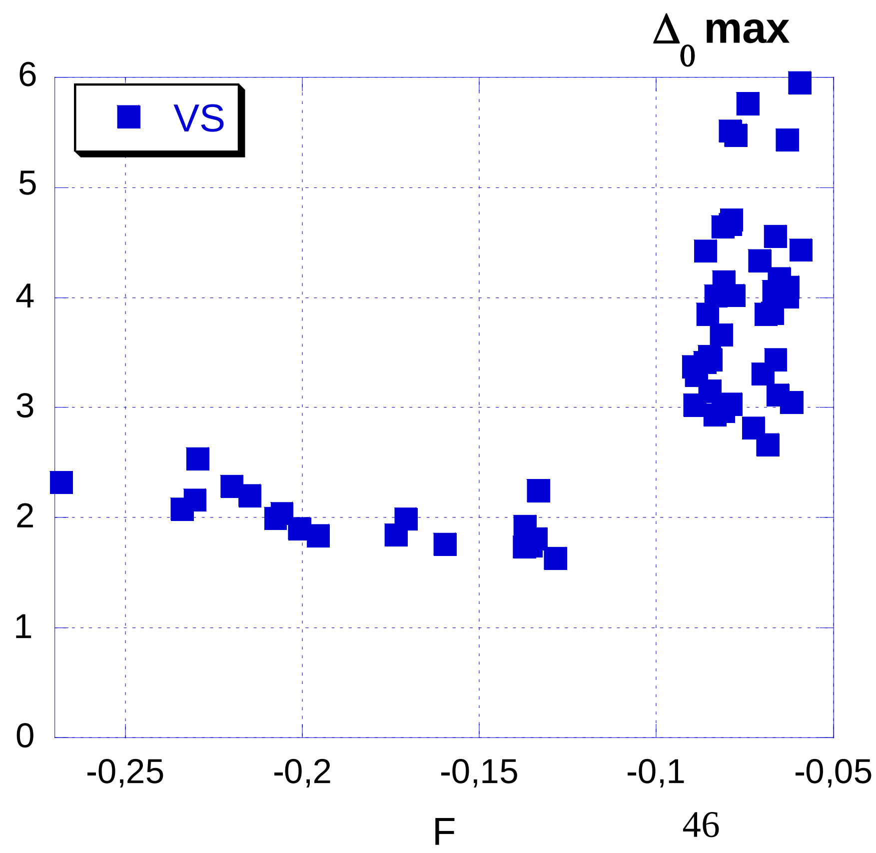
4×48 signals b_r, b_ϕ, I $\rightarrow$ latency time (<500μs) greater than VS (<333μs)

m=0 geometrical distortion

At shallow F this computation is not reliable!

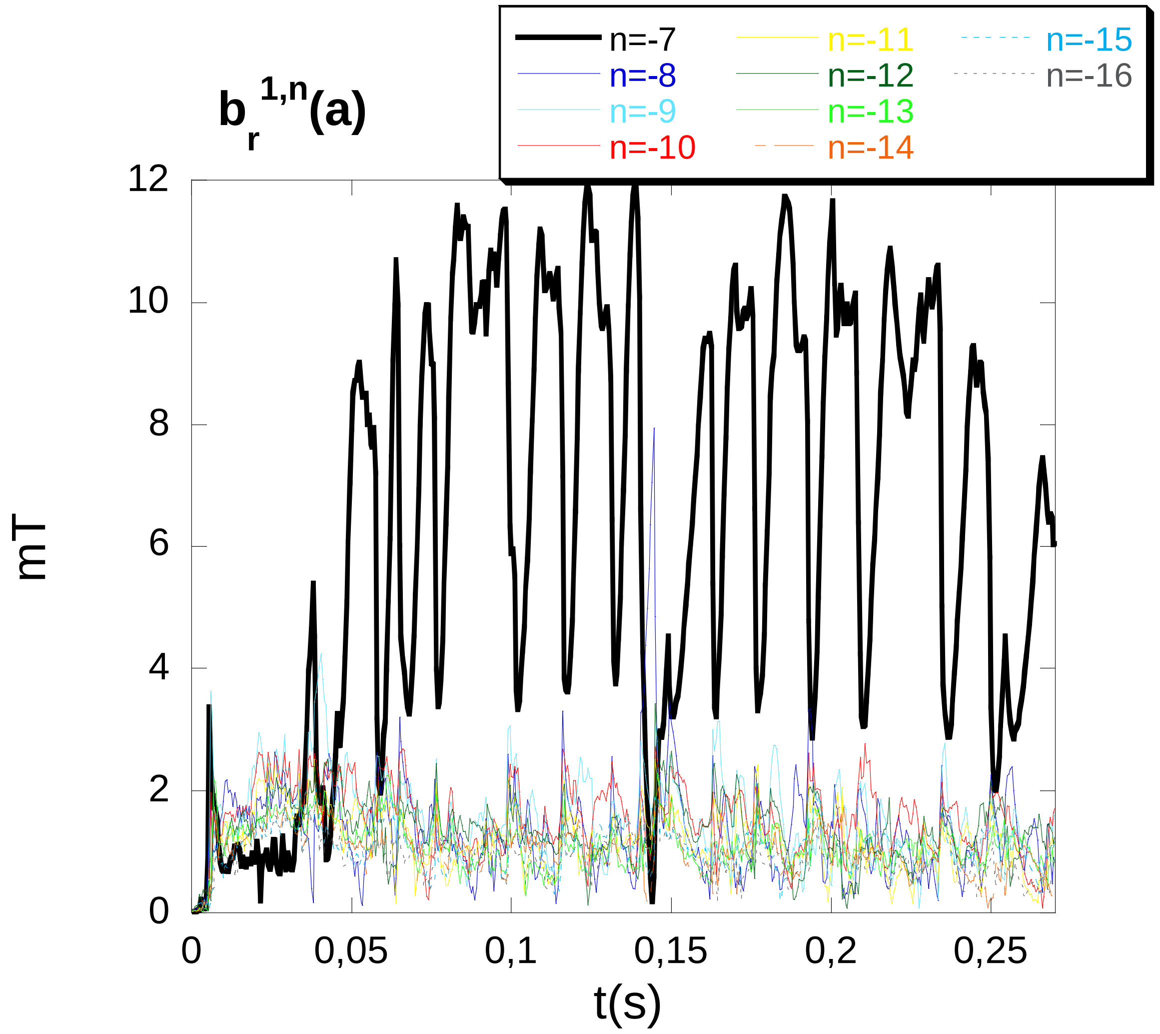
Ip=600kA   F>-0.1



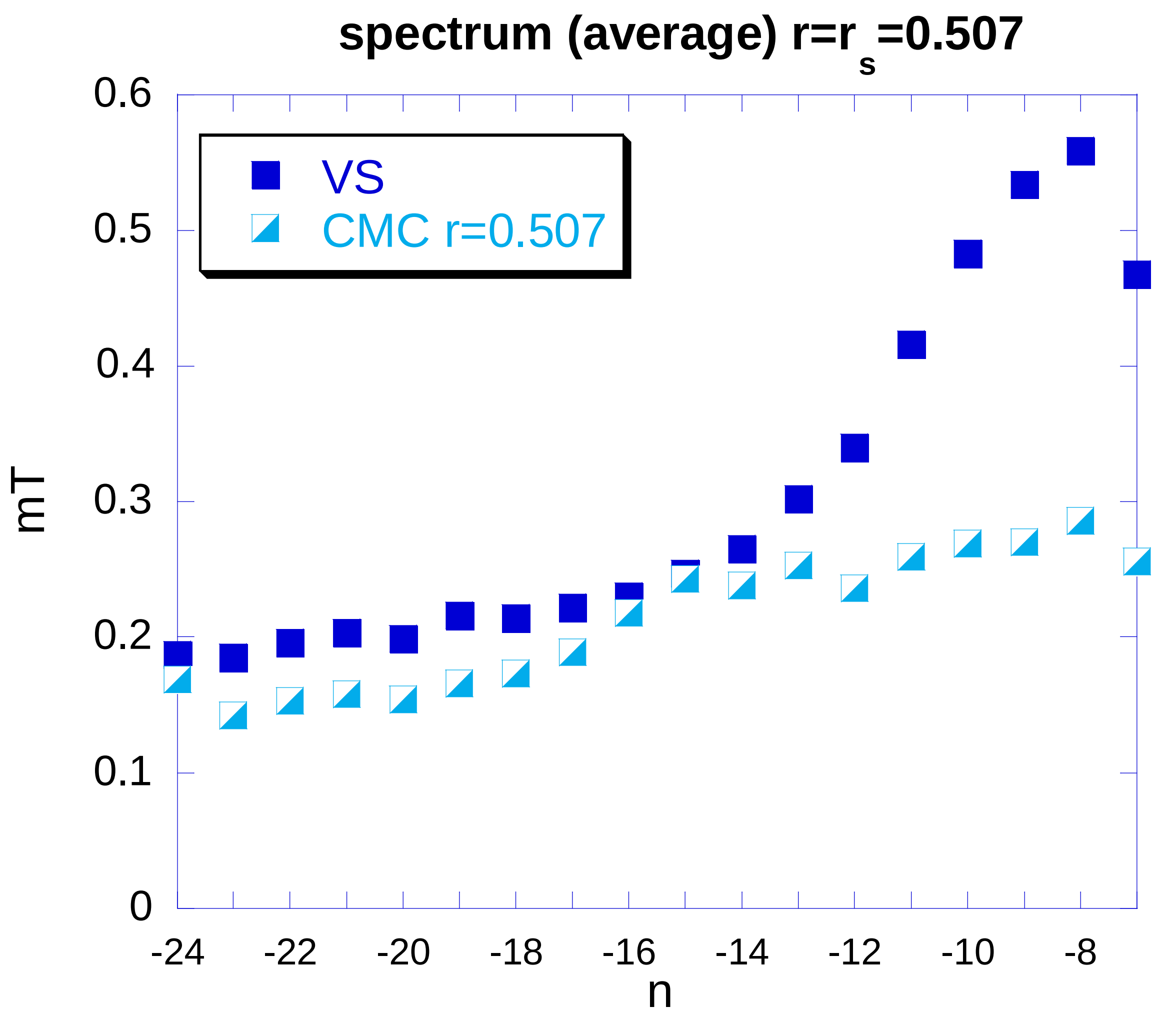


QSH with CMC (I)

#22805 CMC



b_r amplitude reduction (m=1 TMs) (I)



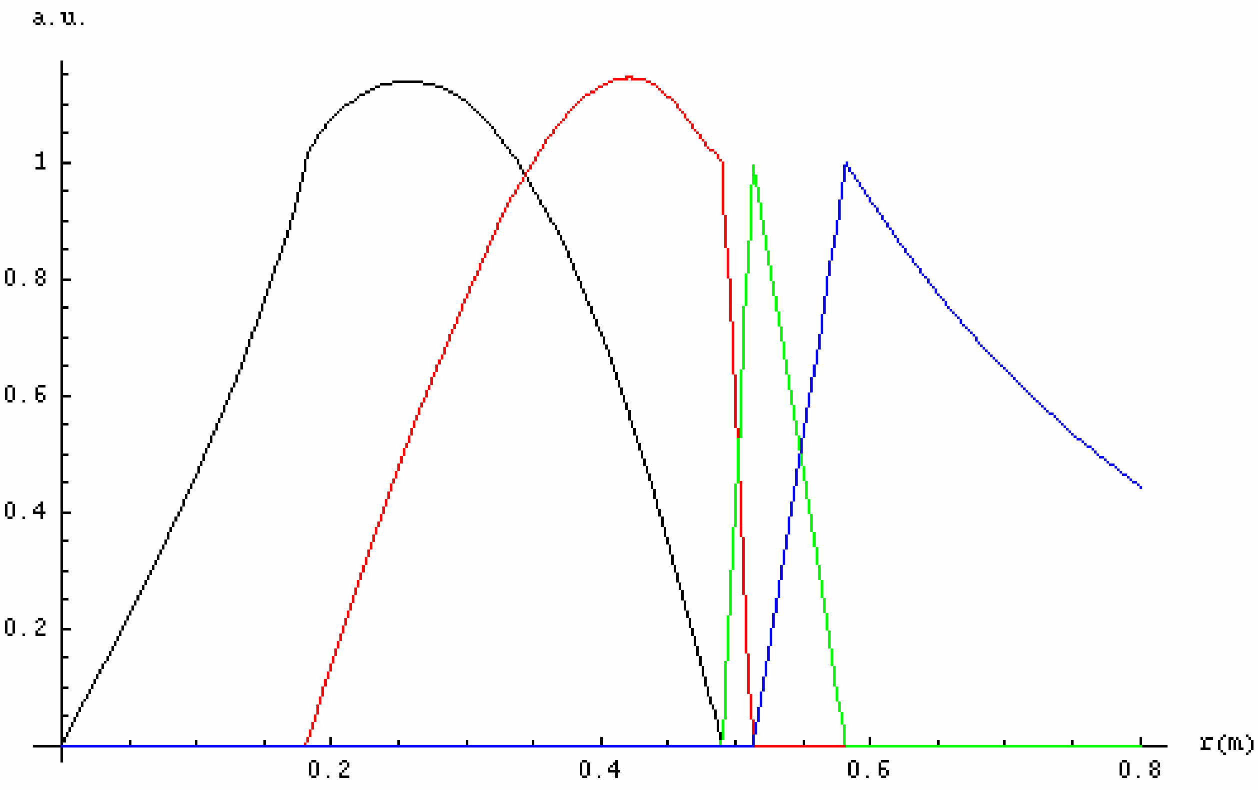
$b_r^{1,n}(r_s = 0.507)$

Ip=600kA F>-0.1

CMC only for

$-16 \leq n \leq -7$

Newcomb equation splitting



$$-ir\,b_r^{m,n} \equiv \Psi(r,t) = \Psi_s(t)\hat{\psi}_s(r) + \Psi_v(t)\hat{\psi}_v(r) + \Psi_b(t)\hat{\psi}_b(r) + \Psi_c(t)\hat{\psi}_c(r)$$

$$r_v \left.\frac{\partial \Psi}{\partial r}\right|_{r_v^-}^{r_v^+} = i\omega\,\tau_v \Psi_v; \quad b\left.\frac{\partial \Psi}{\partial r}\right|_{b^-}^{b^+} = i\omega\,\tau_b \Psi_b; \quad c\left.\frac{\partial \Psi}{\partial r}\right|_{r_c^-}^{r_c^+} = i\mu_0\left(m^2 + n^2\frac{c^2}{{R_0}^2}\right) f(m,n) I_{DFT}^{m,n};$$

Torque balance

Equilibrium frequency ω:

$$\frac{r_{m,n} R_0^2}{m^2 R_0^2 + n^2 r_{m,n}^2} \left| \frac{b_r^{m,n}(r_{m,n})}{B_0} \right|^2 \operatorname{Im}\left[\frac{1}{b_r^{m,n}(r_{m,n})} \frac{\partial b_r^{m,n}}{\partial r} \Bigg|_{r_{m,n}^-}^{r_{m,n}^+} \right] + \frac{2\tau_A^2}{\tau_V}(\omega_0 - \omega) \cdot \left[n^2 \frac{r_{m,n}^2}{R_0^2} \ln\left(\frac{a}{r_{m,n}} \right) - m^2 \cdot f\left(\sqrt{\frac{\tau_V}{\tau_D}} \right) \right]^{-1} = 0$$

EM due to vessel, shell, feedback

Viscous due to fluid motion

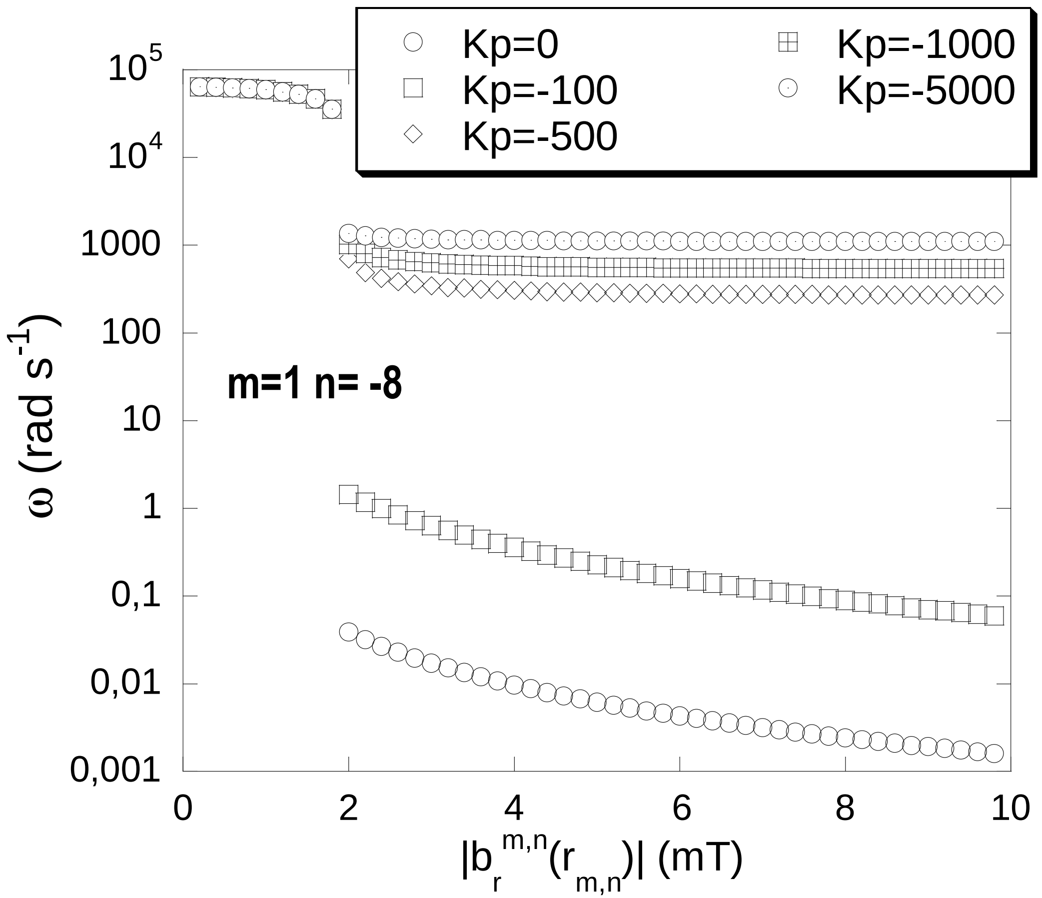
Only qualitative model , because:

Non-linear interaction with other modes neglected

ω_0 , τ_D , τ_V not well known in RFX

Wall locking curves

$$V_{\phi 0} = 10Km/s, \quad V_{\theta 0} = -5Km/s \quad \tau_V = 8ms$$



Comparison with the experiment