Low-q Tokamak Mode Control in RFX-mod

P. Zanca, M. Baruzzo, T. Bolzonella,
G.Marchiori, L. Marrelli, R. Paccagnella,
P. Piovesan, A. Soppelsa

Outline

Feedback on m=2 n=1 RWM in q(a)<2 experiments

- ❑ Intelligent Shell & Clean Mode Control

Cylindrical MHD model of the RWM feedback

- ❑ sidebands aliasing
- ❑ feedback delays
- ❑ radial/poloidal sensors

RFX-mod $q(a) \leq 2$ tokamak

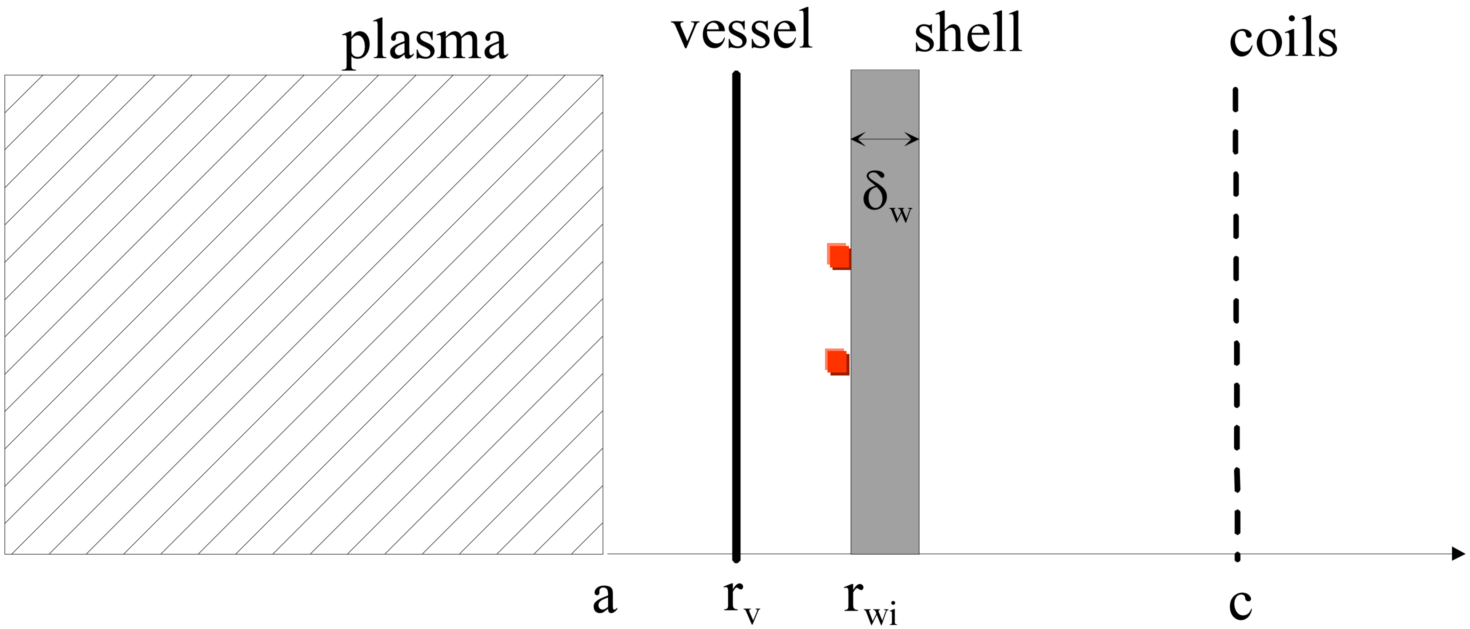
$q(a) \sim 1.8$, $B_\phi(a) = 0.55$T, $I_p = 150$kA, pulse lenght ~ 1s

$n_e R / B_\phi(a) \sim 7$ (density limit for $q(a) \sim 2$)

$T_e \sim 200\text{-}300$eV, $\beta_N = \beta\, a\, B_\phi(a)/I_p \leq 1.5$ %Tm/MA

Feedback control of m=2, n=1 RWM

RFX-mod layout



R_0=2m

a=0.459m

r_v=0.49m

r_{wi}=0.51m

c=0.58m

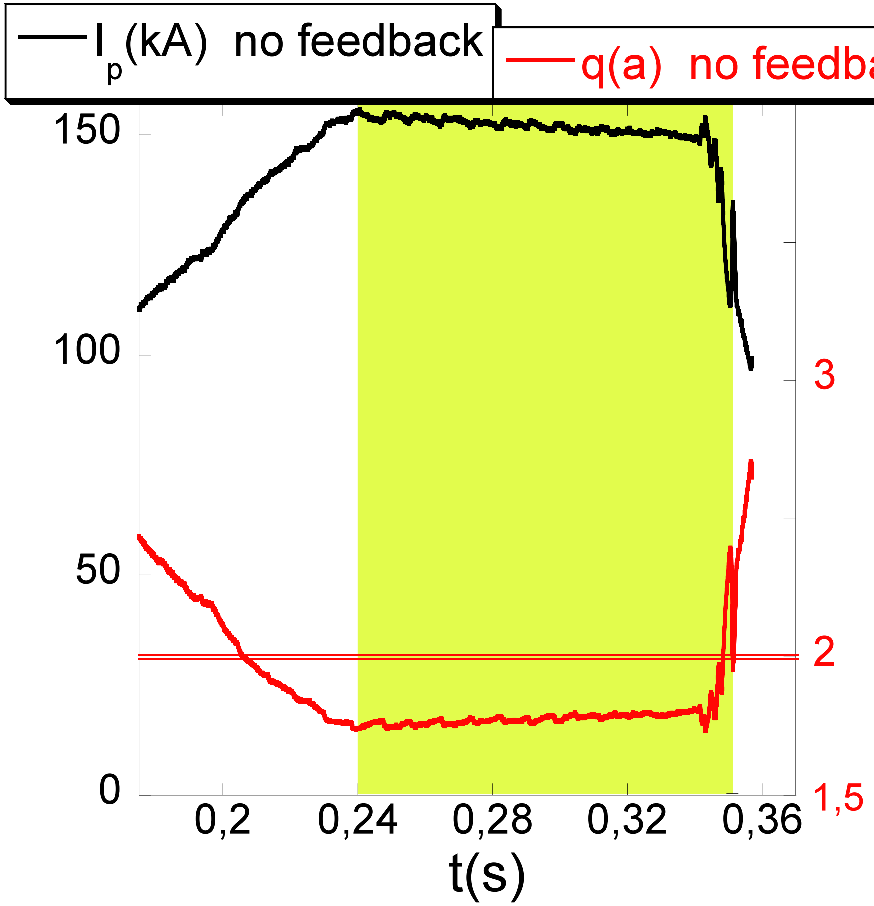
vessel: $\tau_v \approx 2.3$ms

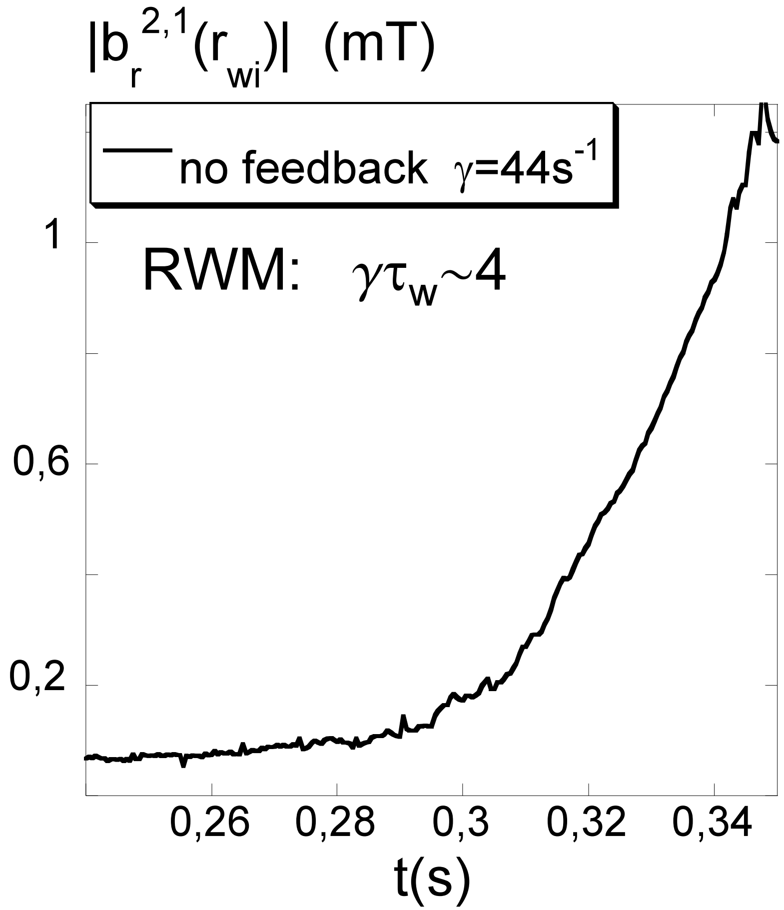
shell: δ_w=3mm, τ_w=100ms

coils: $(M_c=4)\times(N_c=48)$, $\Delta\theta_c=2\pi/M_c$, $\Delta\phi_c=2\pi/N_c$

sensors: $(M_s=4)\times(N_s=48)$ radial ($\Delta\theta_s=2\pi/M_s$, $\Delta\phi_s=2\pi/N_s$) toroidal and poloidal

m=2, n=1 RWM


I_p(kA) no feedback
q(a) no feedback
150
100
50
0
3
2
1,5
0,2
0,24
0,28
0,32
0,36
t(s)


|b_r^{2,1}(r_wi)| (mT)
no feedback γ=44s^-1
RWM: γτ_w~4
1
0,6
0,2
0,26
0,28
0,3
0,32
0,34
t(s)

Feedback algorithms: radial sensors

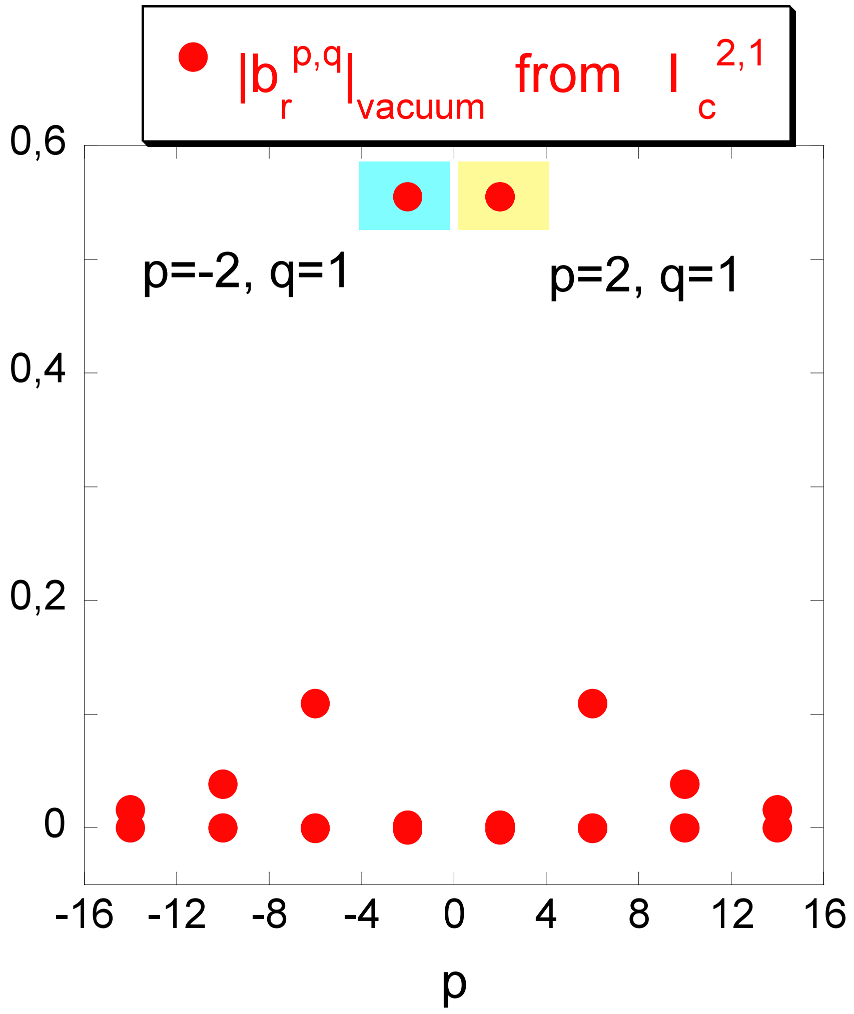
Intelligent Shell (IS) :

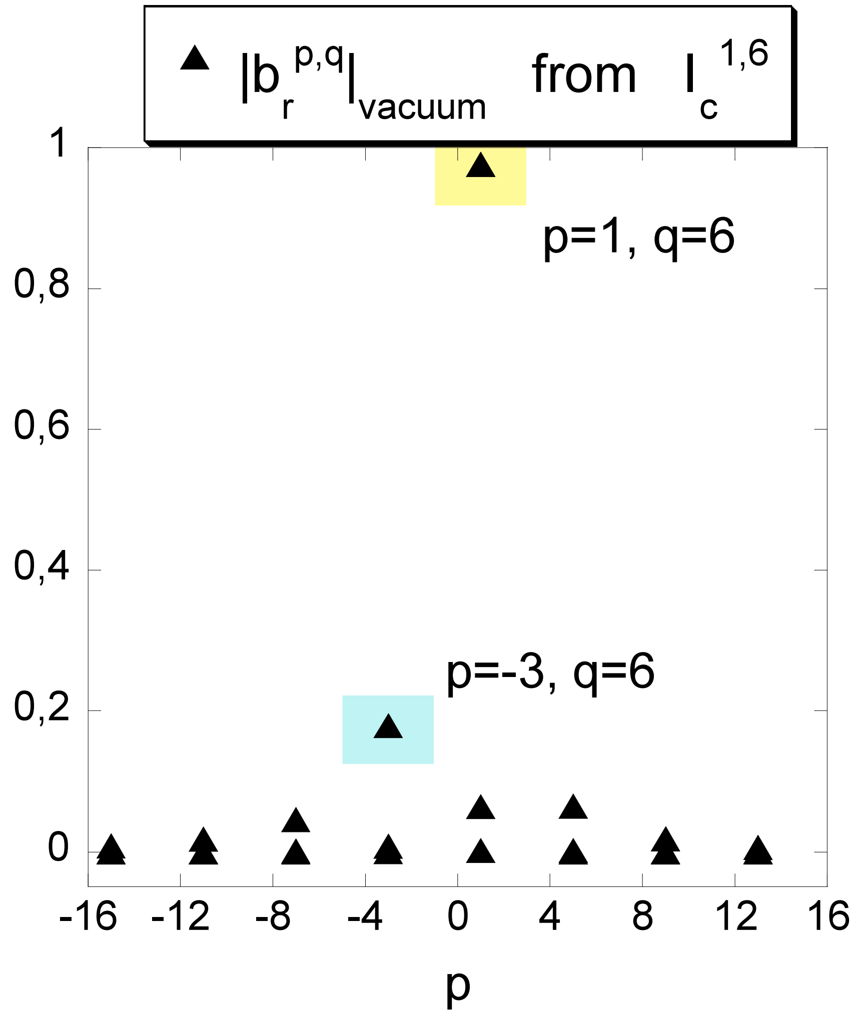
$$b_f = b_{r,DFT}^{m,n} = \sum_{p,q} b_r^{p,q}\left(r_{wi}\right) f_s\left(p,q\right) \qquad p = m + l \times M_s, q = n + k \times N_s$$

$$I_c^{p,q} = I_c^{m,n}$$

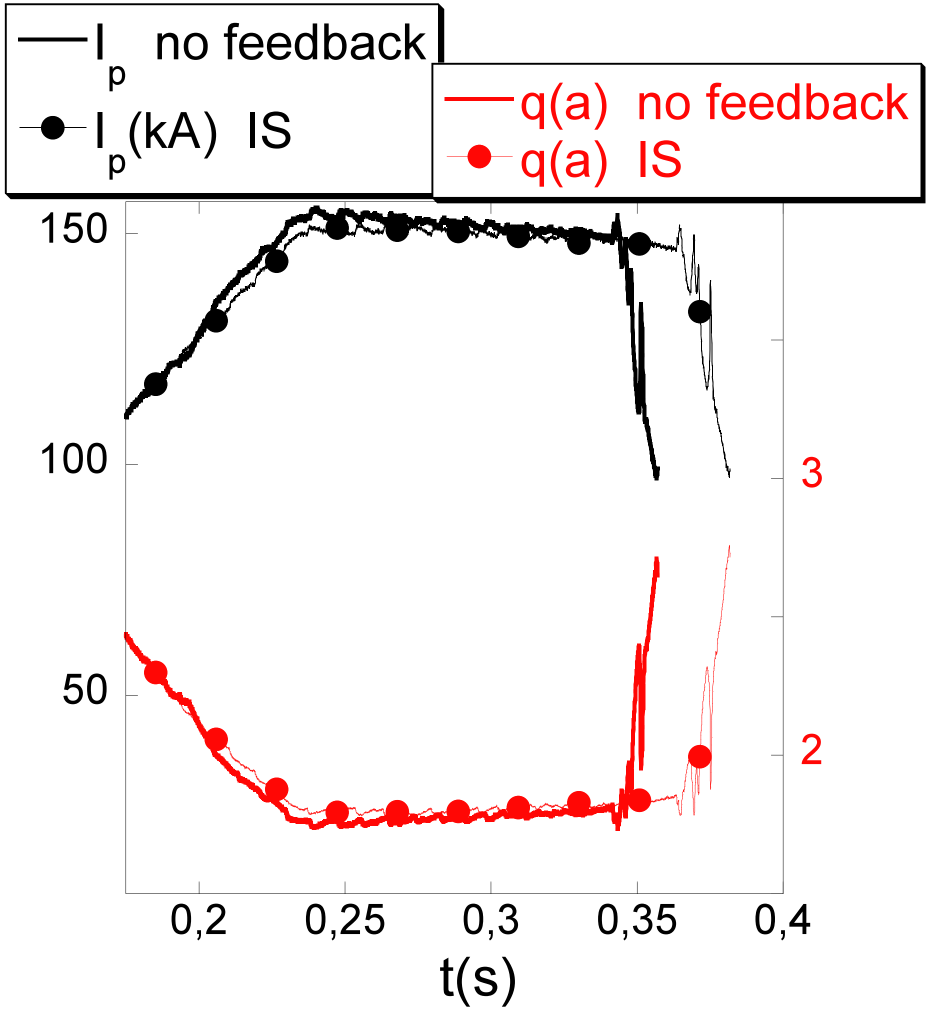
Intelligent Shell: sidebands pollution

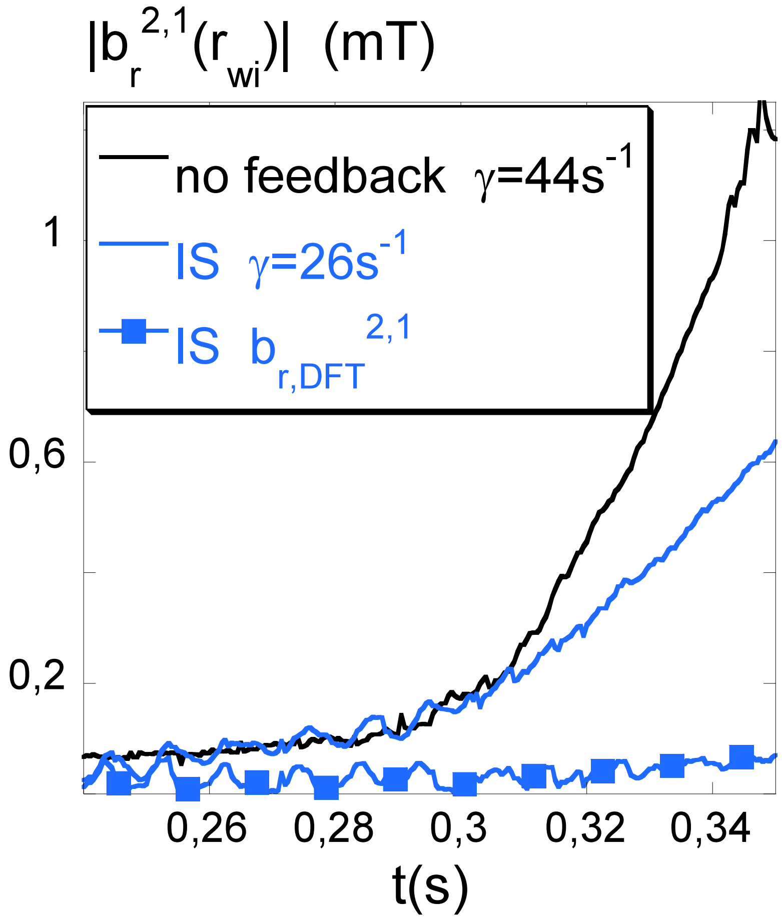
$M_c = M_s = 4 \quad , \; N_c = N_s = 48$





Intelligent Shell: m=2, n=1 control





Feedback algorithms: radial sensors

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Intelligent Shell (IS):

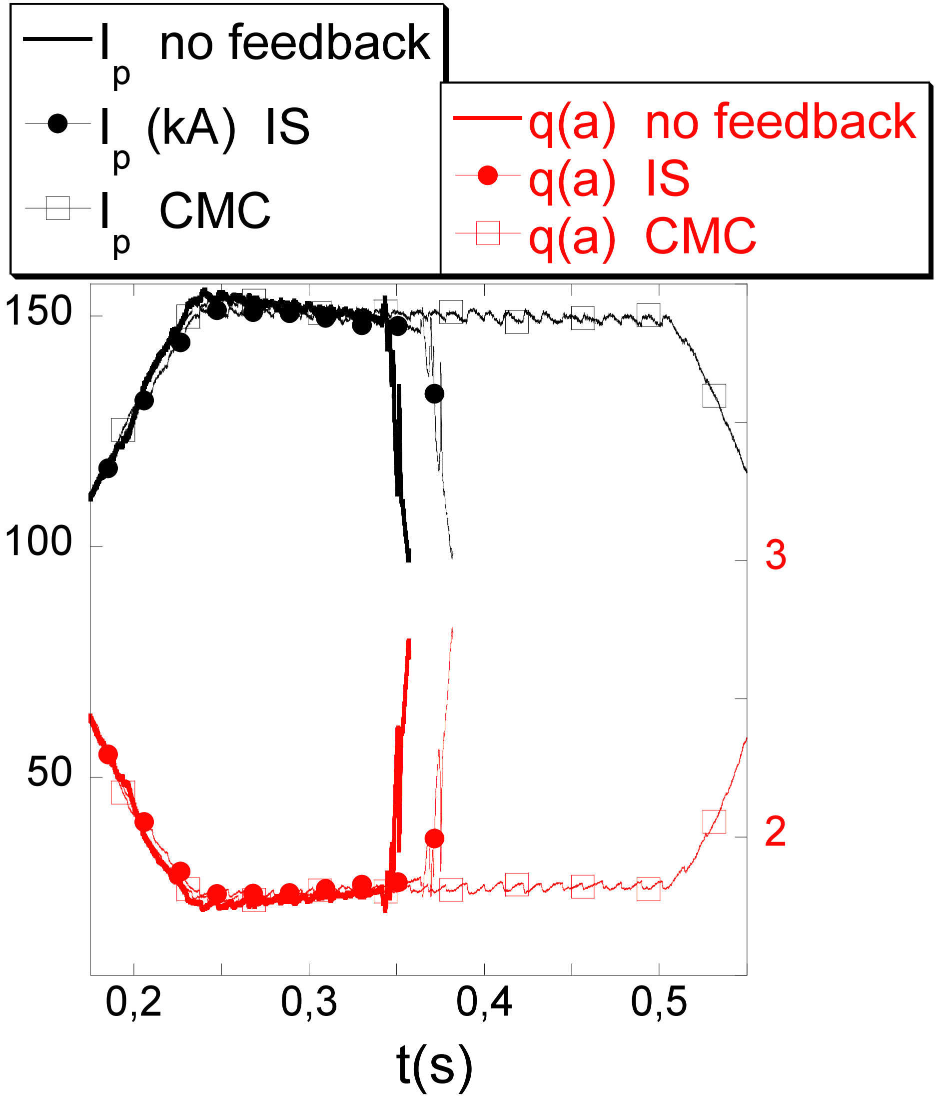
$$b_f = b_{r,DFT}^{m,n} = \sum_{p,q} b_r^{p,q}(r_{wi})\, f_s(p,q) \qquad p = m + l \times M_s,\, q = n + k \times N_s$$

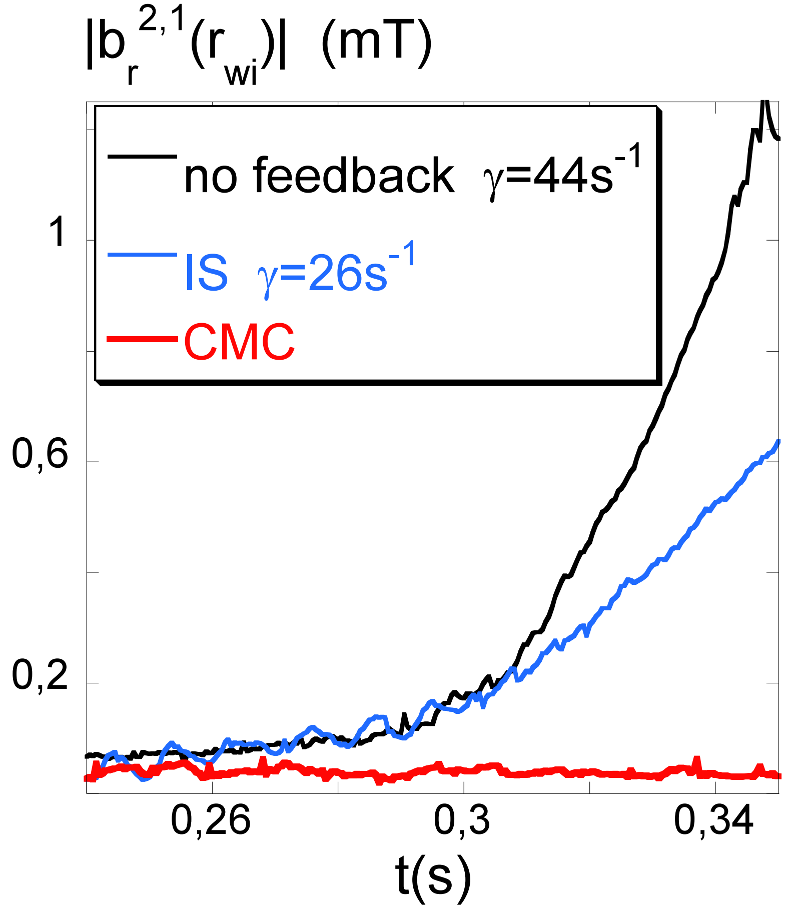
$$I_c^{p,q} = I_c^{m,n}$$

Clean Mode Control (CMC):

$$b_f = b_{r,DFT}^{m,n} - \int_0^t \left[\sum_{(p,q)\in Z^2-(m,n)} \Lambda^{p,q}(t-x) \right] I_c^{m,n}(x)\, dx \;\approx\; b_r^{m,n}(r_{wi})$$

Clean Mode Control on m=2, n=1

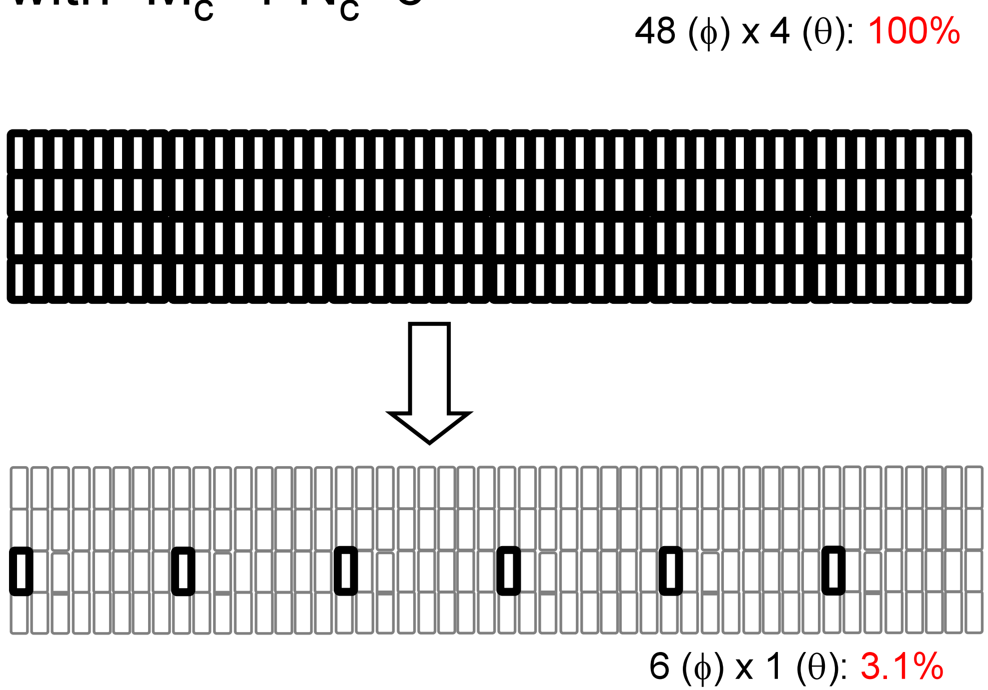




Clean Mode Control on m=2, n=1

$I_c^{2,1}$<200A $\sim$50-100 times smaller than I_c required by the dynamo modes

CMC works even with M_c=1 N_c=6



Outline

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Feedback on m=2 n=1 RWM in q(a)<2 experiments

- Intelligent Shell & Clean Mode Control (radial sensors)

Cylindrical MHD model of the RWM feedback

- sidebands aliasing
- feedback delays
- radial/poloidal sensors

The MHD model

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- Cylindrical geometry, zero-β equilibrium
- Newcomb's equation for $\Psi^{p,q} = -i\, r\, b_r^{p,q}$, $p=m+l\times M_c$, $q=n+k\times N_c$
- Vessel $$\tau_v \left.\frac{\partial \psi^{p,q}}{\partial t}\right|_{r_v} = r \left.\frac{\partial \psi^{p,q}}{\partial r}\right|_{r_v-}^{r_v+}$$
- Shell $$\mu_0 \sigma_w \frac{\partial \psi^{p,q}}{\partial t} = \frac{\partial^2 \psi^{p,q}}{\partial r^2}, \qquad r \in \left[r_{wi}, r_{we}\right]$$
- Coils $$r \left.\frac{\partial \psi^{p,q}}{\partial r}\right|_{c-}^{c+} \propto I_c^{p,q}, \qquad I_c^{p,q} = I_c^{m,n} \qquad \tau_c^{m,n} \frac{dI_c^{m,n}}{dt} + I_c^{m,n} \approx \frac{V_c^{m,n}}{R_c}$$

Continuous-time/discrete-time models

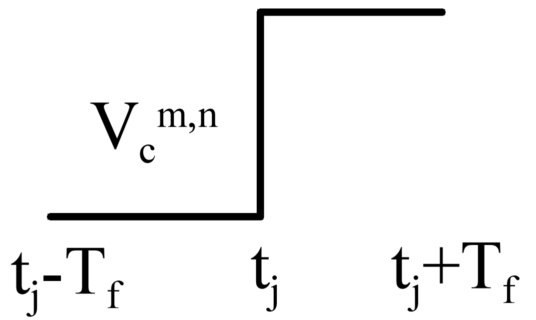
Continuous-time

$$V_c^{m,n}(t) = R_c\left[K_p + K_d \frac{d}{dt}\right] w_f(t)$$

$$\tau_d \frac{d}{dt} w_f(t) + w_f(t) = b_f$$

Delays: 1-pole filter τ_d

Discrete-time



$$\Delta t = \bar{k} T_f$$

$$V_c^{m,n}\left(t_j \le t \le t_j + T_f\right) = \left[K_p + K_d \frac{d}{dt}\right] w_f\left(t_{j-\bar{k}}\right)$$

$$T_f \frac{d}{dt} w_f(t) + w_f(t) = b_f$$

Delays:

- ✓ 1-pole filter T_f
- ✓ true delay $\Delta t \div (\Delta t + T_f)$

Intelligent Shell: m=2 n=1 RWM

q(0)=0.82
q(a)=1.78

$\longrightarrow \gamma=47 s^{-1}$

$b_f = b_{r,DFT}^{2,1}(r_{wi})$

$M_c=M_s=4,\ N_c=N_s=48\ \ \Delta\theta_c=\Delta\theta_s=2\pi/M_c,\ \Delta\phi_c=\Delta\phi_s=2\pi/N_c$ **non-stabilizable**

Benchmark: m=1,n=6 RWM can be stabilized

p=-2, q=1

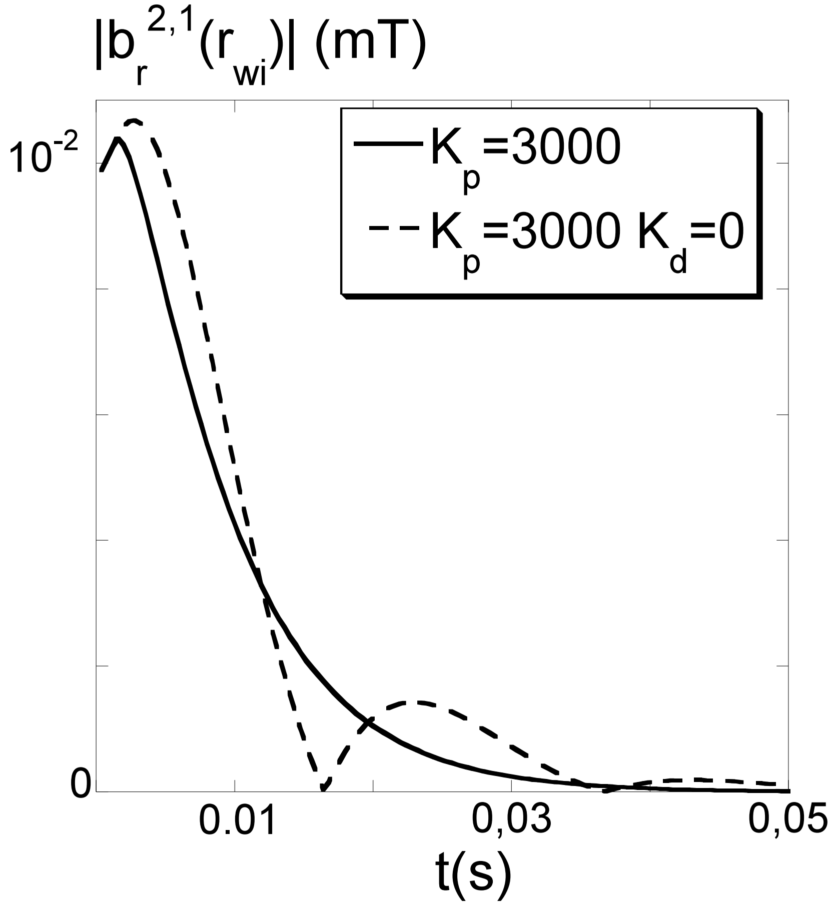
$M_c=M_s=8,\ N_c=N_s=6\ \ \Delta\theta_c=\Delta\theta_s=2\pi/M_c,\ \Delta\phi_c=\Delta\phi_s=2\pi/N_c$ **stabilizable**

$M_c=M_s=8,\ N_c=N_s=6\ \ \Delta\theta_c=\Delta\theta_s=\pi/M_c,\ \Delta\phi_c=\Delta\phi_s=\pi/N_c$ **non-stabilizable**

CMC simulations: RFX-mod case

$b_f = b_r^{2,1}(r_{wi})$

T_f=0.4ms, $\Delta t=2T_f$, $K_d=\tau_c K_p$



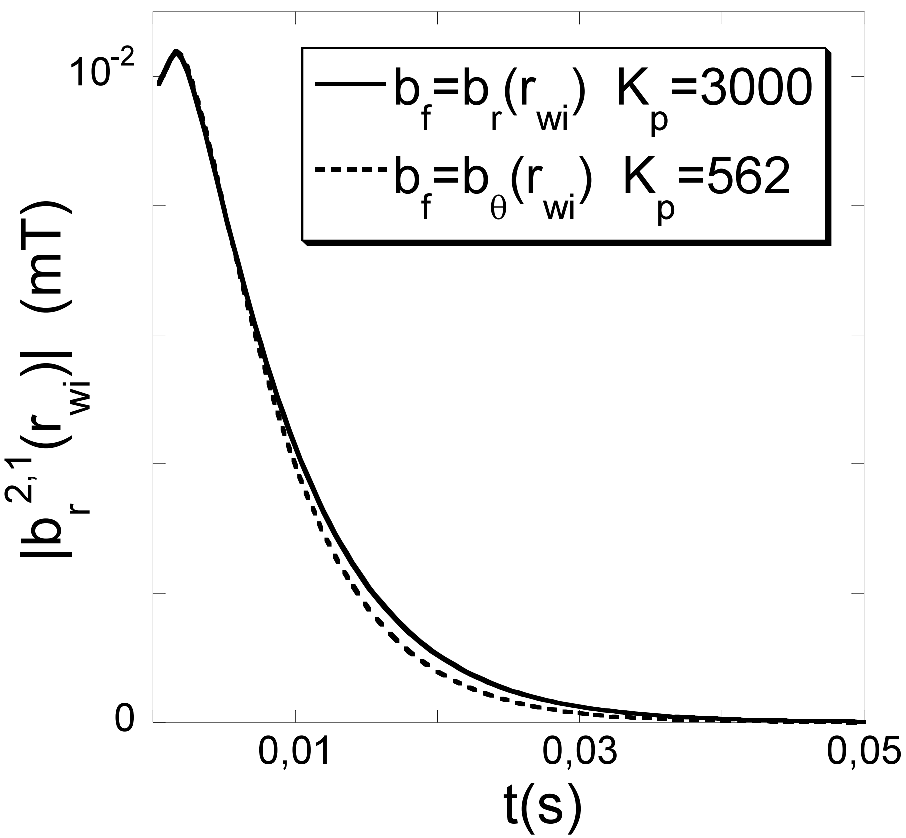
Experimental K_p

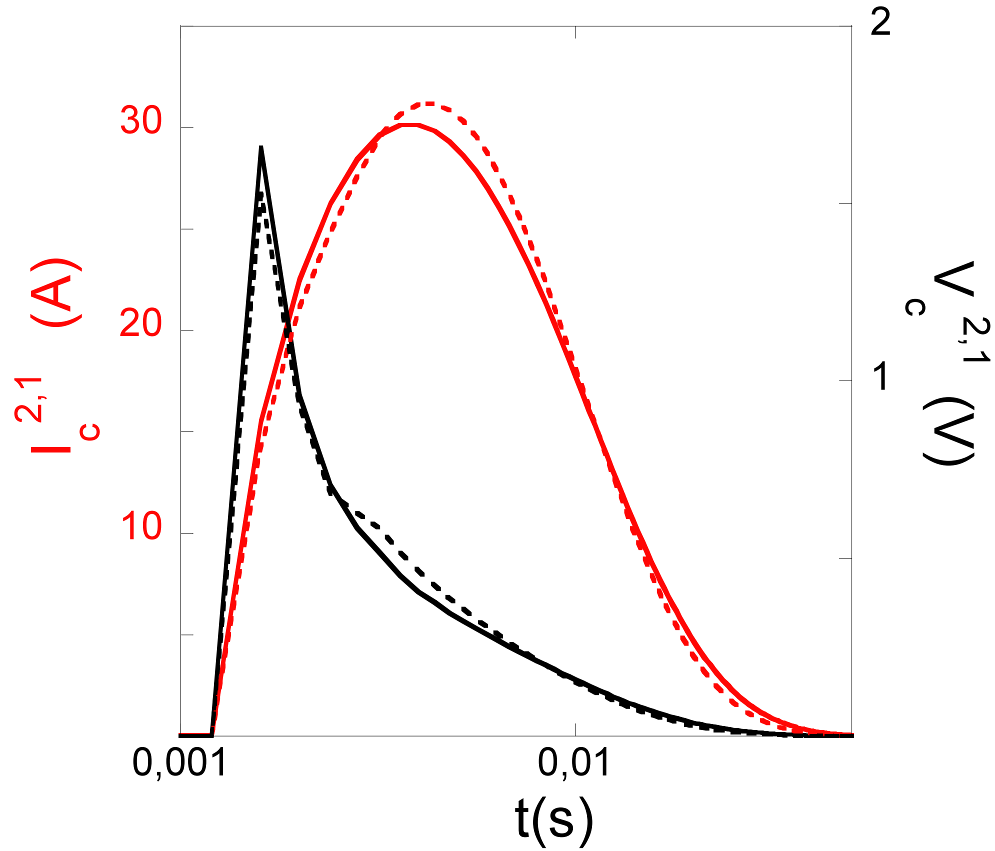
Simulations works also with M_c=1, N_c=6

CMC simulations: comparison b_r, b_θ

$b_f = b_r^{2,1}(r_{wi})$, $b_f = i\, b_\theta^{2,1}(r_{wi})$

T_f=0.4ms, Δt=2T_f, K_d=τ_c K_p





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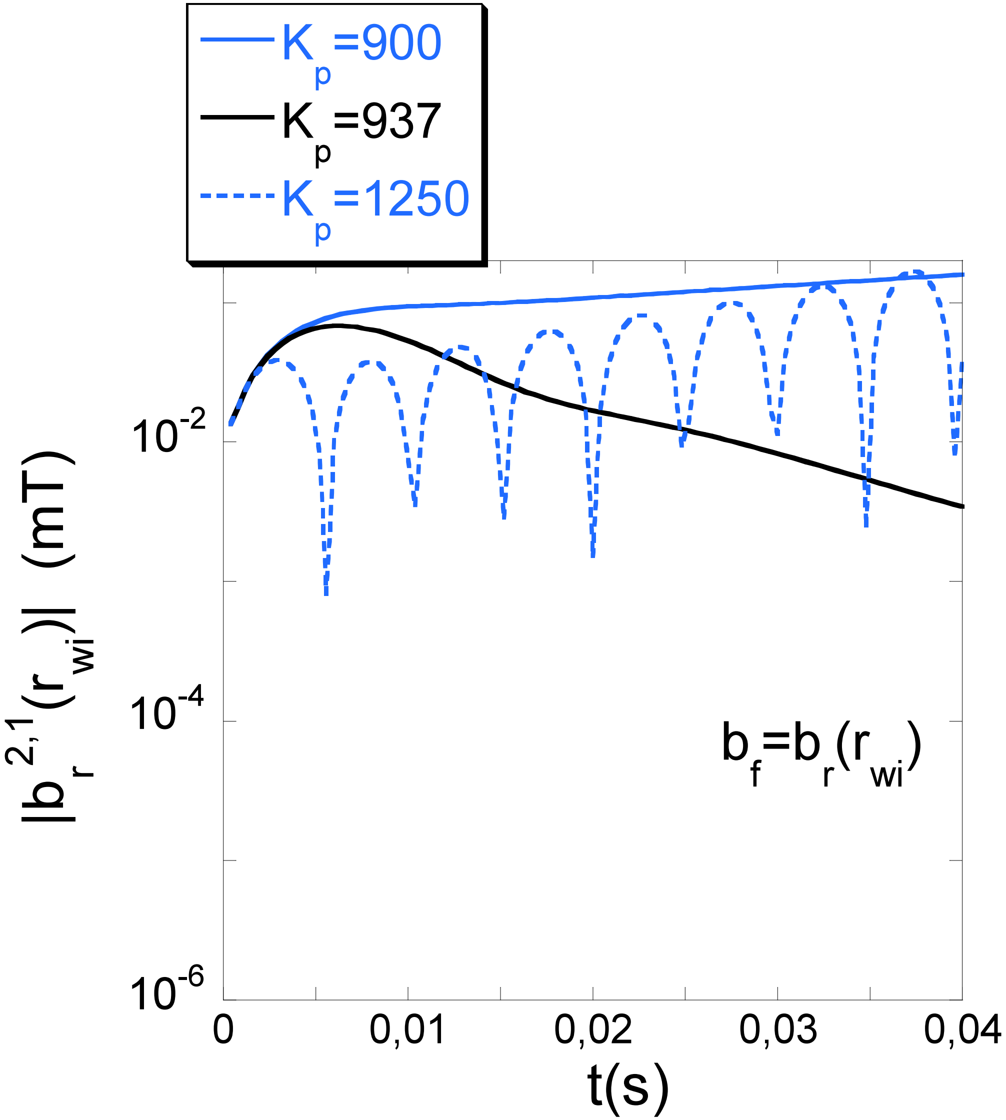
CMC simulations: τ_w=3ms



$\gamma \sim 47 s^{-1} \rightarrow \gamma \sim 672 s^{-1}$

T_f=0.4ms, $\Delta t=2T_f$

$K_d=\tau_c K_p$

$K_{p,max} / K_{p,min} < 1.3$

Continuous-time/discrete-time models

Continuous-time

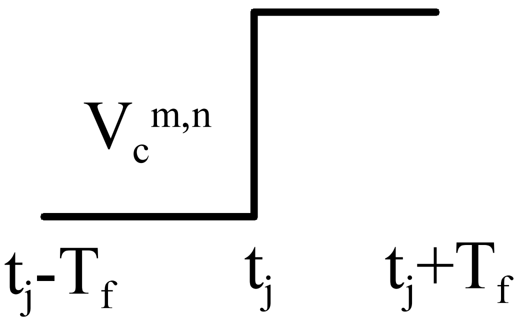
$$V_c^{m,n}(t) = R_c\left[K_p + K_d \frac{d}{dt}\right] w_f(t)$$

$$\tau_d \frac{d}{dt} w_f(t) + w_f(t) = b_f$$

Delays: 1-pole filter τ_d

$$\boxed{\tau_d = T_f + \Delta t + T_f}$$

Discrete-time



$$\Delta t = \bar{k} T_f$$

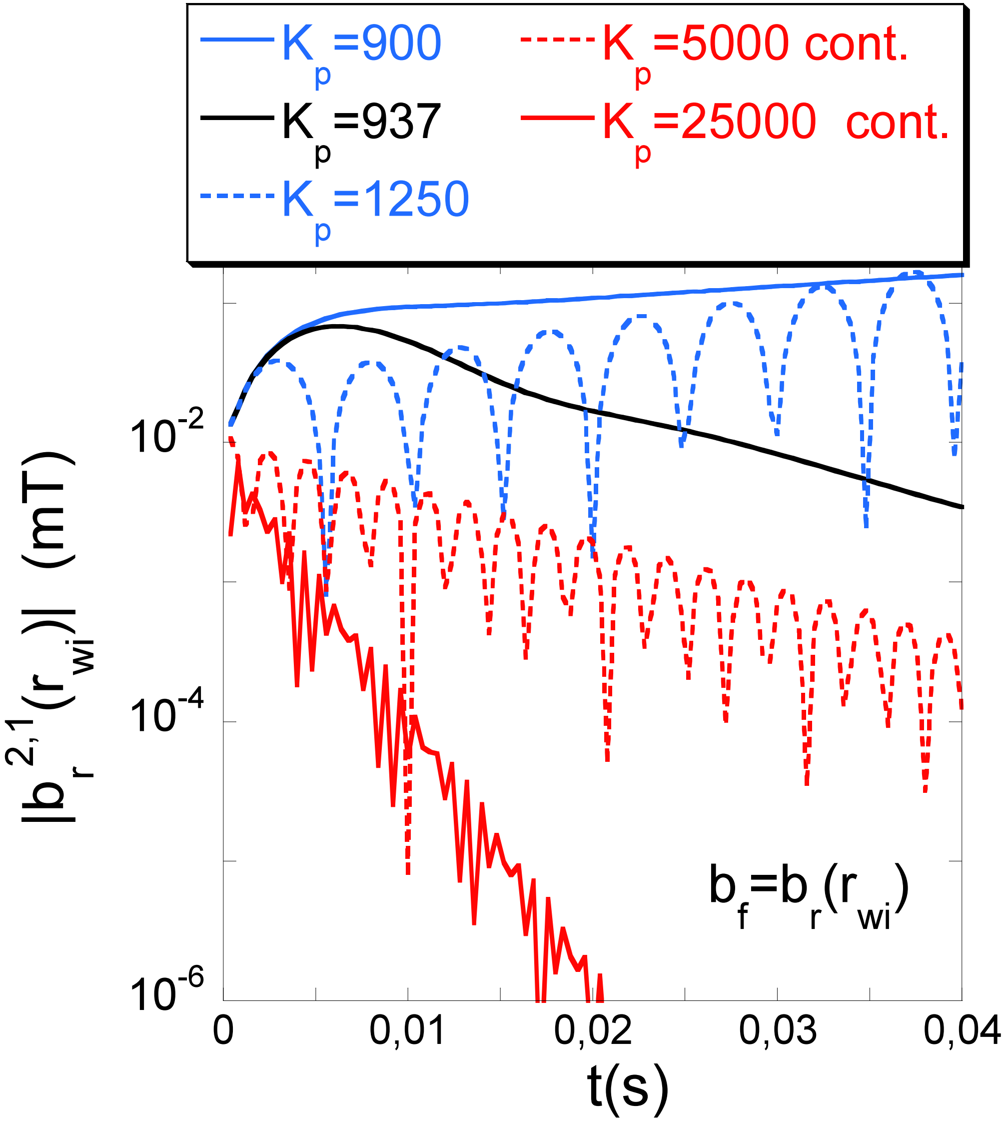
$$V_c^{m,n}(t_j \le t \le t_j + T_f) = R_c\left[K_p + K_d \frac{d}{dt}\right] w_f(t_{j-\bar{k}})$$

$$T_f \frac{d}{dt} w_f(t) + w_f(t) = b_f$$

Delays:

- ✓ 1-pole filter T_f
- ✓ true delay $\Delta t \div (\Delta t + T_f)$

CMC simulations: τ_w=3ms



T_f=0.4ms, $\Delta t=2T_f$

$K_d=\tau_c K_p$

Continuous-time model:

$\tau_d = T_f + T_f + \Delta t$ = 1.6ms

1-pole filter delays are not equivalent to true delays

CMC br: comparative table

τ_w (ms)	$\gamma(s^{-1})$	T_f - Δt	CMC b_r $K_{p,max}/K_{p,min}$
100 ($\tau_w \gg \tau_v$)	47	T_f=0.4ms $\Delta t=2T_f$	17
3 ($\tau_w \approx \tau_v$)	672	T_f=0.1ms $\Delta t=T_f$	8
0	1300	T_f=0.1ms $\Delta t=T_f$	4.7

$K_d=\tau_c K_p$

Explicit mode control τ_W=100ms

$$b_f = b_r^{2,1}(r_{wi}) - [b_r^{2,1}(r_{wi})]_{vac}$$

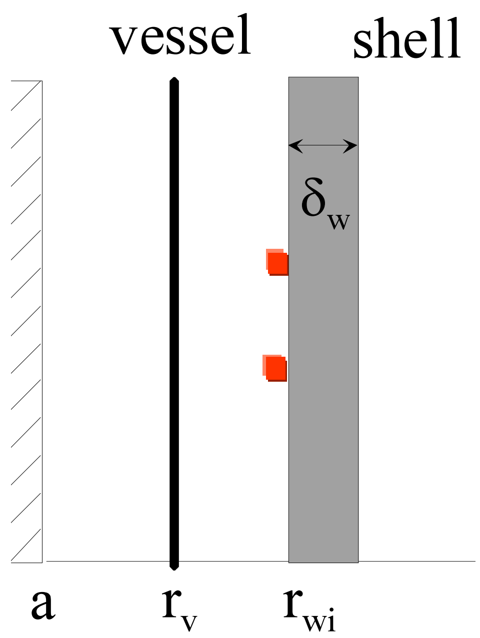
T_f=0.1ms, $\Delta t = T_f$

$K_d = \tau_c K_p$

Not stabilized

CMC b_r, b_θ : comparative table

τ_w (ms)	T_f - Δt	**CMC b_r** $K_{p,max}/K_{p,min}$	**CMC b_θ** $K_{p,max}/K_{p,min}$
100 ($\tau_w \gg \tau_v$)	T_f=0.4ms Δt=2T_f	17	12
3 ($\tau_w \approx \tau_v$)	T_f=0.1ms Δt=T_f	8	1.6
0	T_f=0.1ms Δt=T_f	4.7	1.07

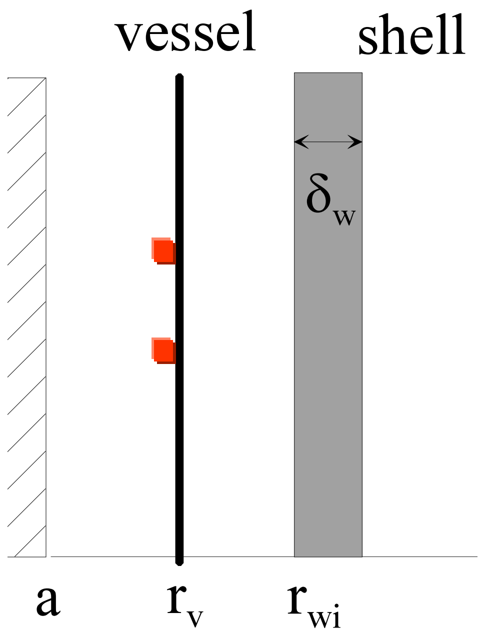


$K_d=\tau_c K_p$

Shielding + discrete-time feedback

CMC b_r, b_θ : comparative table

τ_w (ms)	T_f - Δt	CMC b_r $K_{p,max}/K_{p,min}$	CMC b_θ $K_{p,max}/K_{p,min}$
100 ($\tau_w \gg \tau_v$)	T_f=0.4ms Δt=2T_f	17	/
3 ($\tau_w \approx \tau_v$)	T_f=0.1ms Δt=T_f	8	5.3
0	T_f=0.1ms Δt=T_f	4.7	4



$K_d = \tau_c K_p$

Shielding + discrete-time feedback

CMC b_r, b_θ : comparative table

τ_w (ms)	T_f - Δt	CMC b_r $K_{p,max}/K_{p,min}$	CMC b_θ $K_{p,max}/K_{p,min}$	Explicit MC $b_f = ib_\theta^{2,1}(r_{wi}) - [ib_\theta^{2,1}(r_{wi})]_{vac}$
100 ($\tau_w \gg \tau_v$)	T_f=0.4ms Δt=2T_f	17	12	/
3 ($\tau_w \approx \tau_v$)	T_f=0.1ms Δt=T_f	8	1.6	4
0	T_f=0.1ms Δt=T_f	4.7	1.07	1.04

$K_d = \tau_c K_p$

Shielding + discrete-time feedback

Conclusions

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- Stable q(a)<2 operations at RFX-mod allowed by proper feedback

- Radial sensors can be used within the CMC → [Y. Liu, J.B. Lister, *Nucl. Fusion* **47** (2007) 648]

- Full coils coverage not required (M_c=1, N_c=6)

- Sidebands removal can be considered an electro-technical issue

- Future experiments: shaping, sensors downgrade & poloidal

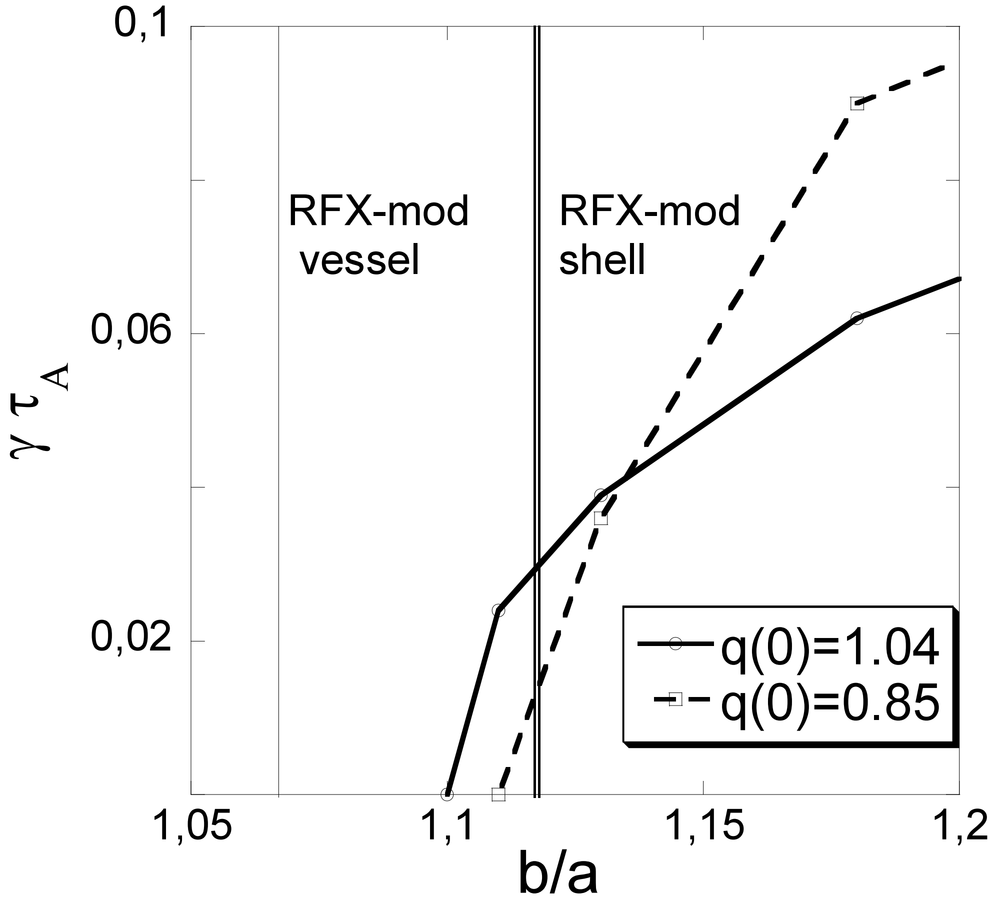
- MHD model reproduces fairly well the experiment

- Importance of the discretization of the feedback (not equivalent to 1-pole filter delays)

- Poloidal sensors: combined discretization and shielding effects

Spare slides

MARS-F stability analysis for m=2, n=1



The ideal mode is stabilized by the vacuum vessel

The MHD model: feedback variable

CMC: $b_f = b_r^{m,n}(r_{wi})$ $b_f = i\, b_\theta^{m,n}(r_{wi})$

Raw control:

$$b_f = b_{r,DFT}^{m,n} = \sum_{p,q} b_r^{p,q}\left(r_{wi}\right) f_s\left(p,q\right)$$

$$b_f = i\, b_{\theta,DFT}^{m,n} = i \sum_{p,q} b_\theta^{p,q}\left(r_{wi}\right)$$

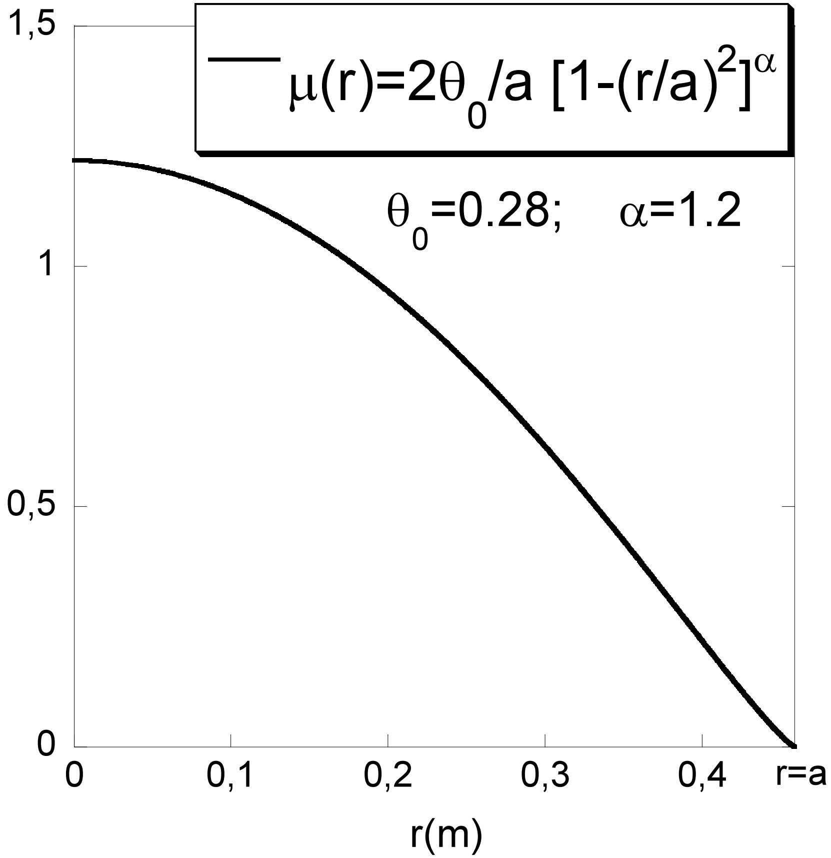
$p=m+l\times M_s$, $q=n+k\times N_s$

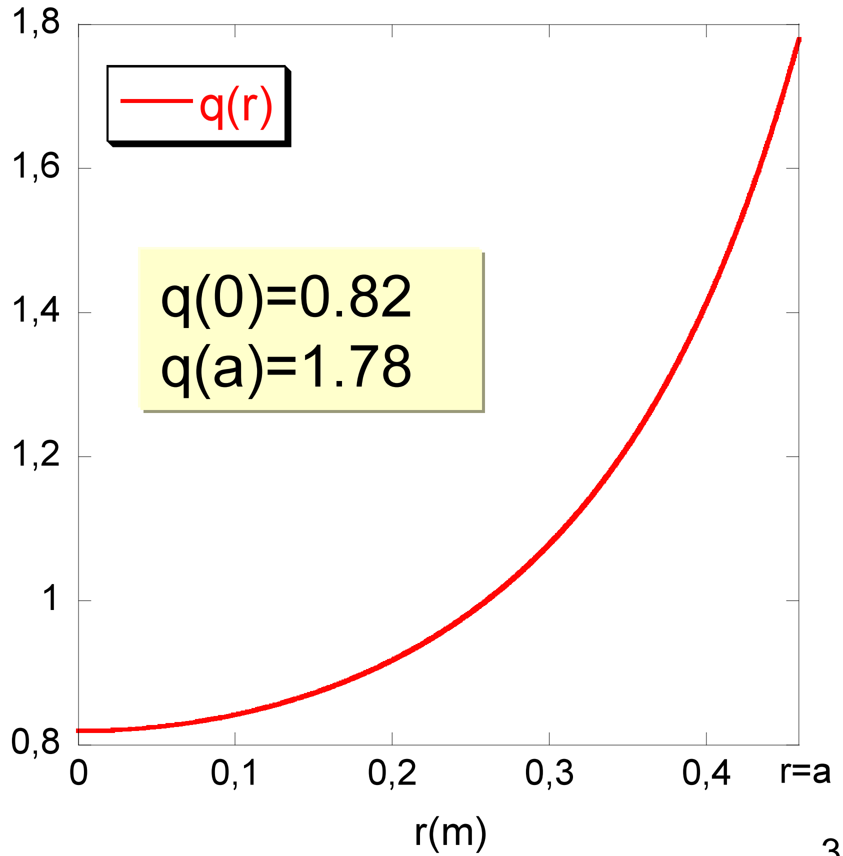
'Explicit Mode Control': $b_f = b_r^{m,n}(r_{wi}) - [b_r^{m,n}(r_{wi})]_{\mathrm{vac}}$

$b_f = i\, b_\theta^{m,n}(r_{wi}) - i[b_\theta^{m,n}(r_{wi})]_{\mathrm{vac}}$

Equilibrium example

$$\mu_0 \mathbf{J_0} = \mu(r)\,\mathbf{B_0}$$





Intelligent Shell: m=2 n=1 RWM

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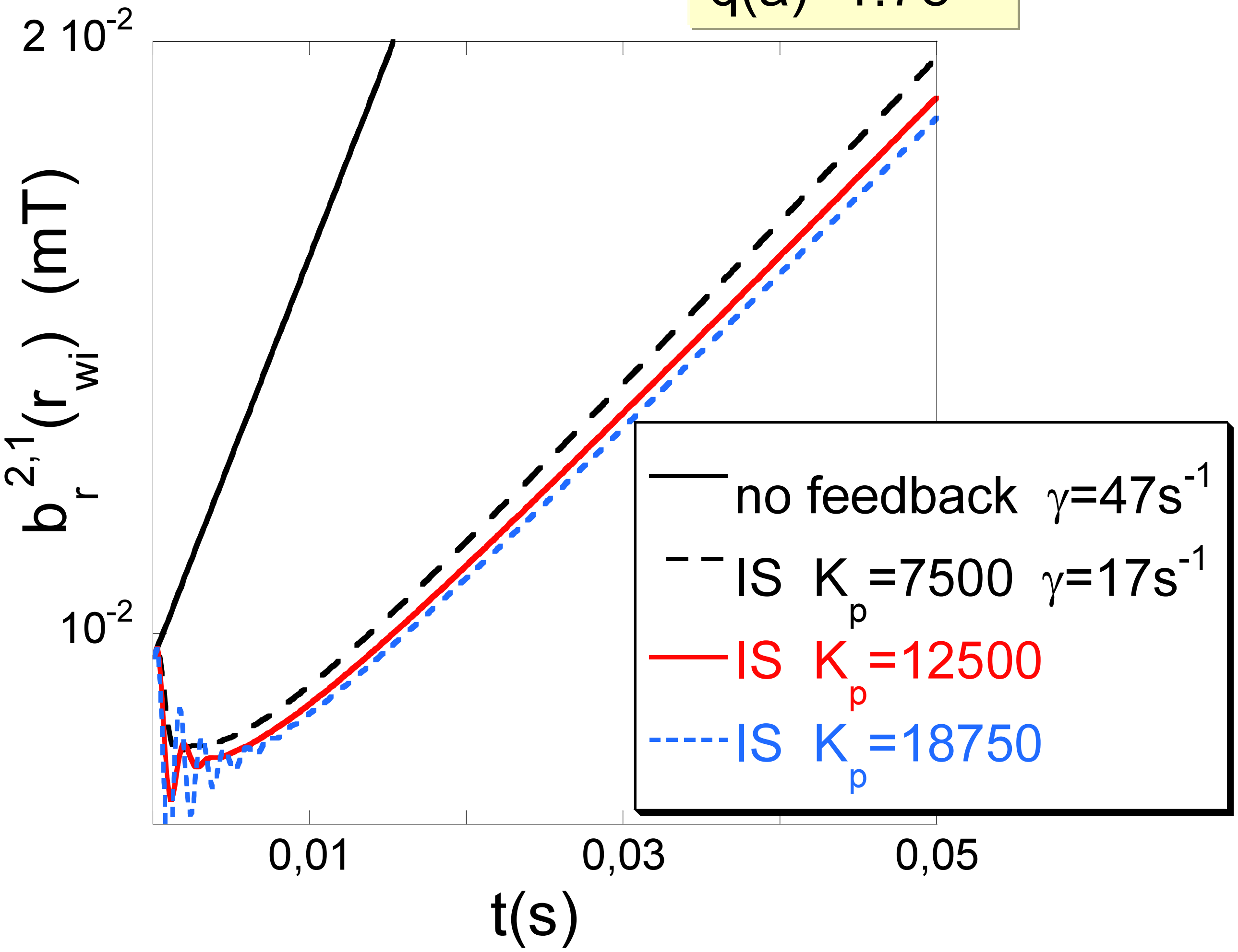
q(0)=0.82
q(a)=1.78



$b_f = b_{r,DFT}^{2,1}(r_{wi})$

$M_c=M_s=4$

$N_c=N_s=48$

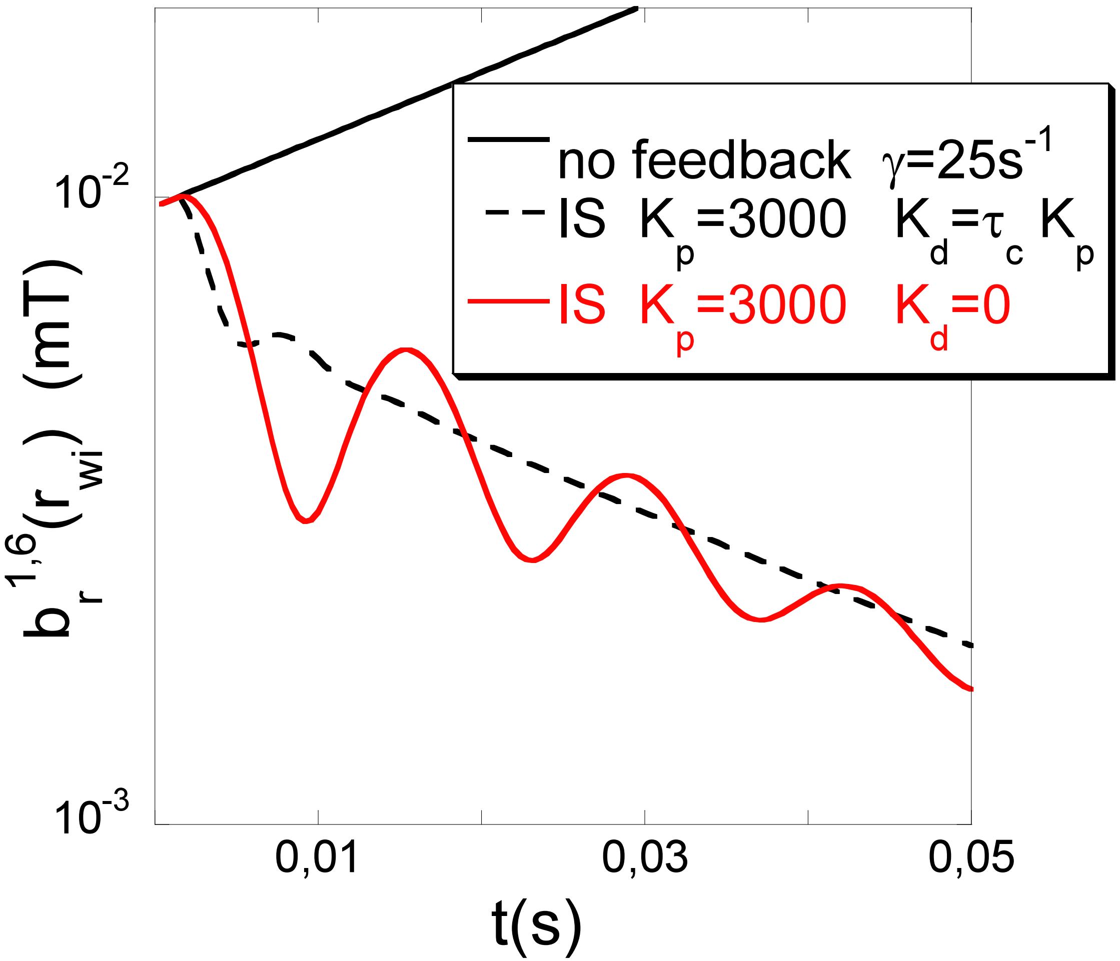
$\Delta\theta_c=\Delta\theta_s=2\pi/M_s$

$\Delta\phi_c=\Delta\phi_s=2\pi/N_s$

T_f=0.1ms, $\Delta t=T_f$

$K_d=\tau_c K_p$

Intelligent Shell: m=1 n=6 RWM



$b_f = b_{r,DFT}^{1,6}(r_{wi})$

$M_c = M_s = 4$

$N_c = N_s = 48$

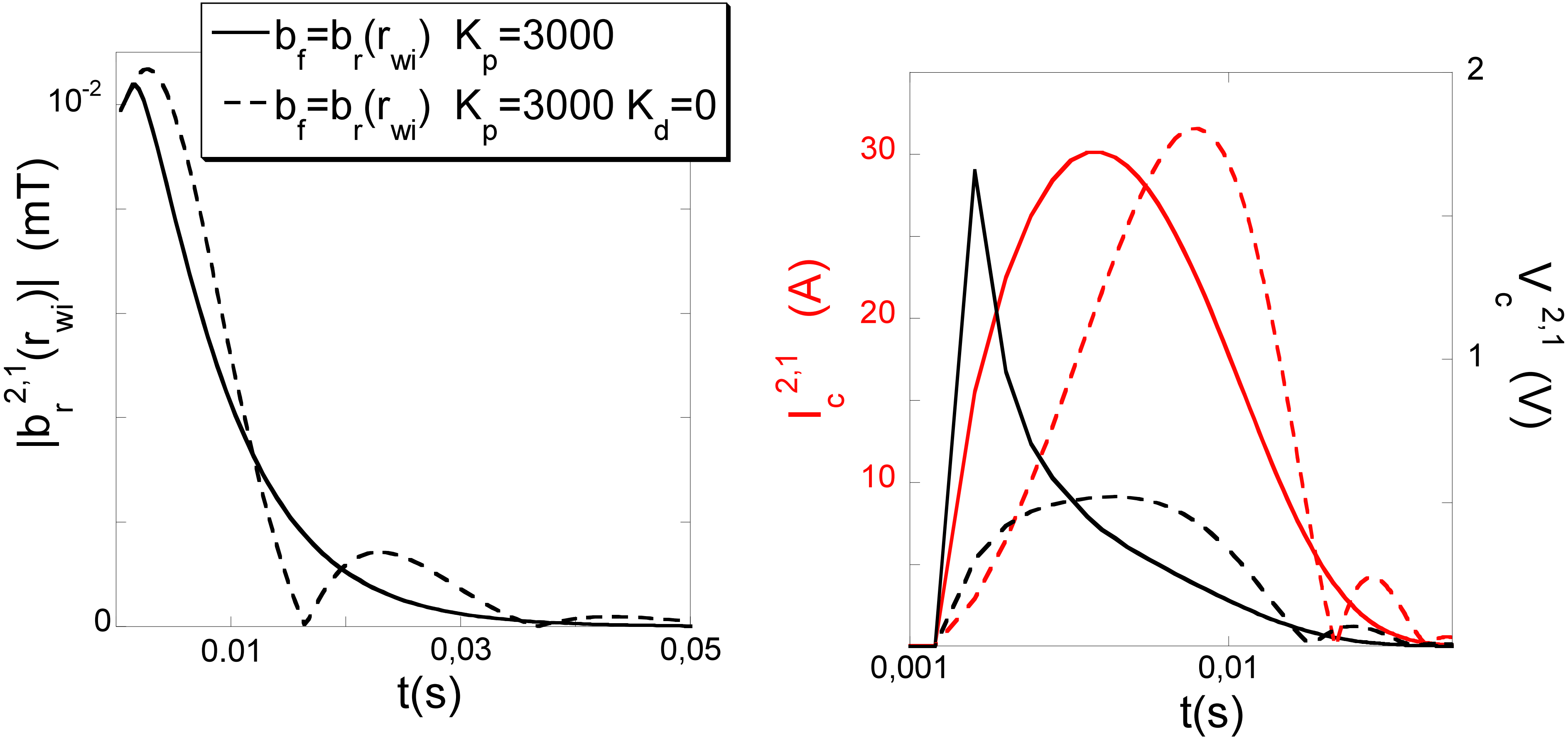
$\Delta\theta_c = \Delta\theta_s = 2\pi/M_s$

$\Delta\phi_c = \Delta\phi_s = 2\pi/N_s$

$T_f = 0.4\text{ms}, \quad \Delta t = 2T_f$

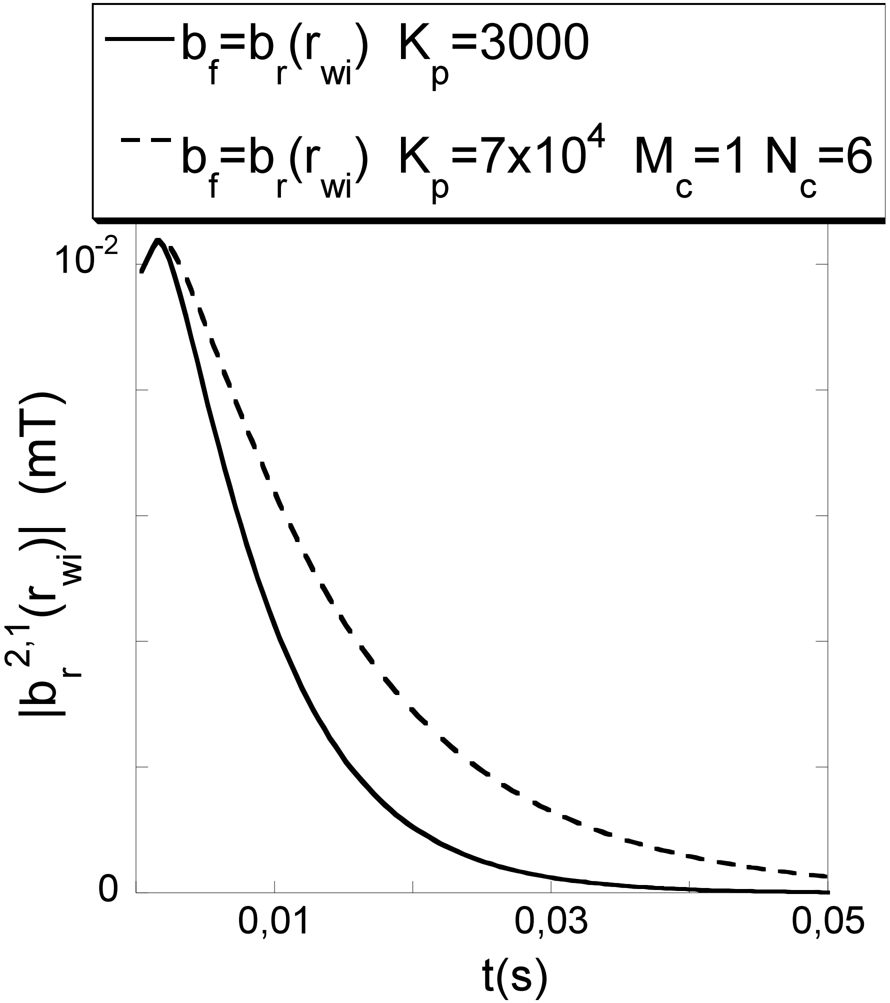
CMC simulations: RFX-mod case

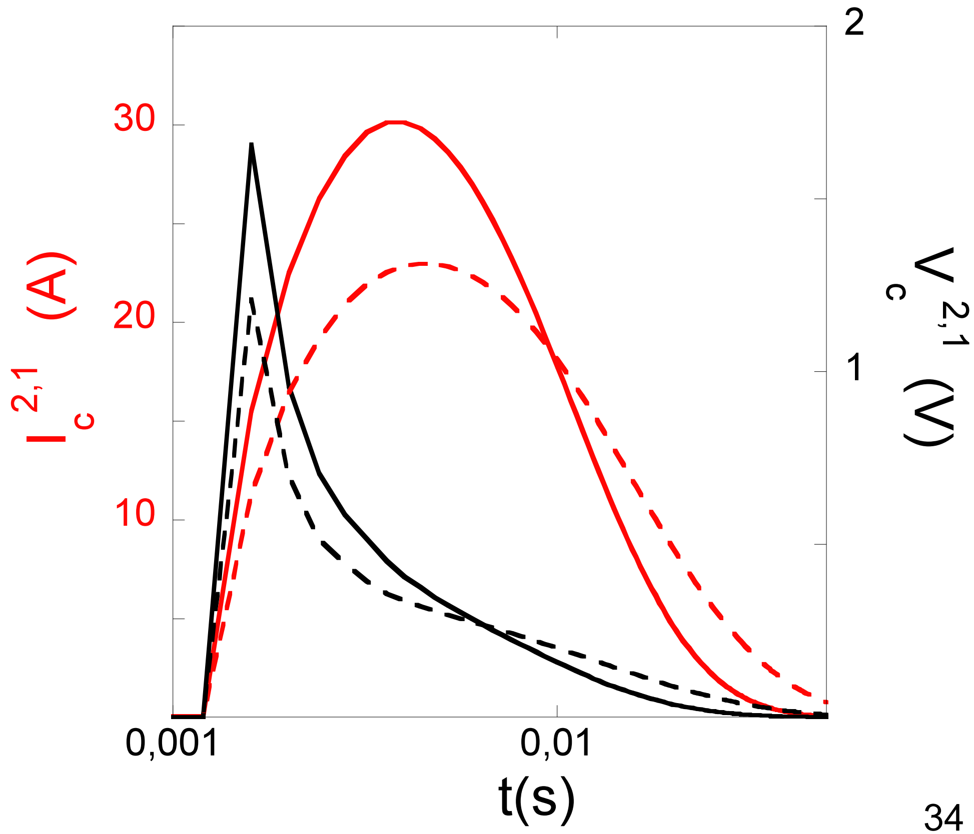
T_f=0.4ms, Δt=2T_f, K_d=τ_c K_p



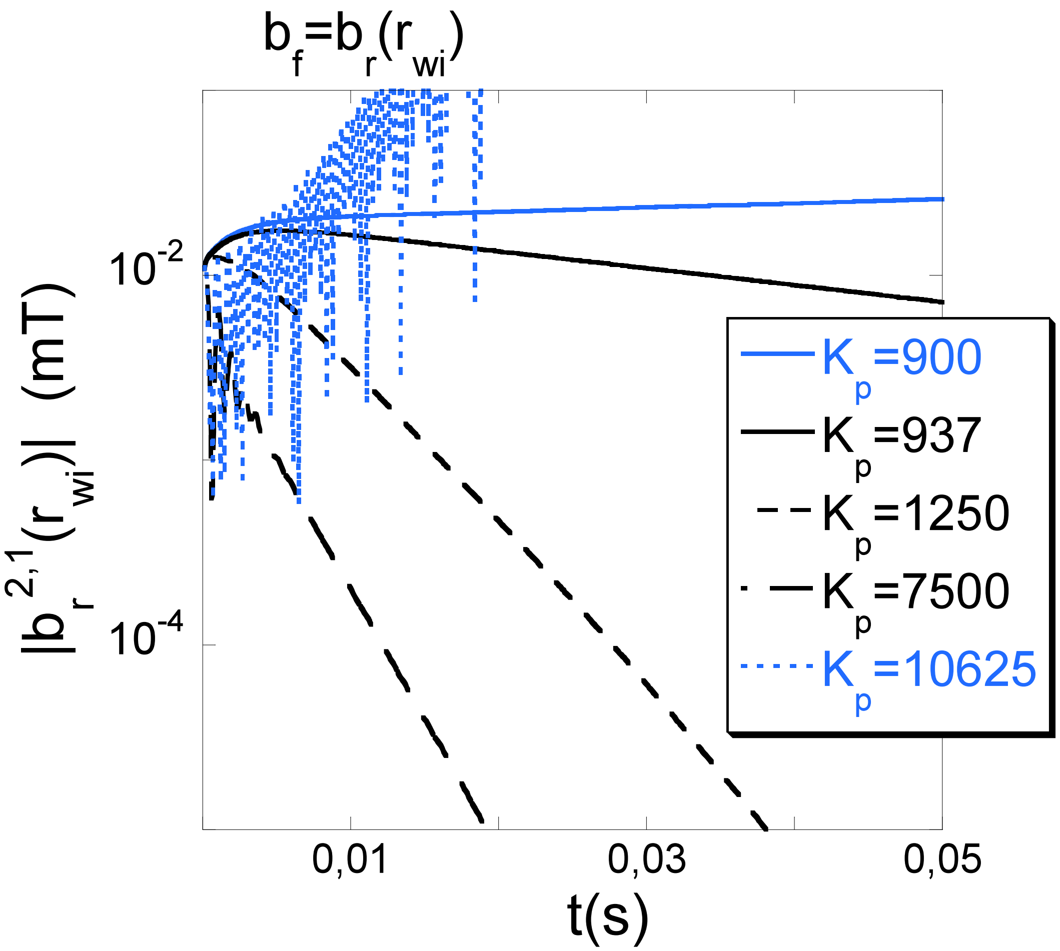
CMC simulations: RFX-mod case

Coils downgrade: M_c=1, N_c=6





CMC simulations: τ_w=3ms



RFX-mod upgrade:

T_f=0.1ms, $\Delta t=T_f$

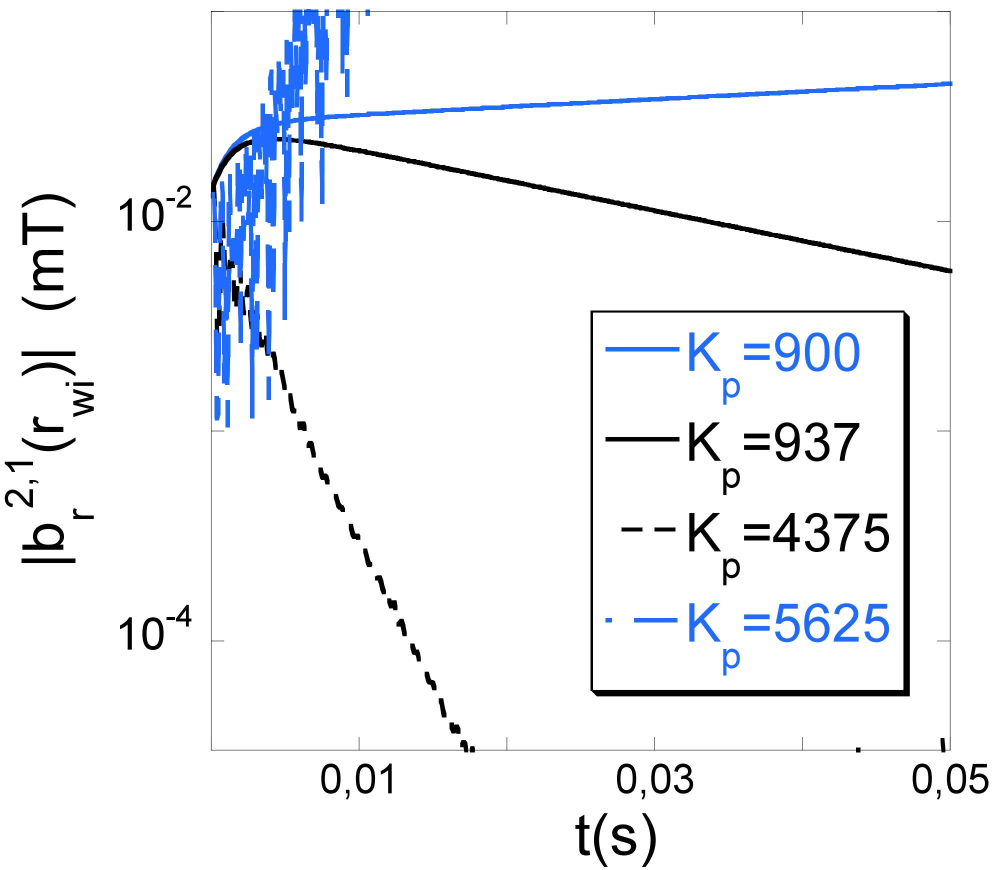
$K_d=\tau_c K_p$

$K_{p,max}/K_{p,min} \sim 8$

CMC simulations: τ_w=0

$\gamma \sim 47 s^{-1} \rightarrow \gamma \sim 672 s^{-1} \rightarrow$ $\gamma \sim 1300 s^{-1}$

$b_f = b_r(r_{wi})$



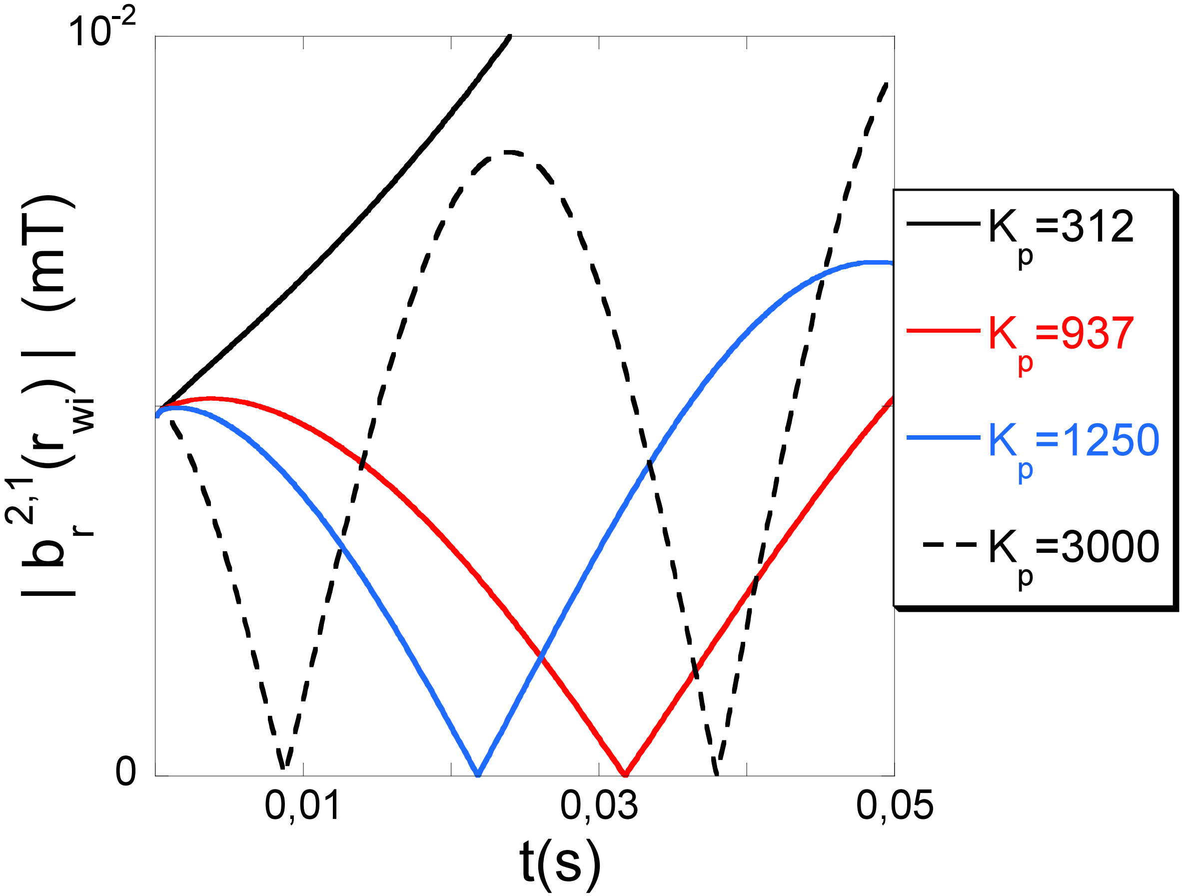
T_f=0.1ms, $\Delta t = T_f$

$K_d = \tau_c K_p$

$K_{p,max} / K_{p,min} \sim 4.7$

Explicit mode control τ_W=100ms

$$b_f = b_r^{2,1}(r_{wi}) - [b_r^{2,1}(r_{wi})]_{vac}$$



T_f=0.1ms, $\Delta t=T_f$

$K_d=\tau_c K_p$

Not stabilized

b_θ : 'Explicit Mode Control' vs raw control

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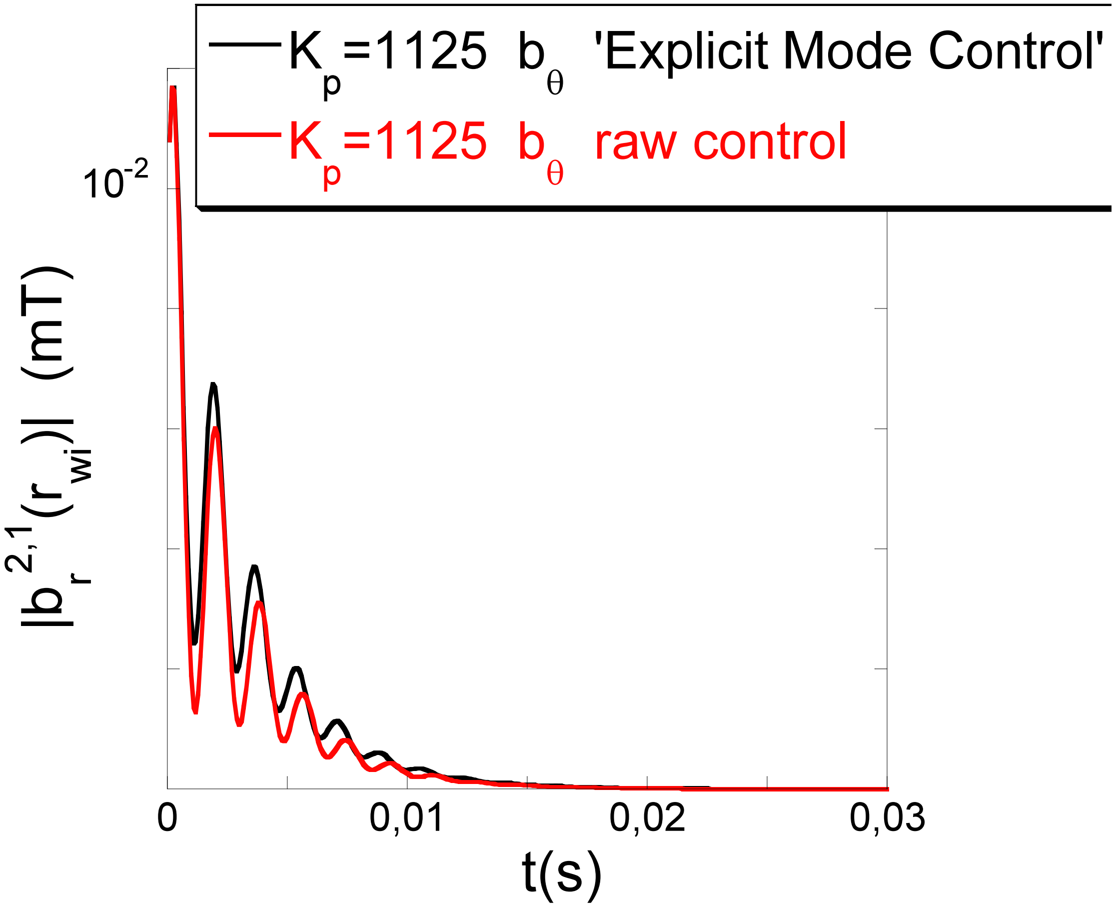

$M_c=M_s=4$

$N_c=N_s=48$

τ_w=3ms

T_f=0.1ms, $\Delta t=T_f$

$K_d=\tau_c K_p$