RWM control in RFX-mod

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On behalf of the RFX-mod team

Outline

- Introduction
- RWM physics in the Reversed Field Pinch configuration
- RFX-mod control system for MHD modes
- RWM characterisation and stabilisation experiments
- Future plans
- Conclusions

Introduction

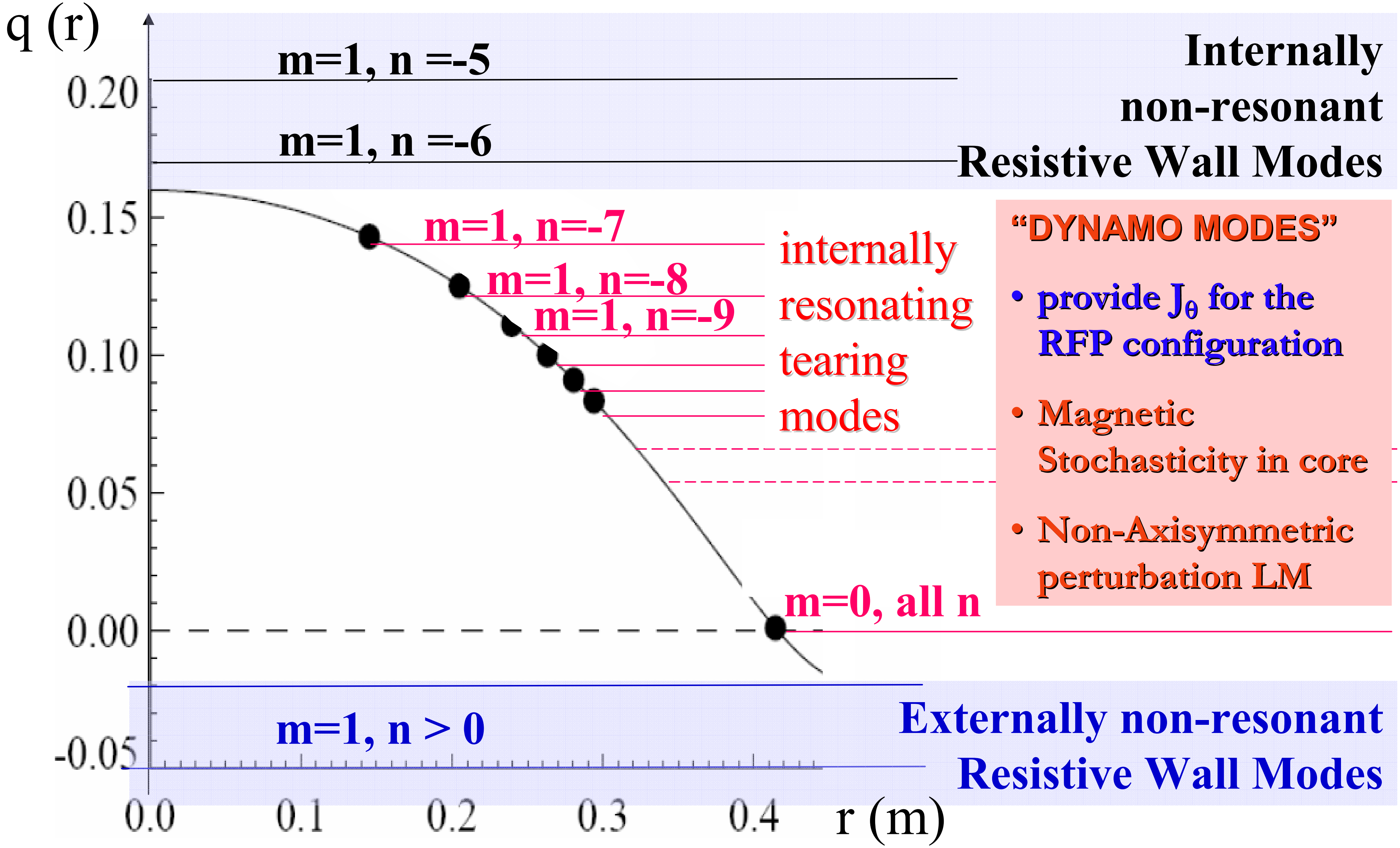
- Advanced tokamak operations at high beta and with a high fraction of bootstrap current need passive (plasma rotation) or active (feedback using active coils) control of Resistive Wall Mode (RWM) instabilities.

- Improved confinement regimes have been found for the Reversed Field Pinch configuration, in particular when active control of field errors and MHD instabilities is successful (B. Chapman, invited talk at APS-DPP06; L. Marrelli, this meeting)

- In RFP plasmas RWMs control is needed to extend the duration of these improved confinement regimes well beyond the diffusion time of passive walls (no need of a close fitting thick stabilising shell).

- The development and optimisation of flexible and reliable active feedback systems is important for both tokamak and RFP configurations.

Reversed Field Pinch Mode Classification



"DYNAMO MODES"

- provide J_θ for the RFP configuration
- Magnetic Stochasticity in core
- Non-Axisymmetric perturbation LM

RWM in RFPs

- RWMs in RFPs grow as current driven, non resonant instabilities.

- Plasma velocities needed for RWM stabilization in RFPs are of the order of the Alfvén velocity (viscosity dissipation and ions sound wave continuous spectrum damping are considered in figure).

- Active feedback control is then, when implemented, the only stabilizing mechanism of RWMs in RFPs.

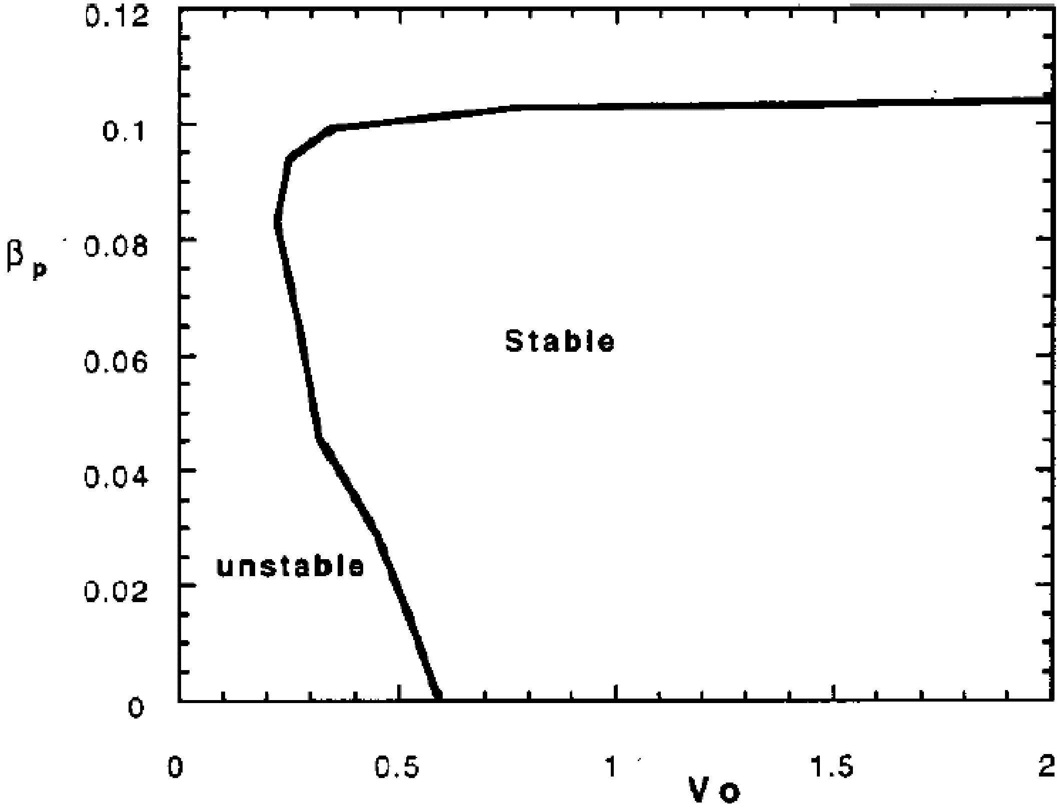


FIG. 15. The stability boundary for β_p vs. v_0 is shown for $\alpha = 6.0$, $\Theta_0 = 1.6$, $b/a = 1.4$, $k = 0.75$, and $\eta_0 = 0.2$.

S.C. Guo, J. P. Freidberg and R. Nachtrieb,"Stability of resistive wall modes in reversed field pinches with longitudinal flow and dissipative effects", PoP (1999)

RWMs in the RFP configuration

"Thin shell" modes were discovered in HBTX1C RFP (Culham, UK) already in 1989

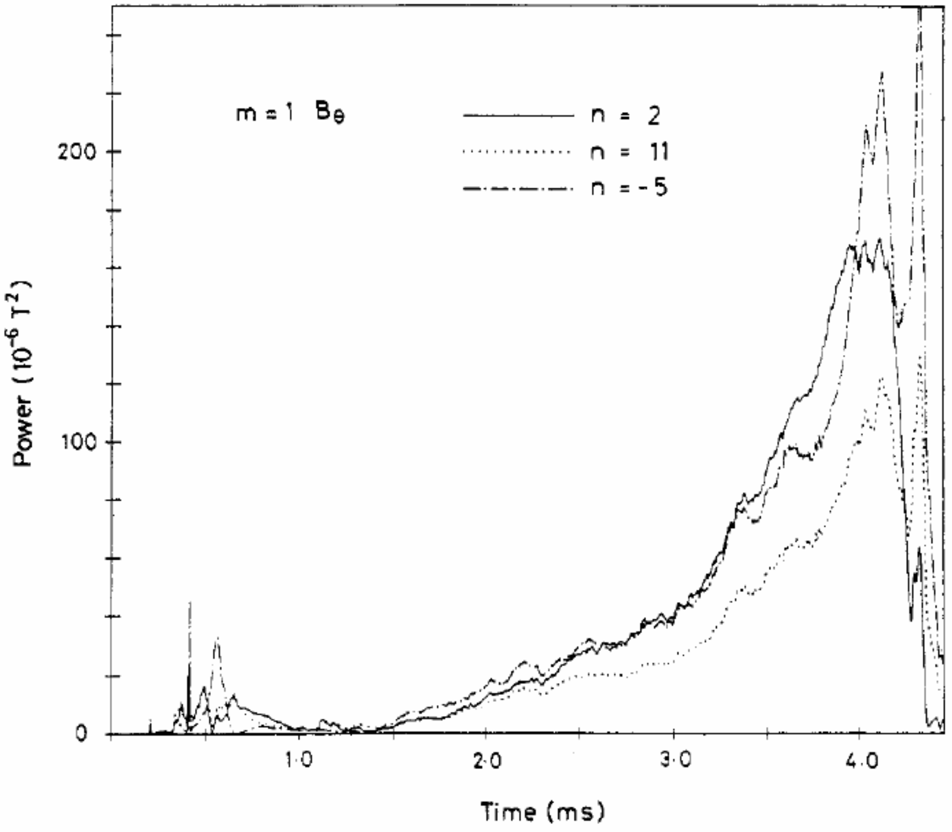


FIG. 6.—Power in the dominating n modes ($m = 1$, B_θ) as a function of time for the discharge illustrated in Fig. 5.

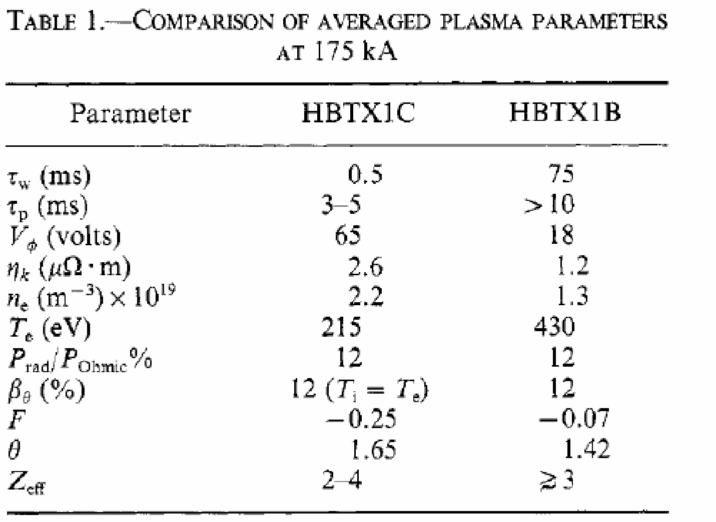
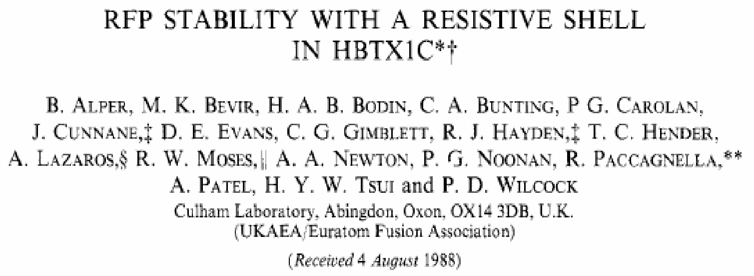


TABLE 1.—COMPARISON OF AVERAGED PLASMA PARAMETERS AT 175 kA

Parameter	HBTX1C	HBTX1B
τ_w (ms)	0.5	75
τ_p (ms)	3–5	>10
V_ϕ (volts)	65	18
η_k ($\mu\Omega\cdot$m)	2.6	1.2
n_e (m^{-3}) $\times 10^{19}$	2.2	1.3
T_e (eV)	215	430
P_{rad}/P_{Ohmic}%	12	12
β_θ (%)	12 ($T_i = T_e$)	12
F	-0.25	-0.07
θ	1.65	1.42
Z_{eff}	2–4	$\gtrsim 3$



RFP STABILITY WITH A RESISTIVE SHELL IN HBTX1C*†

B. ALPER, M. K. BEVIR, H. A. B. BODIN, C. A. BUNTING, P G. CAROLAN,
J. CUNNANE,‡ D. E. EVANS, C. G. GIMBLETT, R. J. HAYDEN,‡ T. C. HENDER,
A. LAZAROS,§ R. W. MOSES,|| A. A. NEWTON, P. G. NOONAN, R. PACCAGNELLA,**
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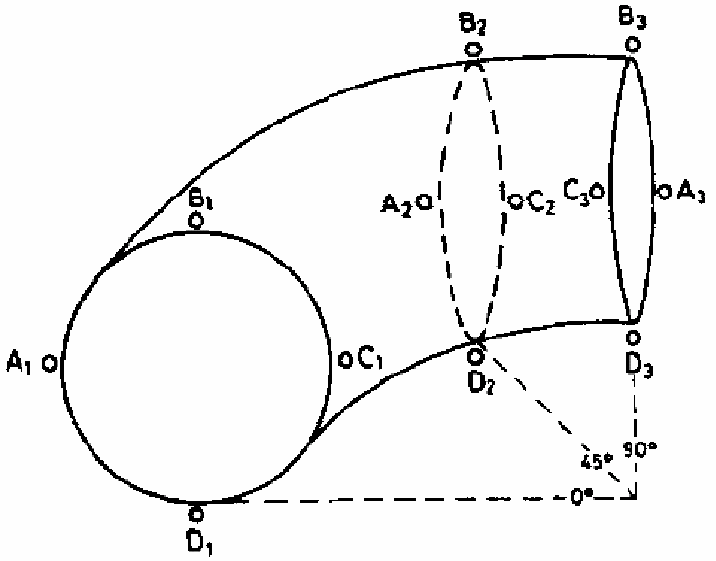
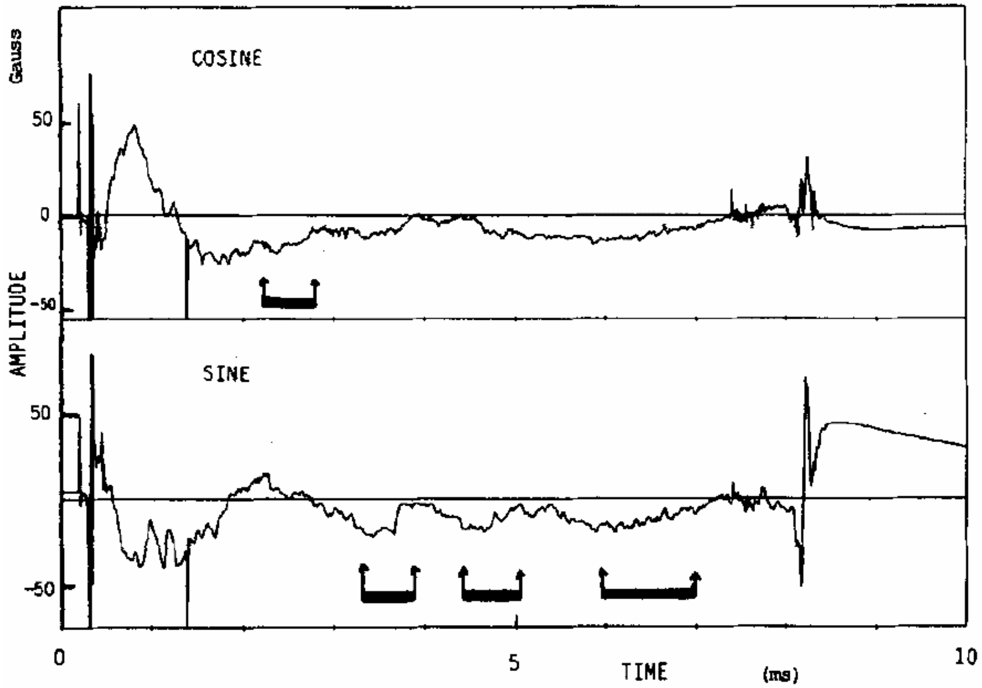
(*Received 4 August* 1988)

B. Alper et al.," RFP stability with a resistive shell in HBTX1C", PPCF 1989

RWM in RFPs: first control attempts



$$\text{Cosine}(1,2) = (A_1 - C_1)_0 + (B_2 - D_2)_{45} + (C_3 - A_3)_{90} + \cdots$$
$$\text{Sine}(1,2) = (B_1 - D_1)_0 + (C_2 - A_2)_{45} + (D_3 - B_3)_{90} + \cdots$$



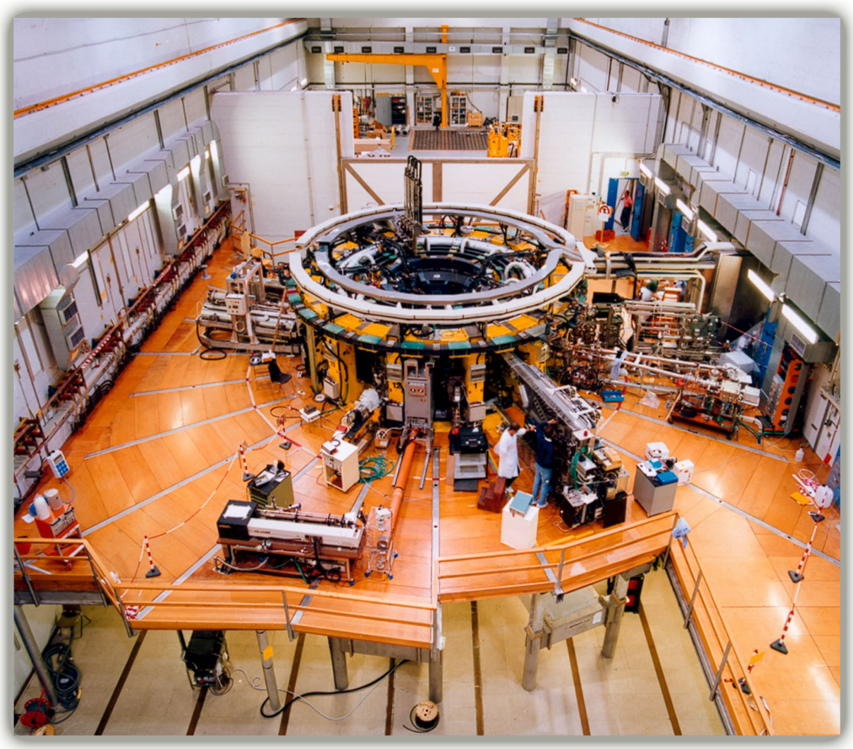
Detection system of the (m,n)=(1,2) external kink mode on HBTX 1c

Two helically wounded coils used to control the growth of the (1,2) mode

B. Alper et al.," A review of results from the HBTX reversed field pinch", PoF B (1990)

RFX-mod

The device



R=2m, a=0.459,
Ip> 1 MA (up to 2MA)

Passive structure:
$\tau_{Bv,shell}$= 50 ms, $\tau_{Bv,eff} \approx$ 62 ms

The mission:

Demonstrate the operation of the largest existing RFP

- in the MA regime
- without a thick shell
- with real-time control of:
  - Equilibrium
  - MHD modes (internal tearing and RWM)

First plasma: 20 December 2004

First active control operations: August 2005

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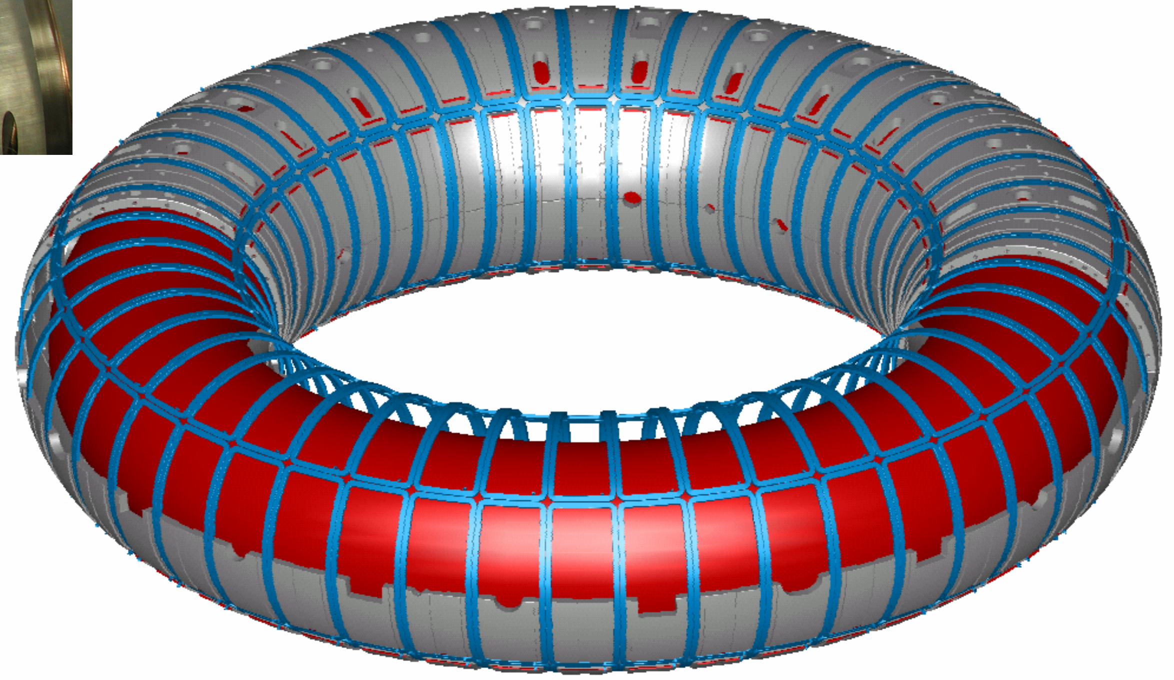
Full coverage with active coils

Total of 192 active coils.

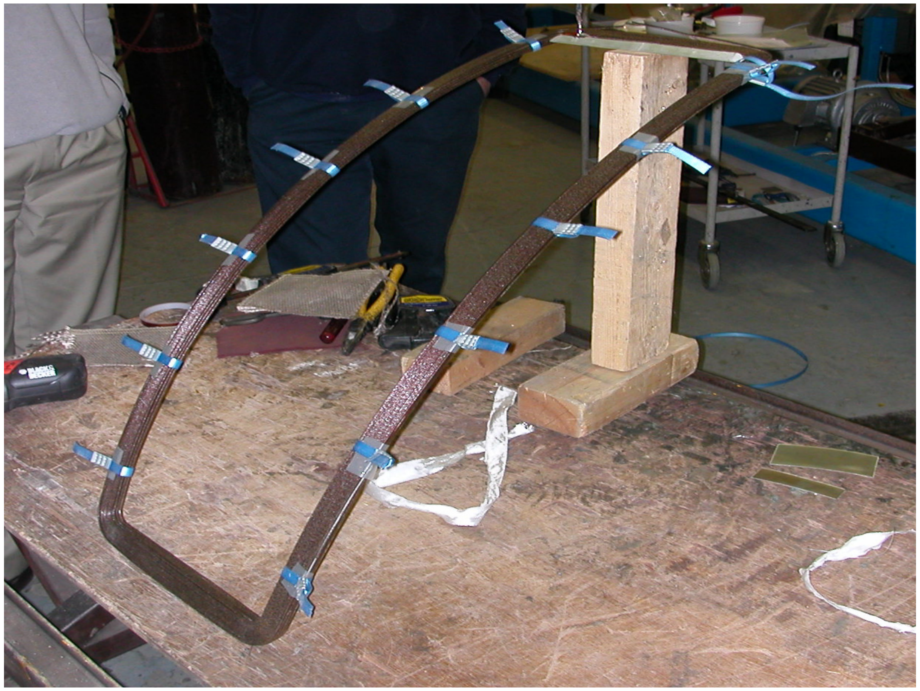
100% coverage of the mechanical structure external surface.

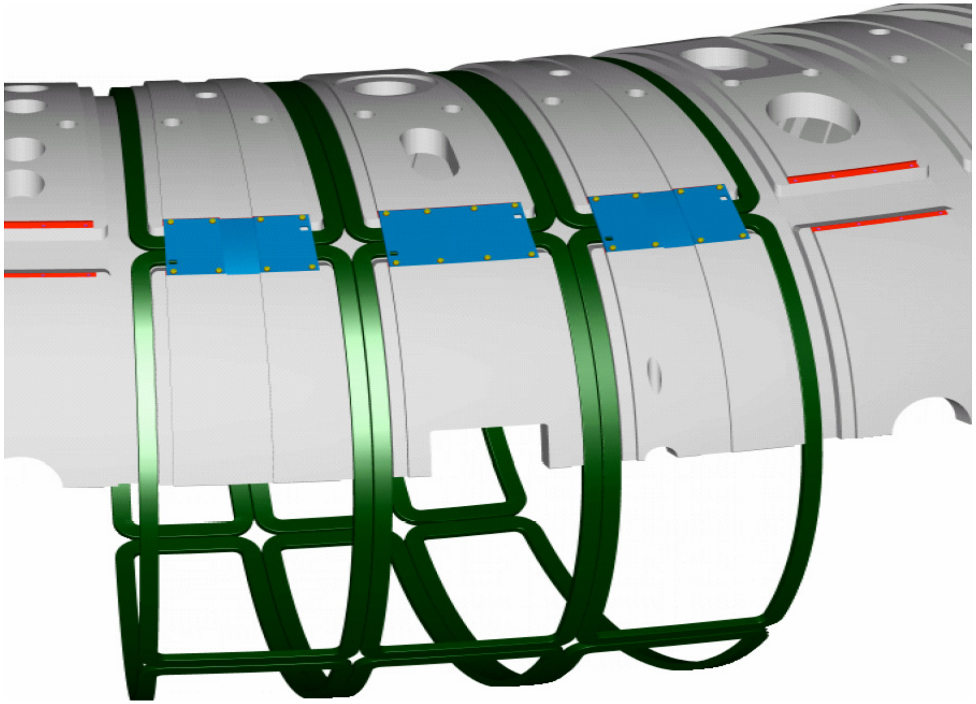
Each saddle coil is fed with its own power supply.



Radial field at 24 kAt	* (mT)*
DC	*50*
@10Hz	*35*
@50Hz	*12*
@100Hz (I=16 kAt)	*3.5*

The new RFX-mod active coil system





Turns	60 (4 layers x 15 turns)
Section	3.6 mm^2
I_{nom}	400 A (0.3s)
V_{nom}	650 V
Material	Copper
Insulation	grade 2 Dacron glass tape, epoxy pre-impregnated, final vacuum impregnation with epoxy resin

One poloidal array

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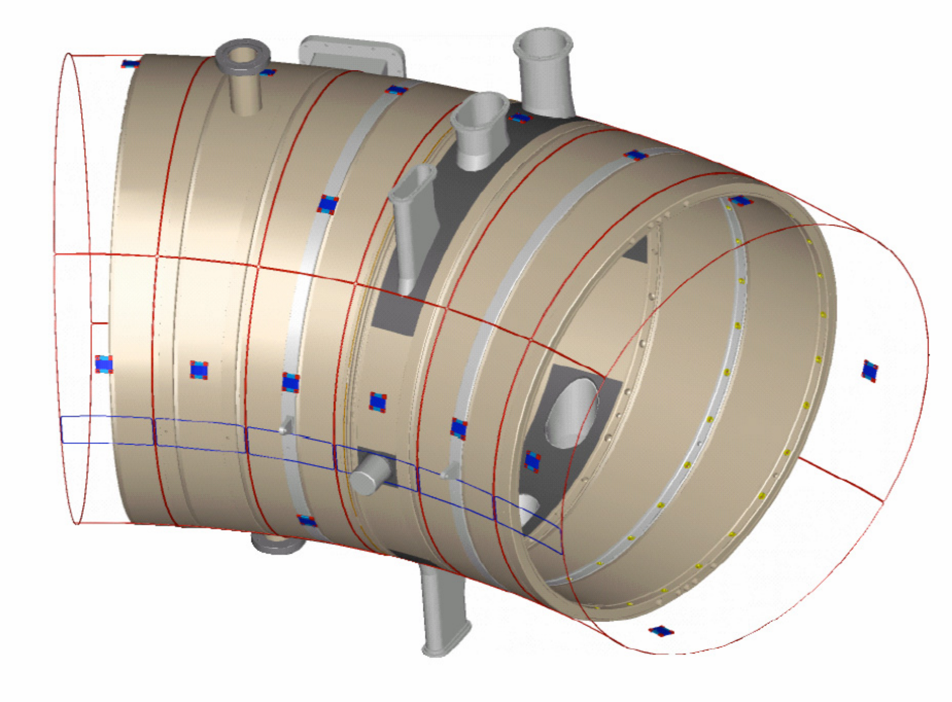
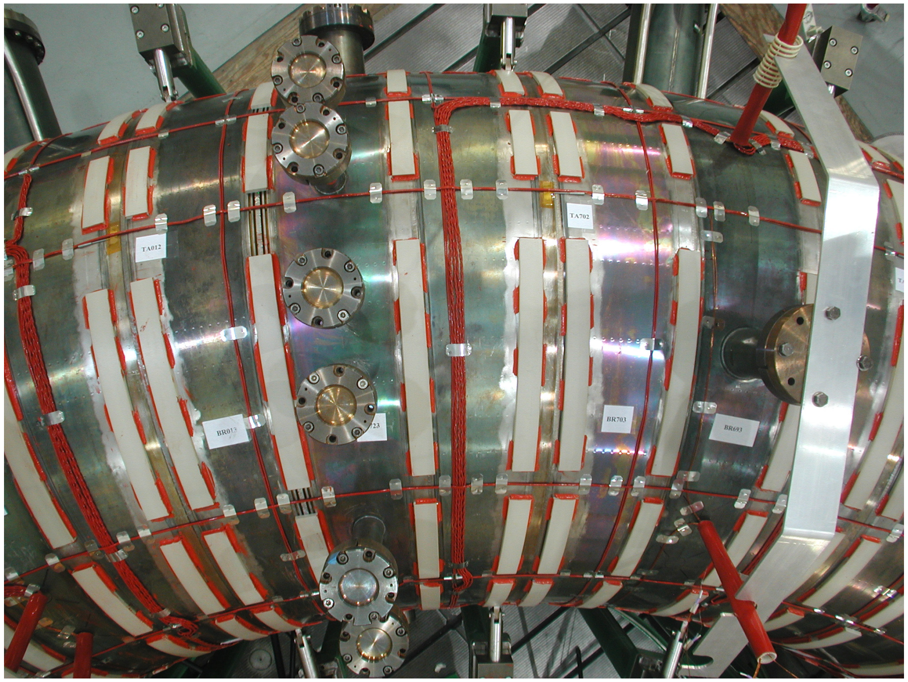
MHD diagnostics: external probes

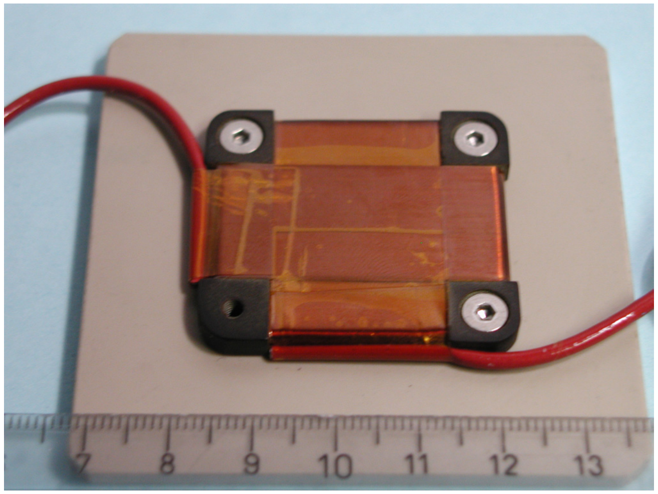




48 x 4 = 192 Br saddle probes
48 x 4 = 192 Bt and Bp pick up probes

+ other probes for toroidal and poloidal Vloop, plasma current, halo current measurements

TOTAL ≈ 650 probes



MHD control software

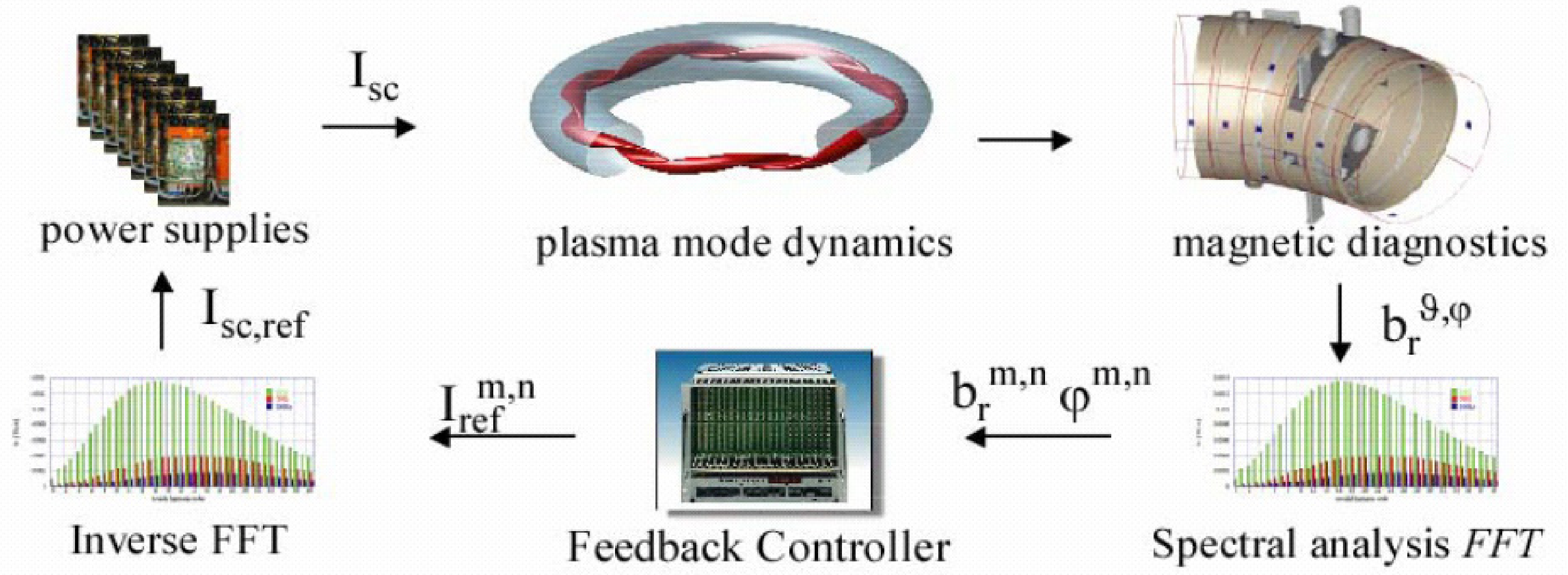


Fig. 6 Mode Control System scheme

Cavinato et al., SOFE 2005

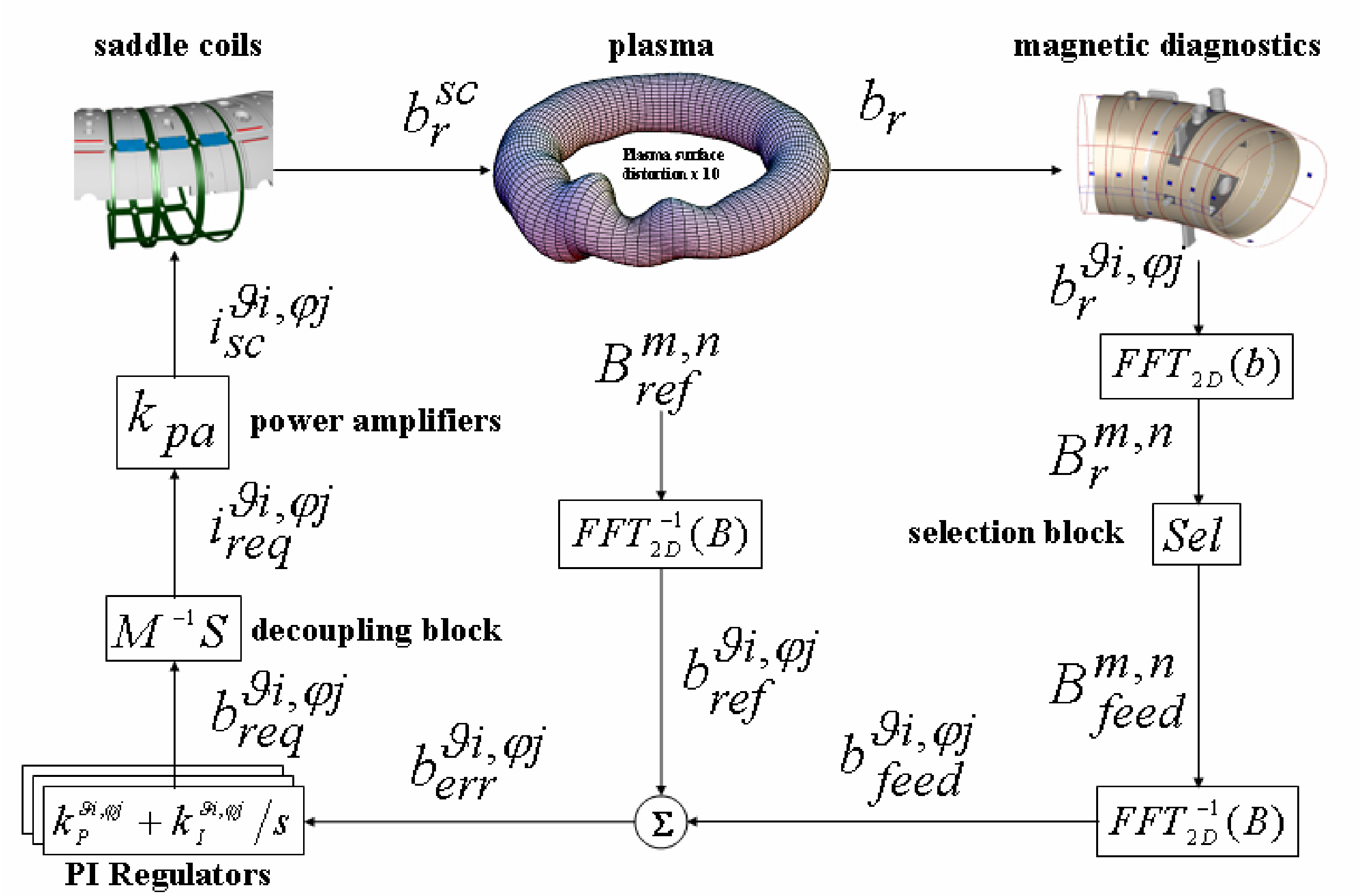
Control software:

Real time FFT and inverse FFT of 192 Br measurements
Max latency time: 330 μs
m modes: 0, 1, -1, 2 (partial)
n modes: 0-23

Different MHD control scenarios can be implemented:

- Intelligent shell (local radial field compensation)
- Selective Virtual Shell (cancels all harmonics but some, e.g. m=1, n=0 equilibrium field)
- Virtual Shell + rotating perturbations (phase and amplitude of selected harmonics set to follow given waveforms)
- Mode Control (regulators applied to modes rather than to single coils)

MHD control scenarios: Virtual Shell



- ***Virtual Shell (VS)***: active cancellation of radial magnetic field due to plasma instabilities and machine field errors, at radius of field sensors: analogy with passive cancellation by ideal superconducting shell [*see C.M. Bishop, Plasma Phys. Controlled Fusion, 31, 1179 (1989)*]
- ***Selective Virtual Shell (SVS):*** control system can act on modes selectively

A. Luchetta et al., IAEA conference, Chengdu (2006)

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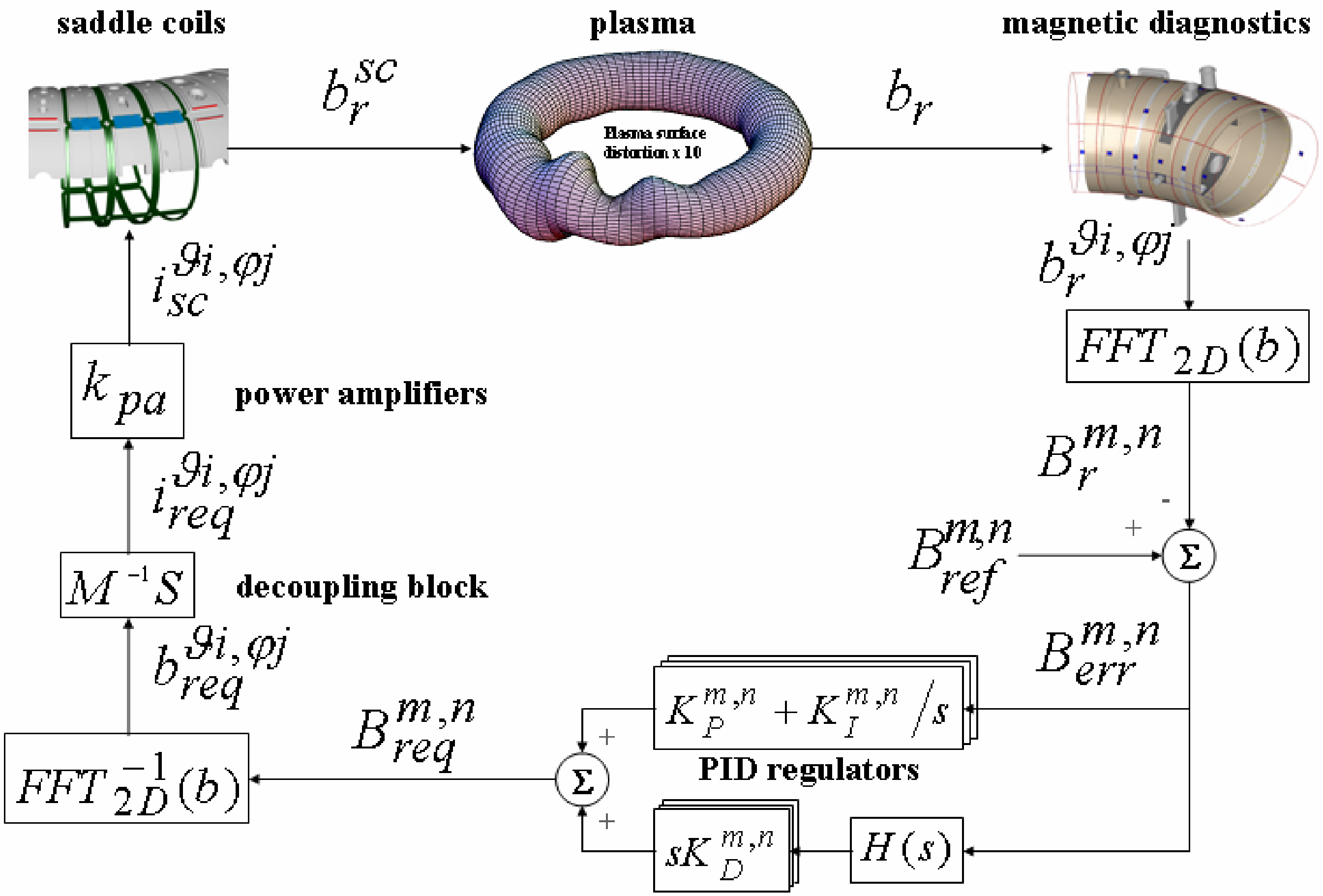
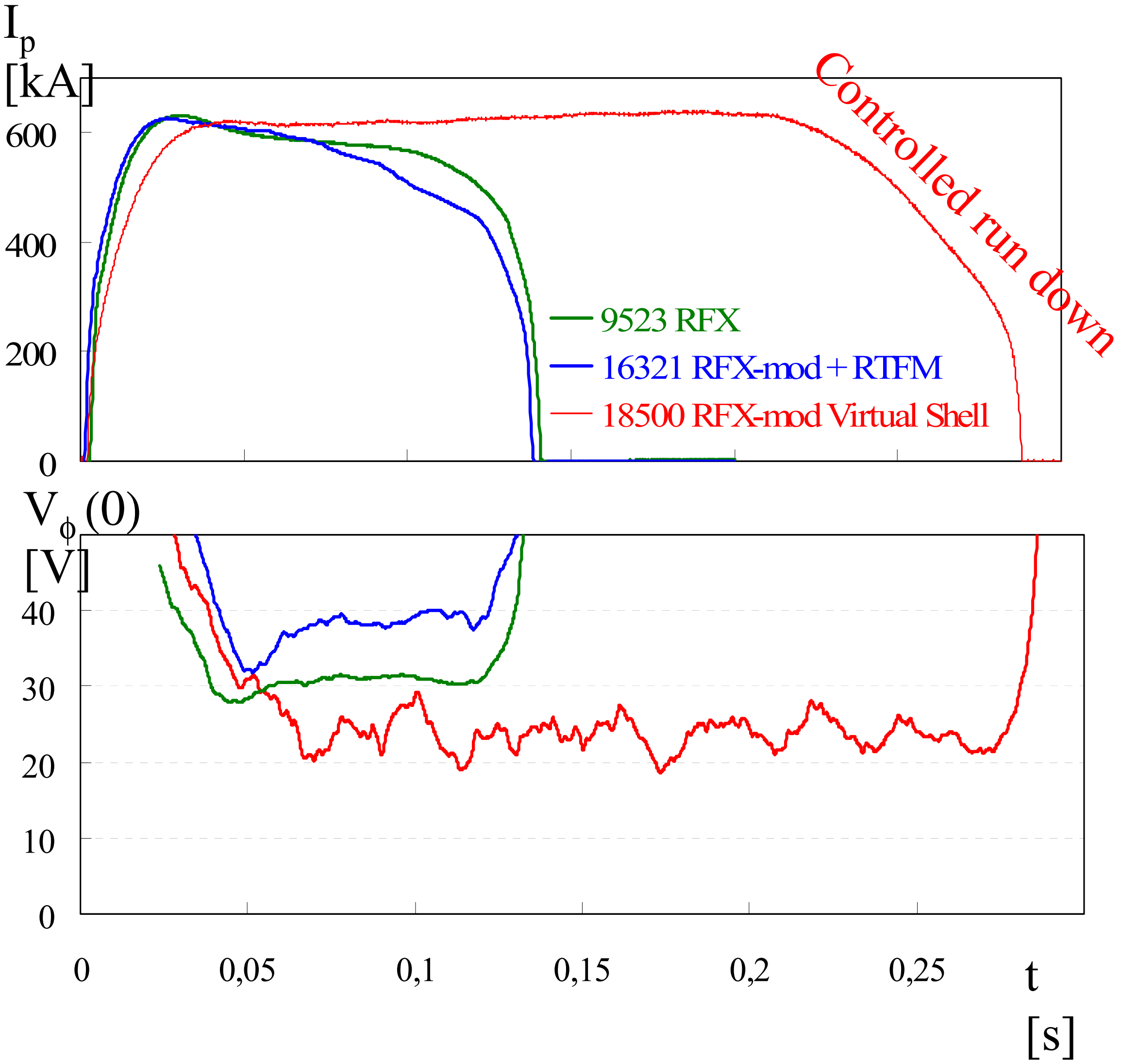
MHD control scenarios: Mode Control



- ***Mode Control (MC)***: controls single modes or groups of modes (from 1 to all)
  each mode is assigned its own regulator.
  derivative control to compensate for radial field penetration delay due to the passive structures (delay depends on mode number)
  1-pole Butterworth filter to smooth the derivative action.

A. Luchetta et al., IAEA conference, Chengdu (2006)

MHD control results



Benchmark pulses at 0.6 MA:

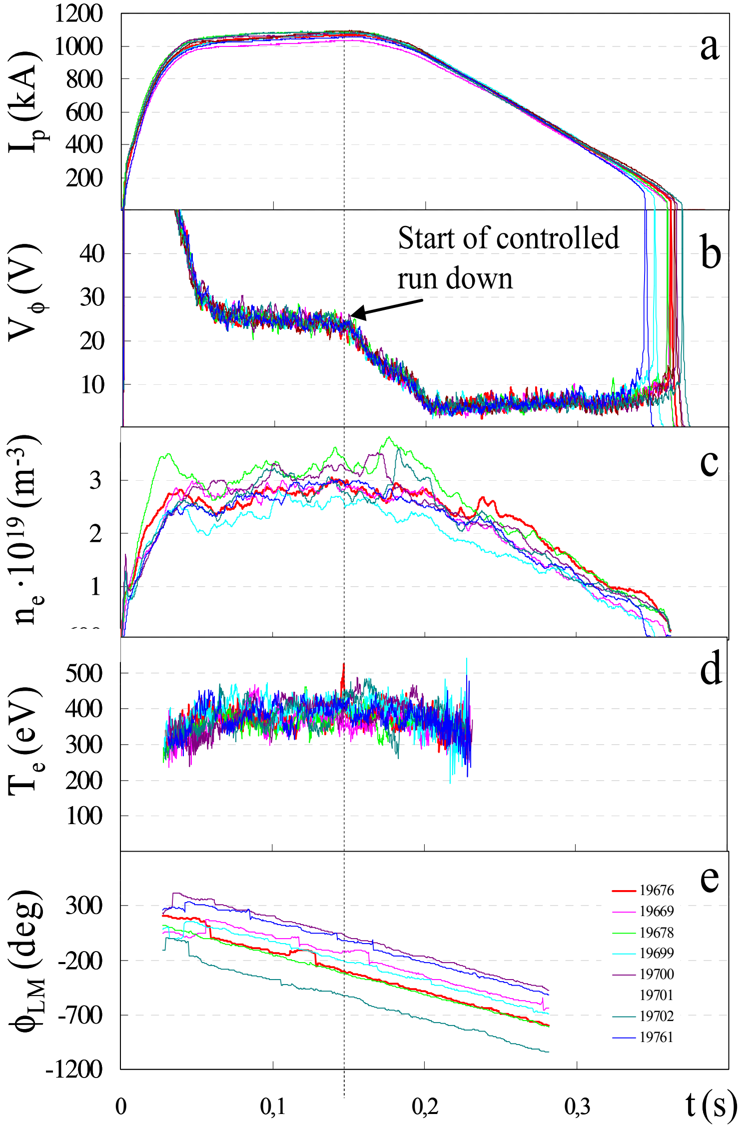
- RFX
- RFX-mod "passive" shell
- RFX-mod Virtual Shell

Main results

- ✓ pulse length = 0.37s (x 3 RFX, x 7 τ_{Bv})
- ✓ -25% V_{loop}
- ✓ + 30% T_e, T_i
- ✓ > 2 × τ_E

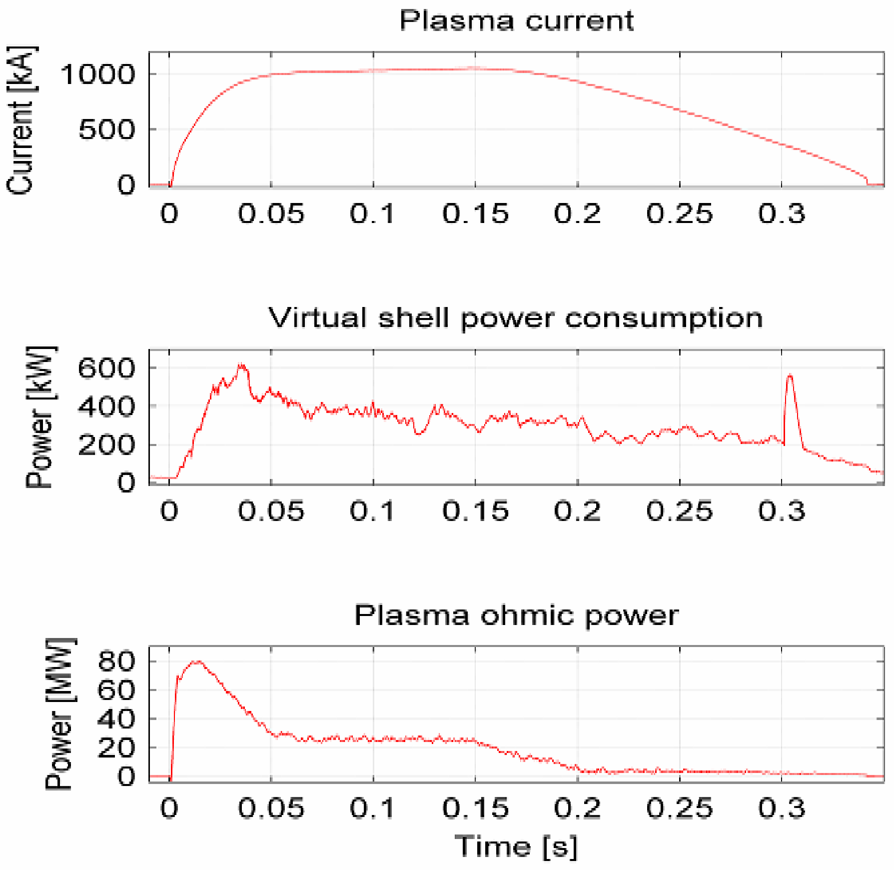
S. Martini et al., IAEA conference, Chengdu (2006)

MHD control results



Long and reproducible 1MA pulses

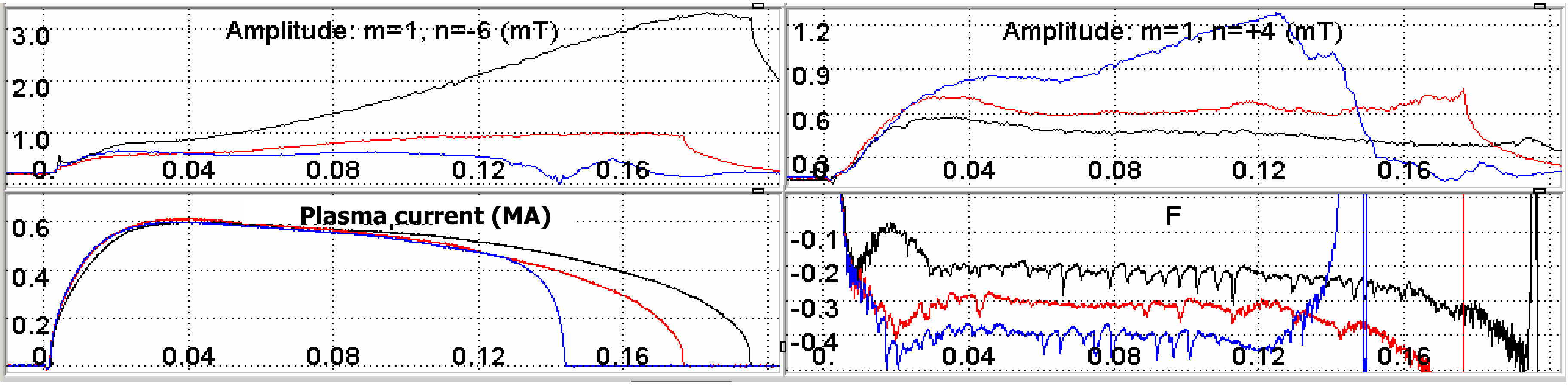
Good control of plasma-wall interaction by external rotation of dynamo modes (alleviation of phase- and wall-locking)



S. Martini et al., IAEA conference, Chengdu (2006)

A. Luchetta et al., IAEA conference, Chengdu (2006)

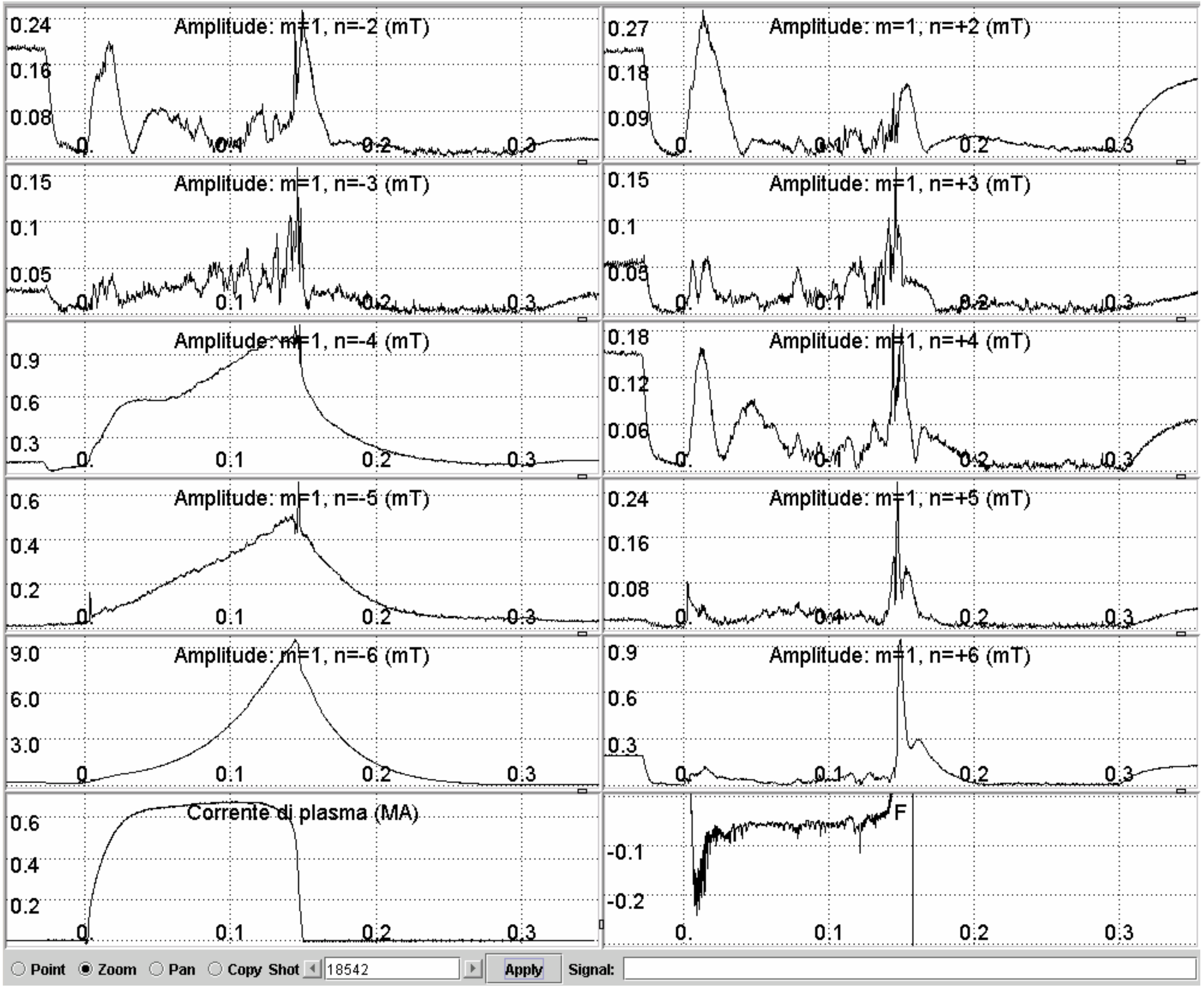
RWM identification



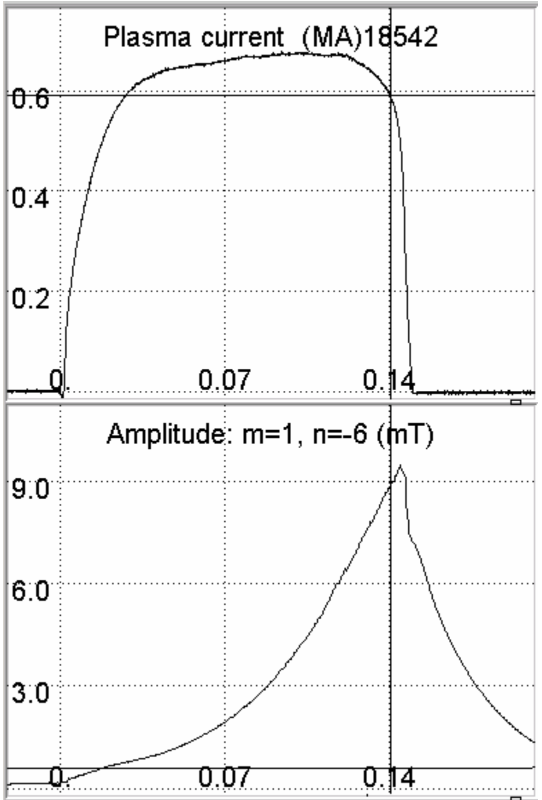
By changing the amplitude of the (reversed) toroidal field at the edge the spectrum of unstable RWM can be changed (F=Bt(a)/<Bt>):

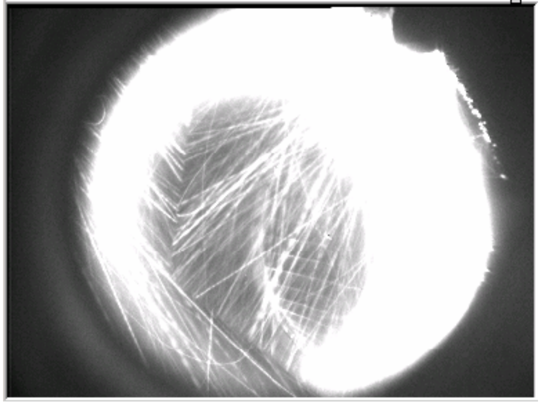
- Selective Virtual Shell: free growth of m=0,1,2 |n|=2,3,4,5,6.
- Multi-mode RWM spectrum is typical of RFP configuration
- Different growth rates can be measured and compared with theory.

RWM characterisation: F=-0.07



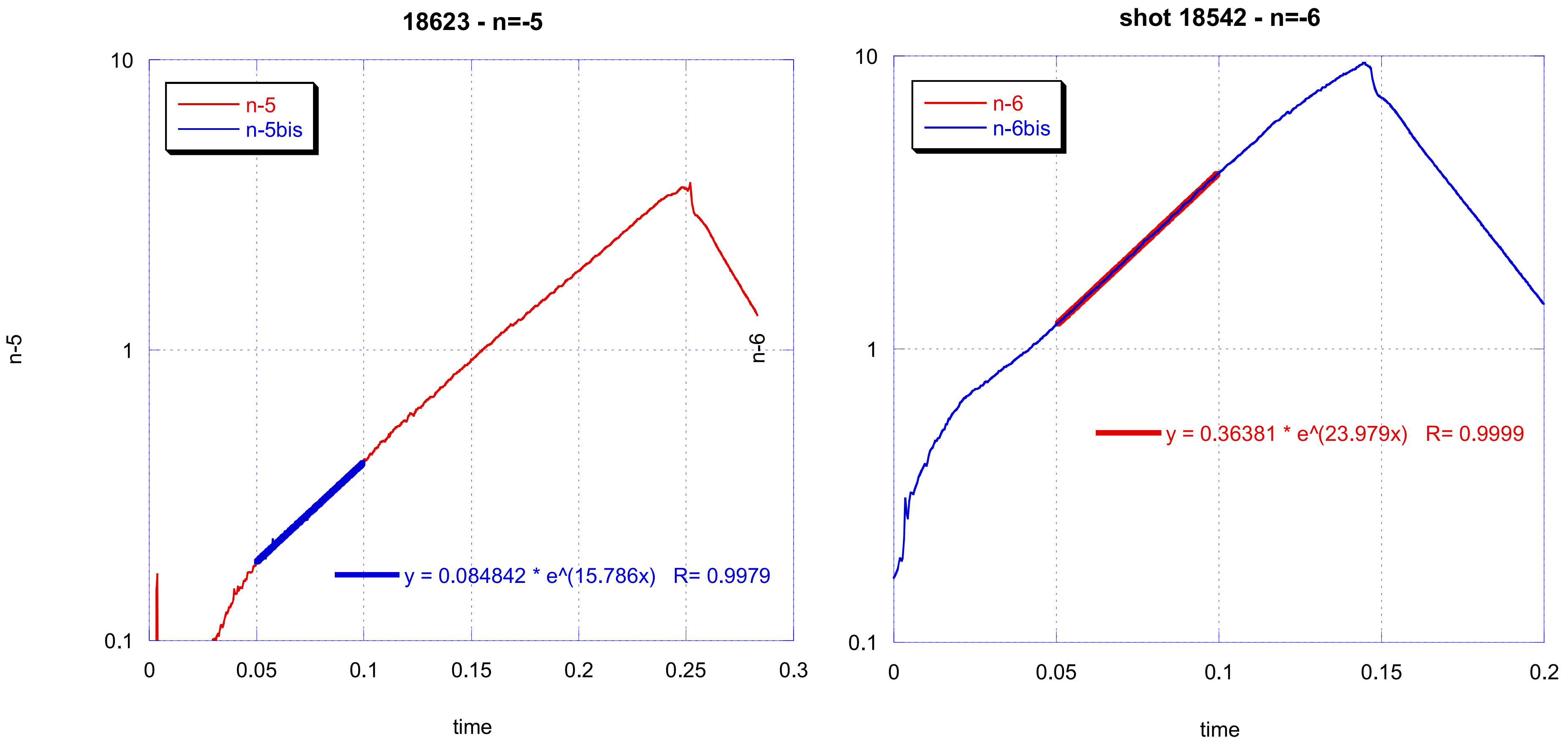
○ Point ● Zoom ○ Pan ○ Copy Shot 18542 Apply Signal:





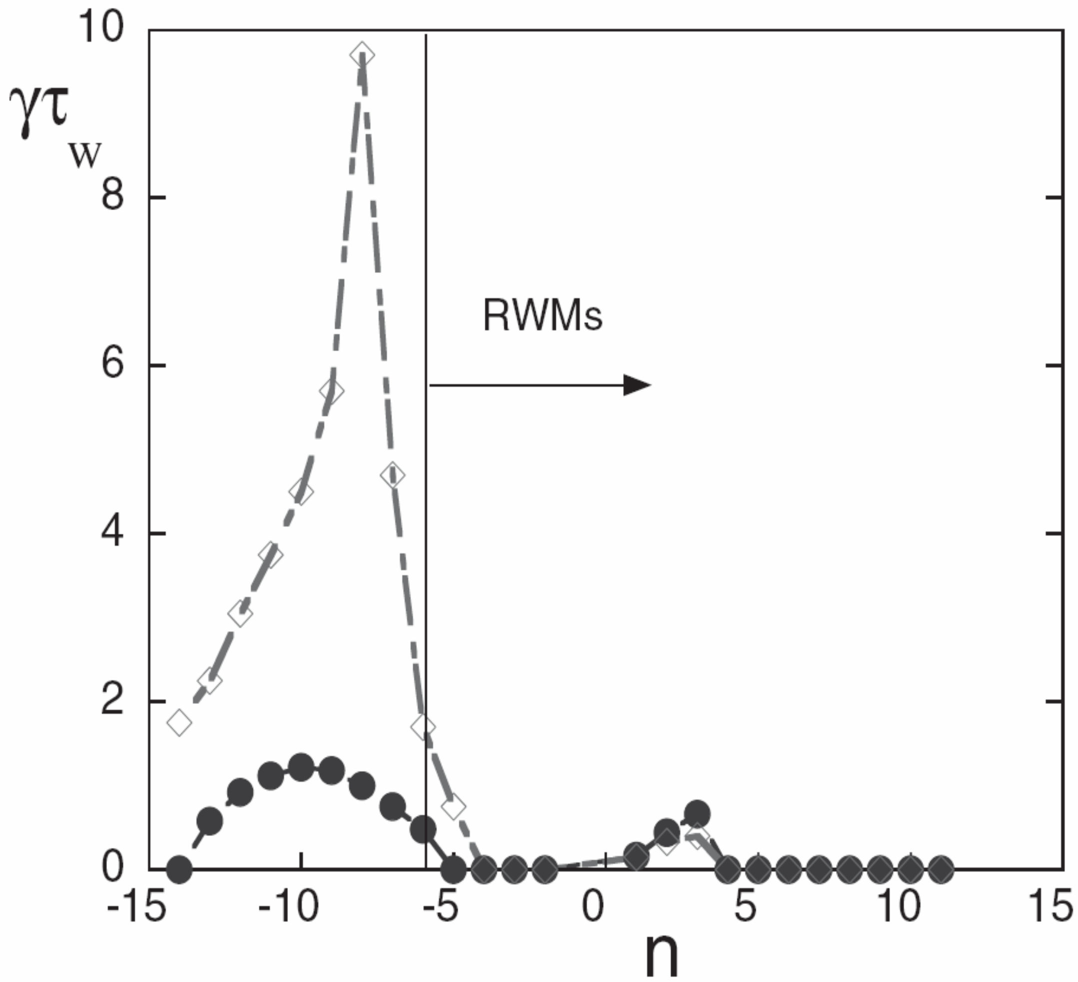
Free growth of m=1, n=-4,-5,-6

RWM characterisation



RWM experimental growth rates: (m=1, n=-5) and (m=1, n=-6); F=-0.07

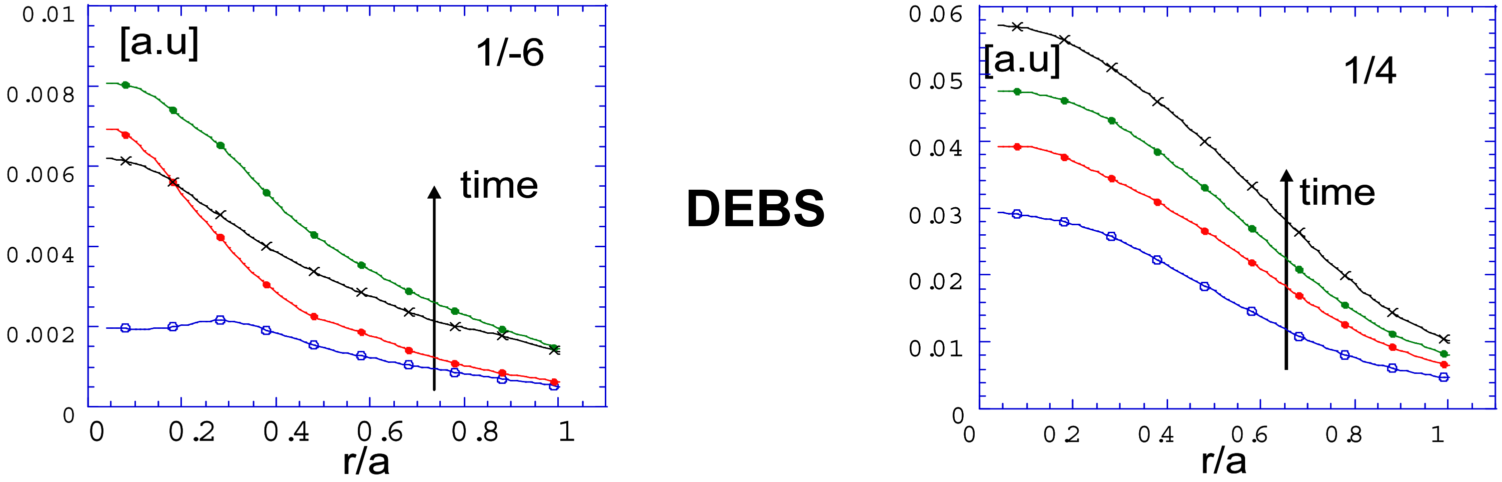
RWM numerical modelling



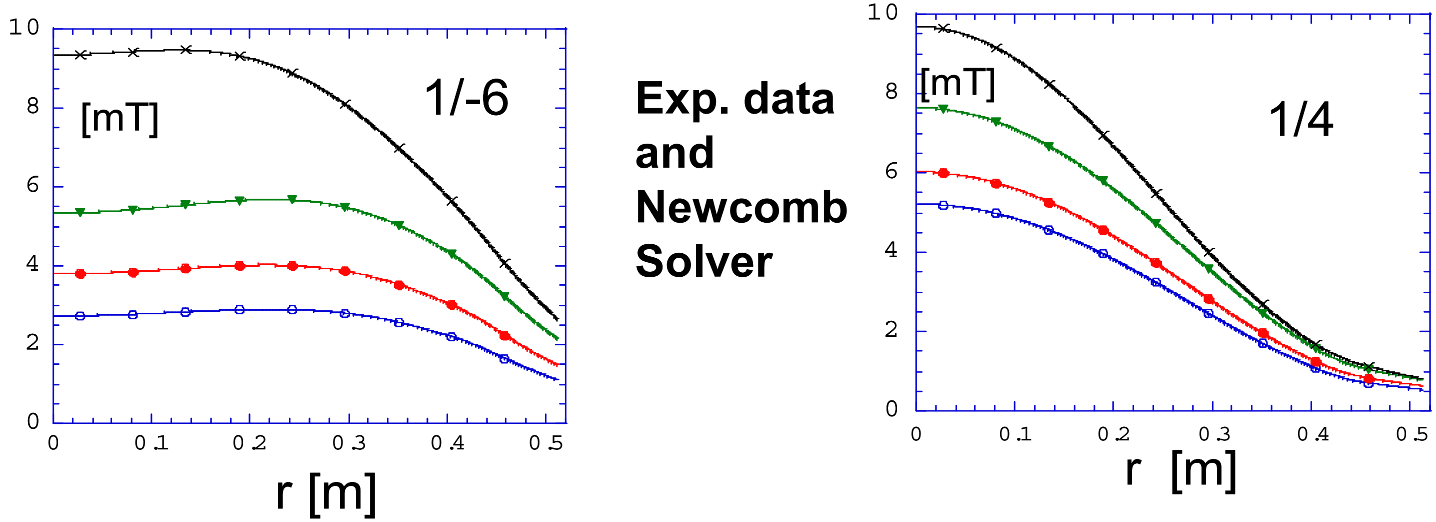
Linear m=1 growth rates normalized to the wall time vs n for two different RFP equilibria (2-D stability calculation).

R. Paccagnella et al., PRL (2006)

Experiment vs. numerical modelling



DEBS

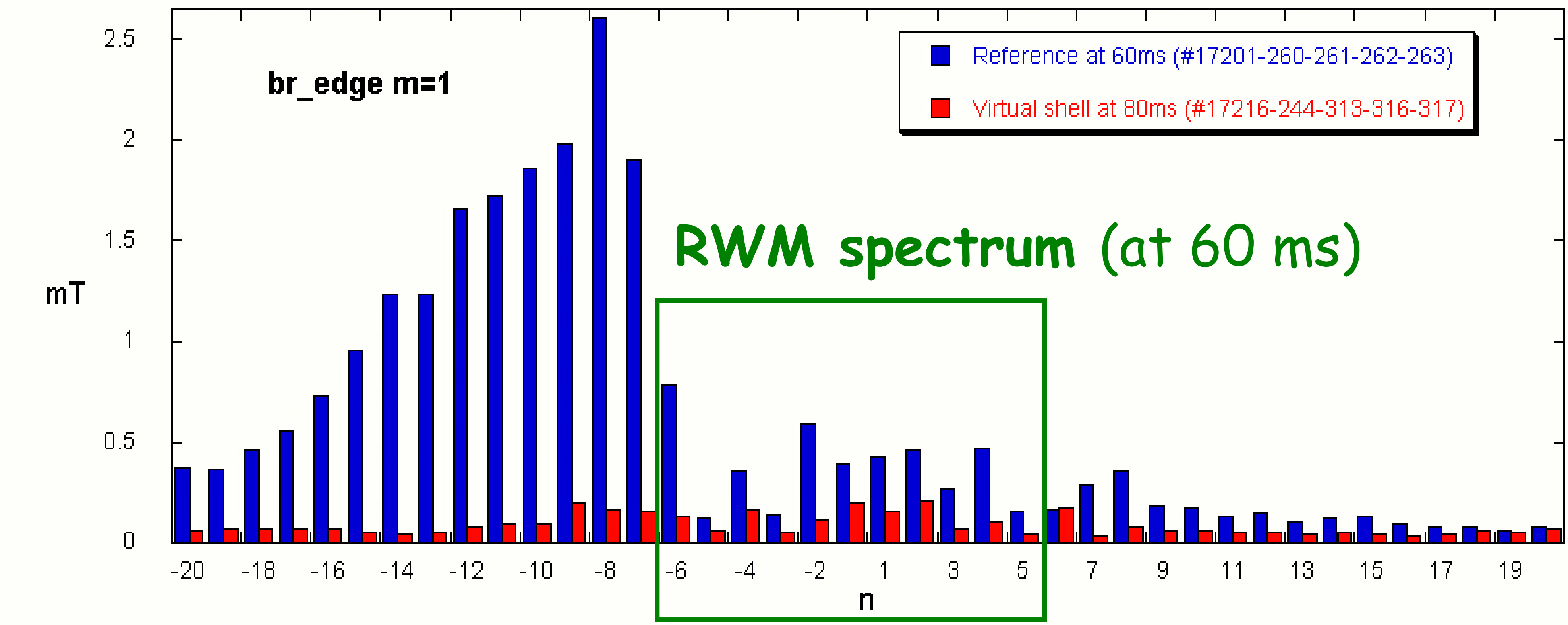


Exp. data and Newcomb Solver

Radial magnetic field profile in time (simulation top and experimental data + Newcomb solver (#17278) bottom)

R. Paccagnella et al., IAEA conference, Chengdu (2006)

RWM stabilization experiments



P. Zanca

Comparison between the m=1 toroidal mode spectrum with (red) and without (blue) active control (virtual shell scenario) for the radial component of magnetic field at the edge.
Maximum (internal) Br amplitude reduced as well of a factor 2 to 5.

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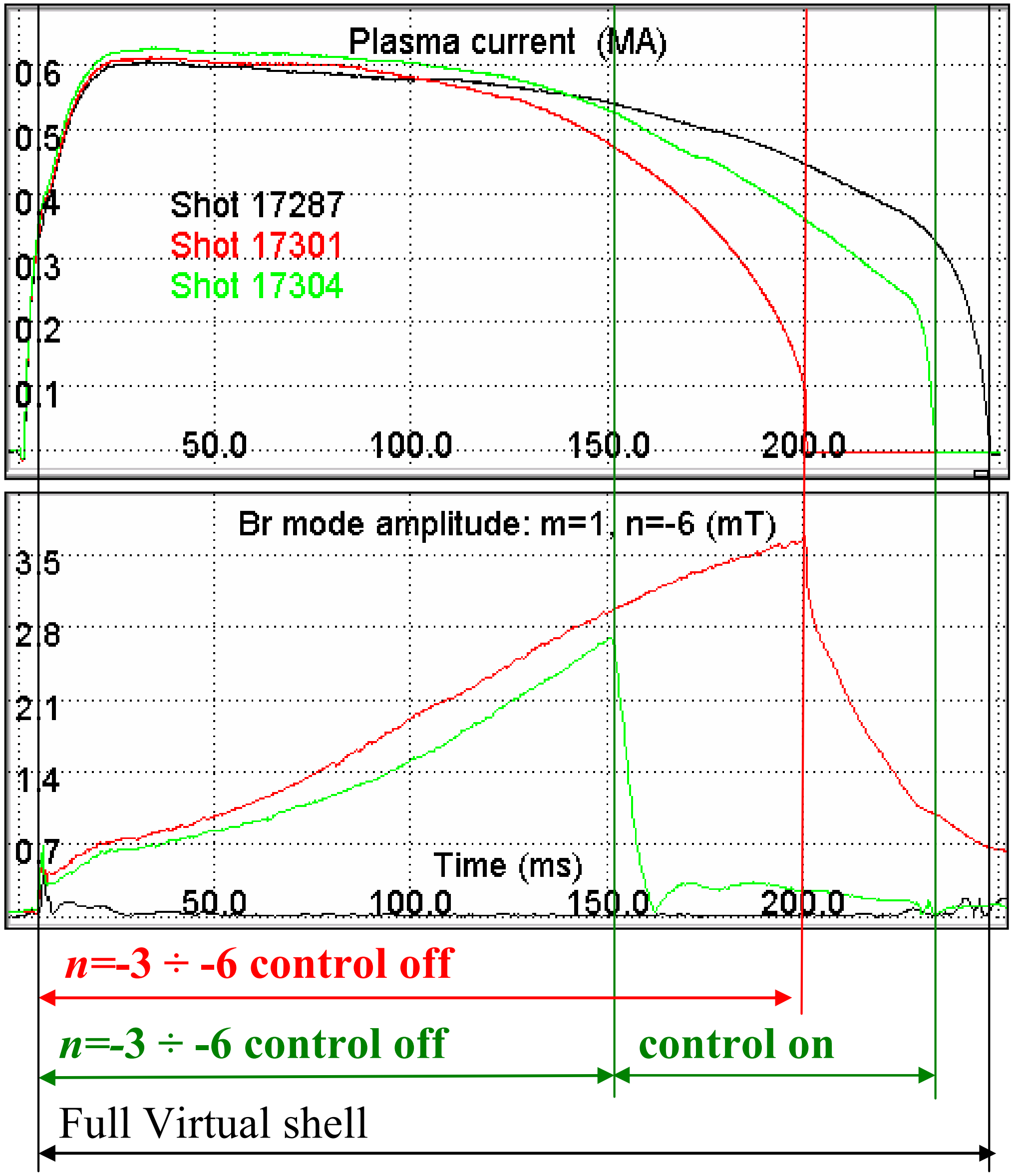
RWM stabilization experiments

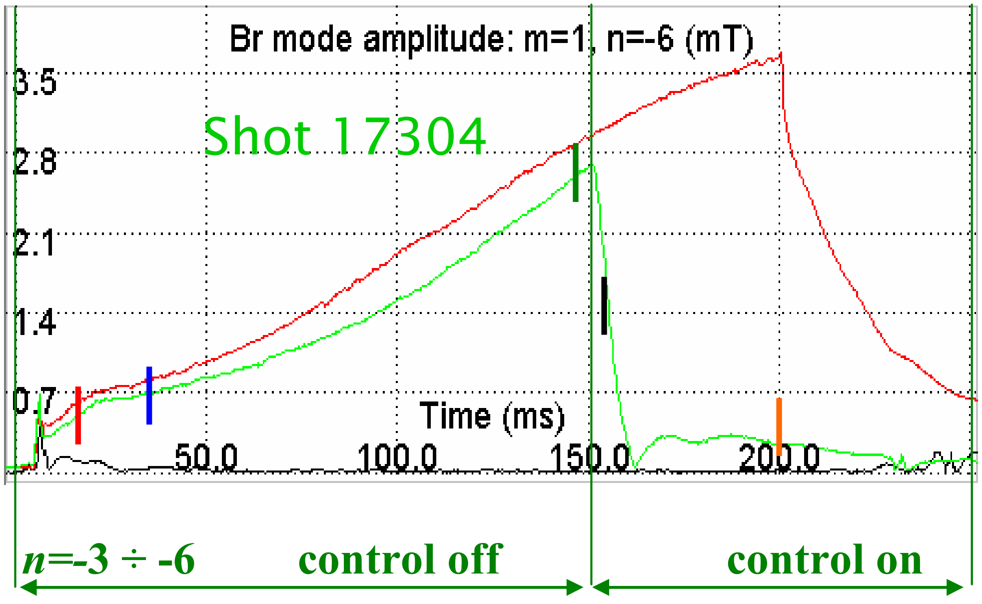


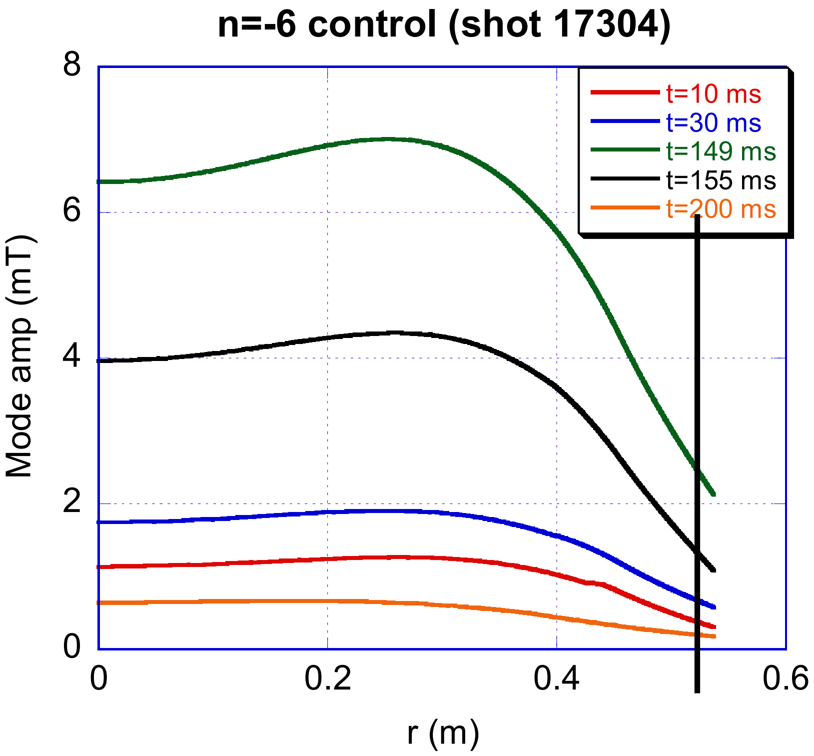
- 17287-> full Virtual Shell
- 17301-> Selective Virtual Shell: free evolution *m=1, n=-3 ÷ -6.* (*n=-6* most unstable)
- 17304-> same as 17301, but with control on *m=1, n=-6* from t=150 ms onward

Great system flexibility:

- independent control of m=0,+/-1 -> test of toroidal effects
- independent coil control -> VS reconfiguration, decoupling matrix
- independent mode control -> interaction of RWMs with pre-programmed error fields and/or with tearing modes

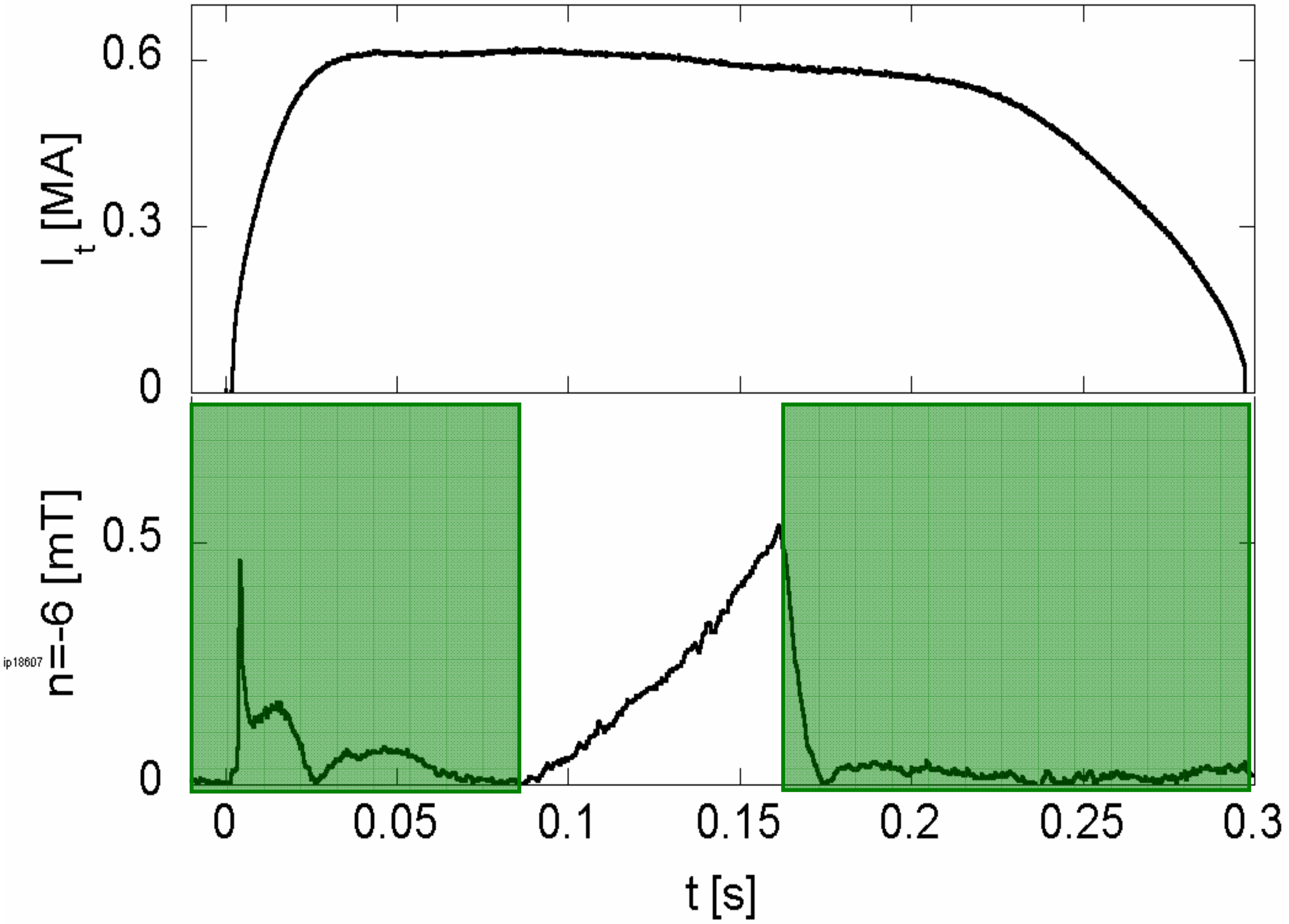
RWM stabilization experiments




n=-6 control (shot 17304)

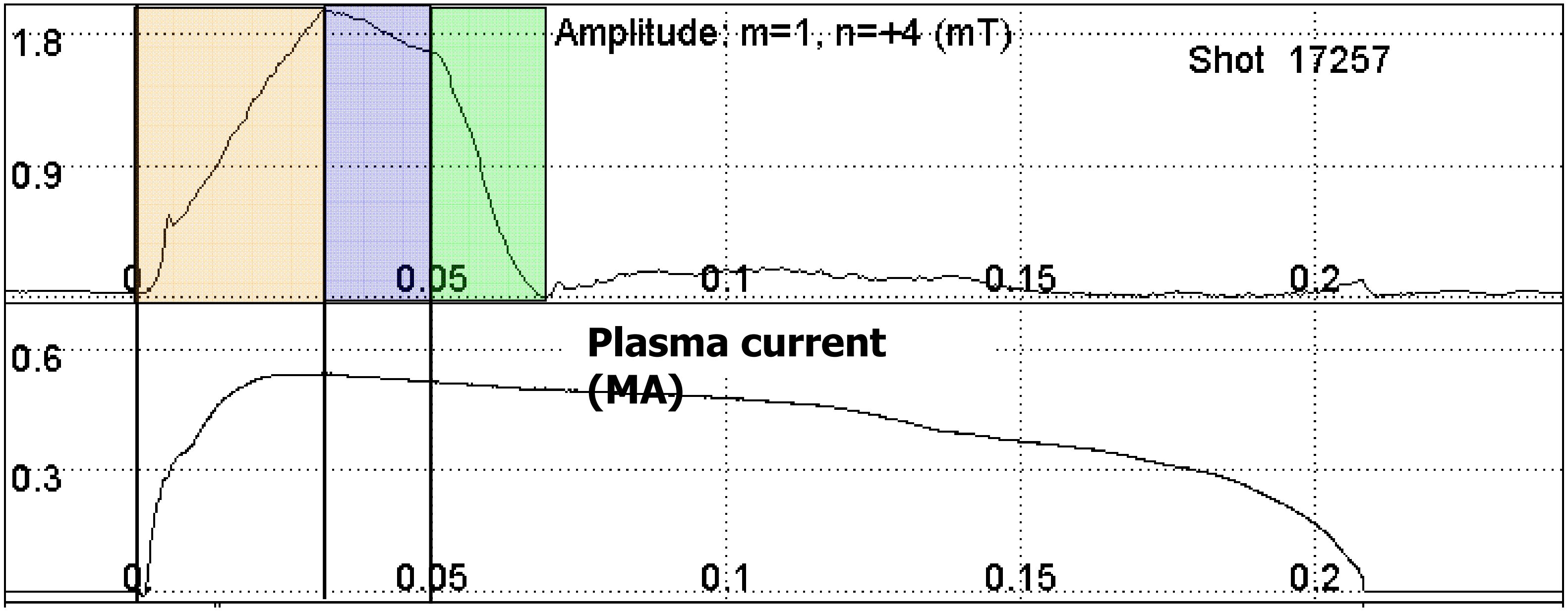
D. Terranova, P. Zanca

RWM stabilization experiments



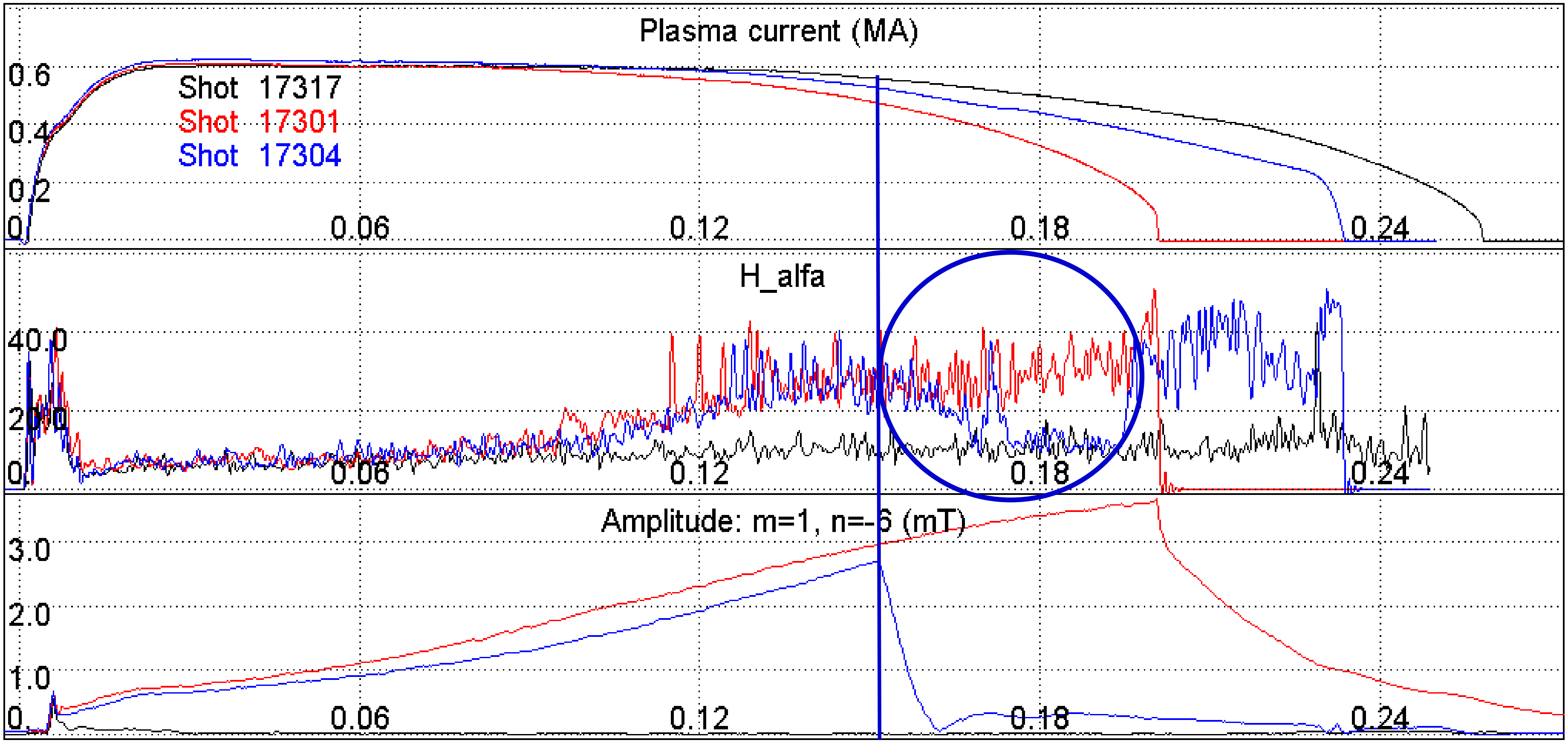
The flexibility of the control system is used to test its capabilities on small instab

Resonant Field Amplification experiments



- ☐ From 0 to 30 ms an external error field m=1, n=4 is applied; all other modes are controlled.
- ☐ From 30 to 50 ms external (1,4) is switched off and plasma is let free to evolve: (1,4) is stable and its amplitude decay.
- ☐ From 50 ms on also (1,4) is controlled and its amplitude is forced to 0 with a much faster time constant.

RWM physics on RFX-mod: influxes



RWM mode control strongly reduce Hα radiation

L. Carraro

RFX-mod future plans

- Up to now first very positive tests on RWMs physics and control
- New experiments:
  - characterization of different equilibria (different RWM spectrum
  - systematic Resonant Field Amplification studies
  - virtual shell at variable radius
  - use of different component (Bt) as input for the control
  - complex gains
  - different control schemes (algorithms), decoupling matrix
  - toroidal effects and coupling with tearing dynamo modes
  - full integration with improved confinement scenarios
- Open to suggestions!

Conclusions

✓ RFPs can successfully test “pure” FB stabilization of RWM (minor flow effect, weak toroidal coupling)

✓ RFX-mod developed a flexible control system under challenging boundary conditions: many input signals, many modes to control, fast response required (and RWM control is not the most difficult thing to do!)

✓ Multiple RWMs stabilization obtained in T2-R and RFX-mod

✓ Clear and detailed experimental data allows the study of (non-controlled) RWM physics and the benchmark of numerical codes (both 2-D and 3-D)

✓ RFX-mod is showing that high plasma current (Ip>1MA) and high beta (β_p>0.1) operations are possible for the Reversed Field Pinch configuration without the need of a thick passive shell