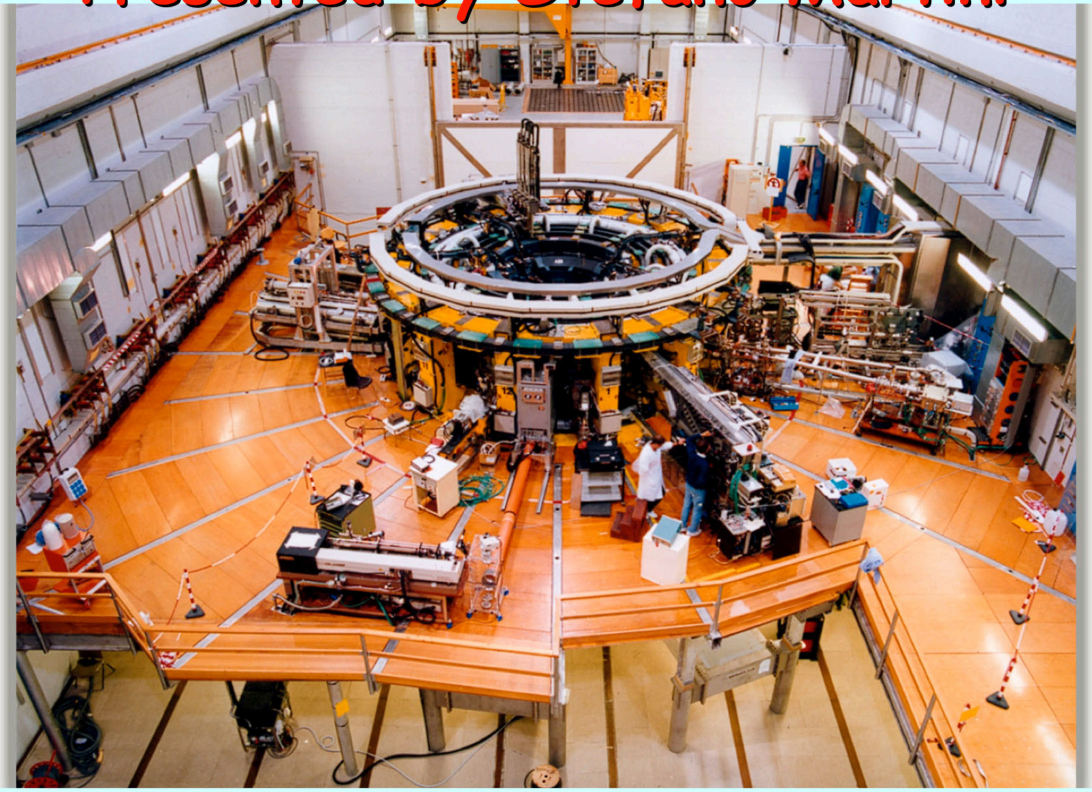
RFX Program on Active Control

Consorzio RFX -Associazione Euratom-ENEA sulla fusione - Padova, Italy

Presented by Stefano Martini



at the 9TH WORKSHOP ON MHD STABILITY CONTROL: "CONTROL OF MHD STABILITY: BACK TO THE BASICS": NOVEMBER 21-23, 2004, PPPL

Hopefully this is the last workshop…

OPS…

I FORGOT A SLIDE FROM LAST YEAR WORKSHOP!

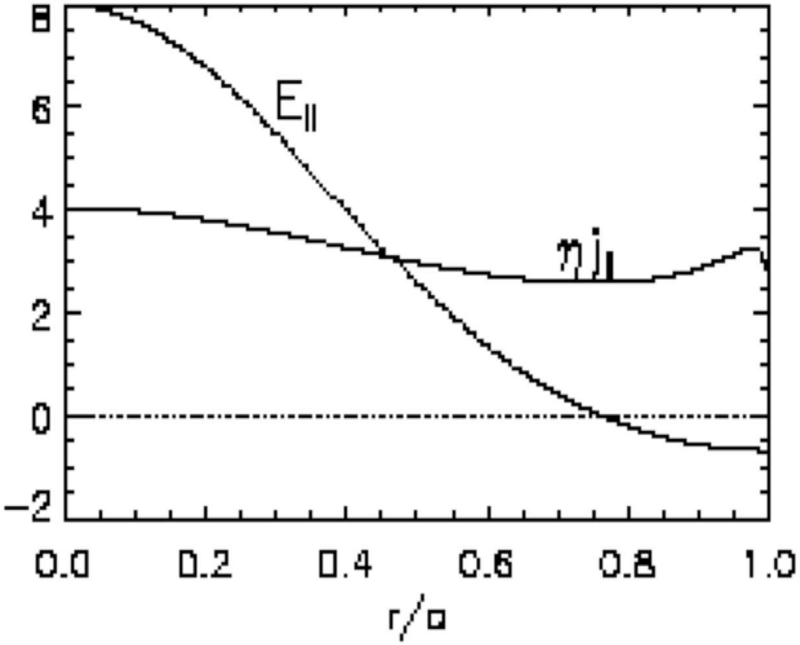
COVERING THE WHOLE PLASMA SURFACE

OUTLINE OF TALK

- Introduction: RFP and MHD dynamo
- Previous mode control experiments on RFX
- What has been learned from other RFPs
- RFX reloaded
- What we expect to do on the new RFX

The RFP dynamo

- The current profile in a RFP cannot be driven in steady state by a constant inductive electric field E_o

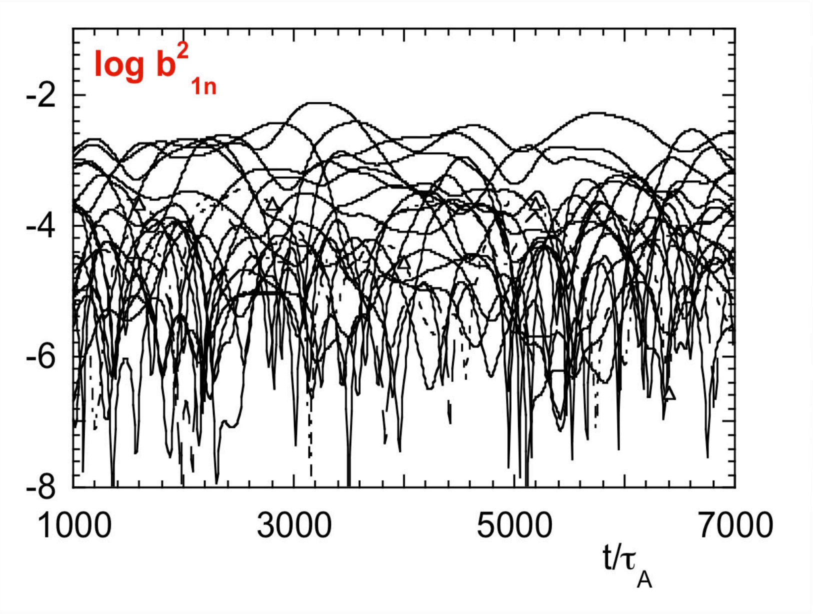


- ….but RFP plasmas last much longer than the resistive diffusion time! (actually, as long as E_o is applied)

- An additional "dynamo" electric field E_d is necessary to maintain the toroidal magnetic flux.

Turbulent dynamo: self-organization

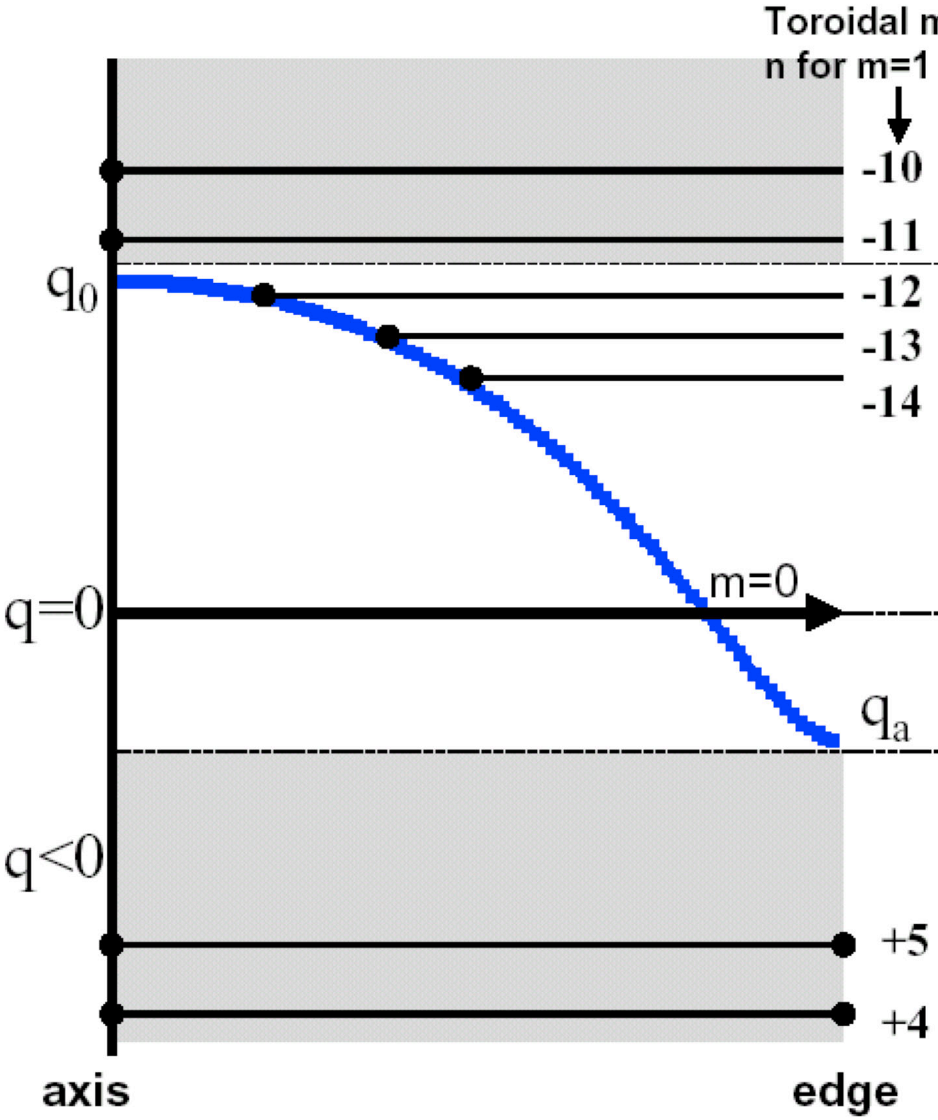
- A wide experimental and numerical database supports the MHD turbulent dynamo theory:



$$\vec{E}_d = \langle \tilde{v} \times \tilde{b} \rangle$$

E_d is produced by the coherent (non-linear) interaction of many MHD modes => **Multiple Helicity (MH) dynamo**

Mode Classification



Internally non-resonant
RWMs

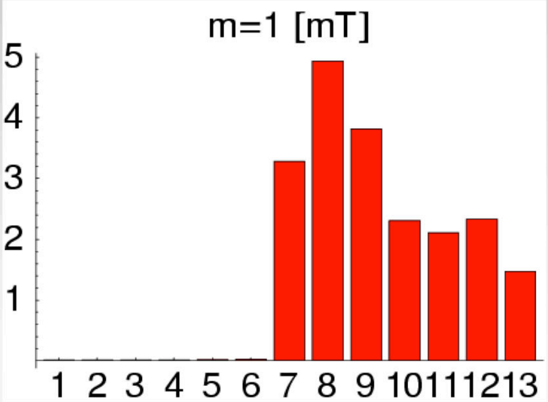
RFP

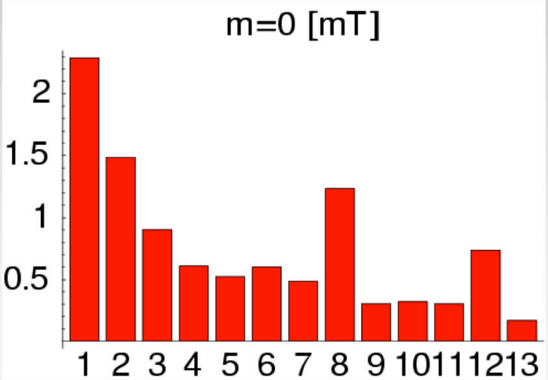
"DYNAMO MODES"

Externally resonant

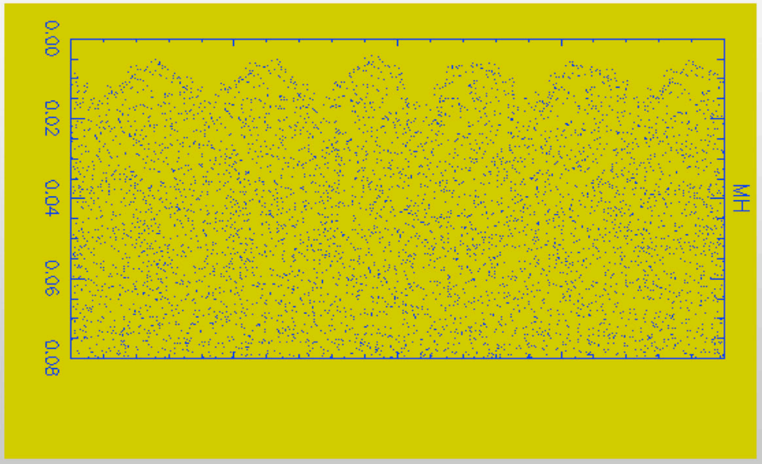
Externally non-resonant
RWMS

The standard Multiple Helicity RFP





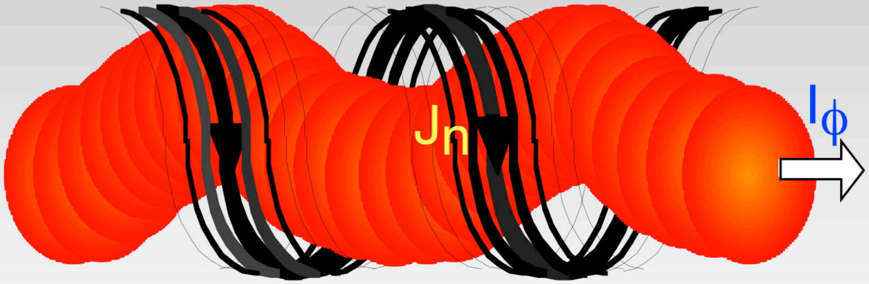
- m=1 “dynamo” modes (resonant inside the Bt reversal surface)
- m=0 non-linearly generated and/or linearly unstable



Magnetic stochasticity allover the plasma !

The slinky

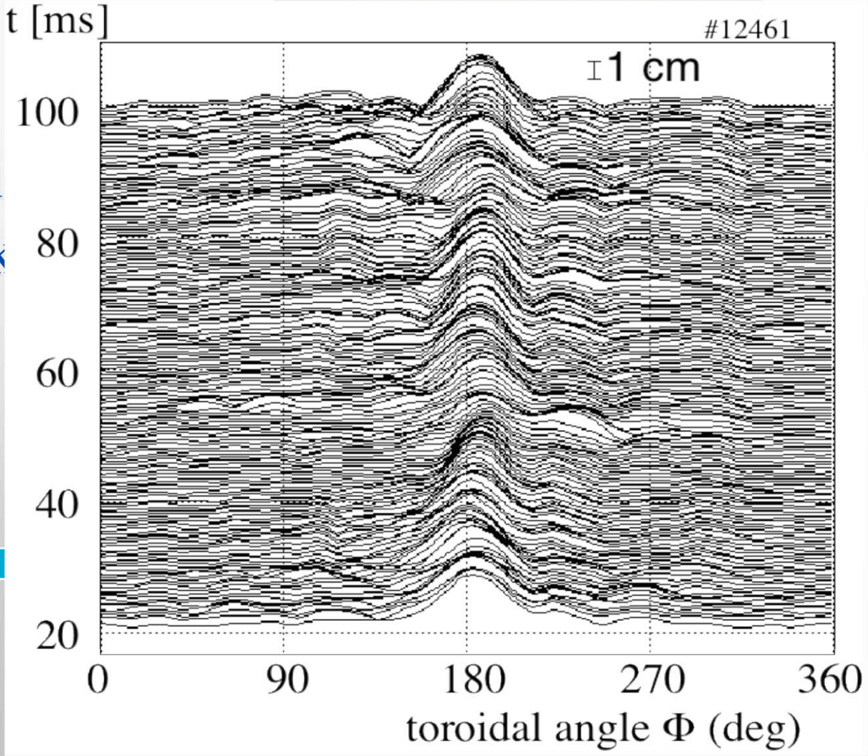
Each mode is associated to an helical perturbation of the plasma



The Phase Locking of many modes results in a non-axisymmetric deformation, the so-called “slinky”

Braking torques by the vessel and fi
errors cause Wall Locking of the slink

Localised plasma-wall interaction ⇒ 100 MW/m²



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Previous MHD control experiments

Previously MHD mode control on RFX based on :

- Reduction of field errors
- **Control of modes via the Bφ coils:**
  - Active control of poloidal current:

    Pulsed => PPCD

    Oscillating => OPCD
  - Active rotation of the locked modes (RTFM)

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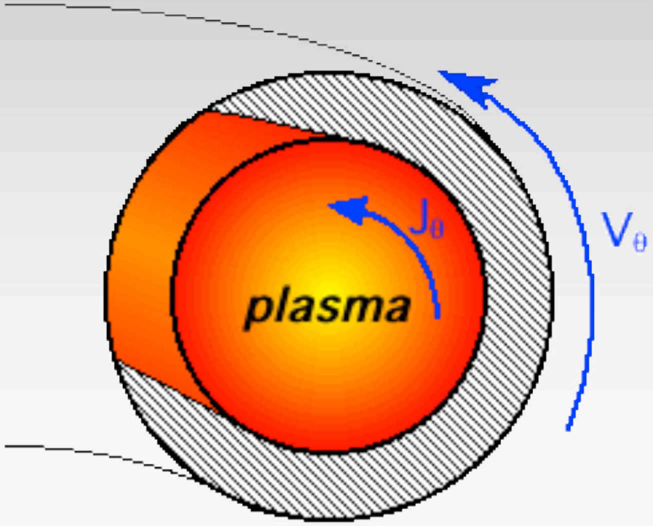
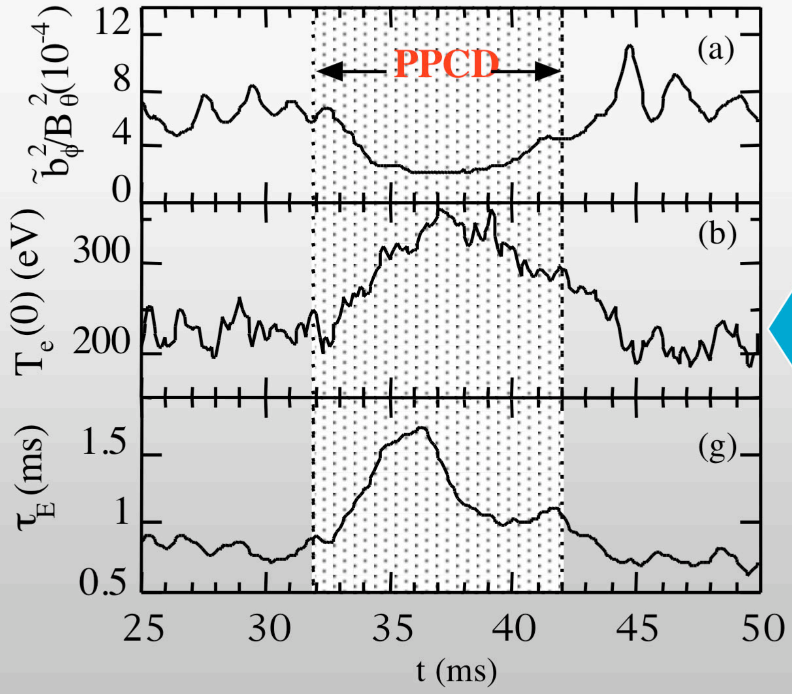
Pulsed Poloidal Current Drive

External poloidal current drive (first tested on MST) transiently quenches the spontaneous dynamo.





Strong reduction of magnetic fluctuations and improved confinement

Oscillating Poloidal Current Drive

Oscillating poloidal electric field imposed by a GTO switch system

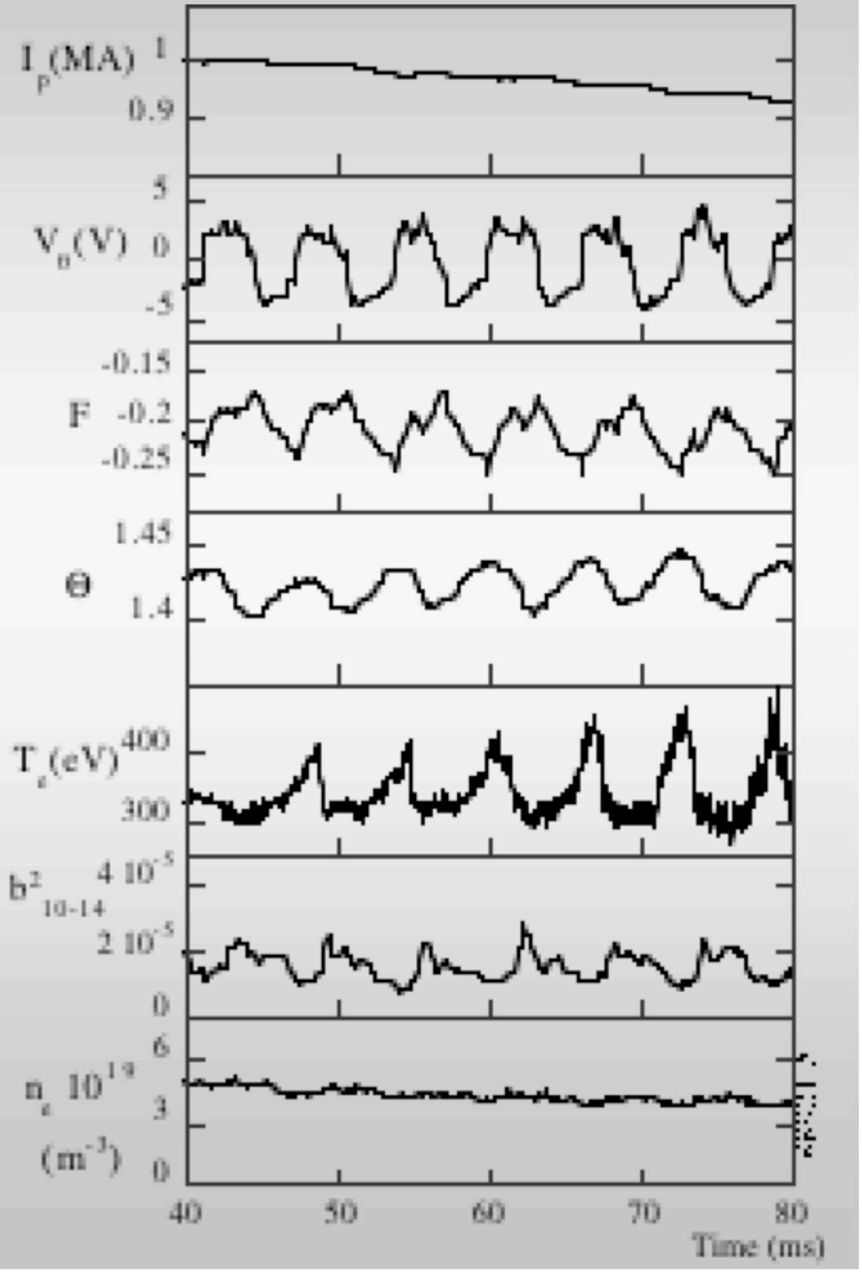
During co-drive phase confinement improves as for PPCD

Edge transport barrier not affected during counter-drive phase

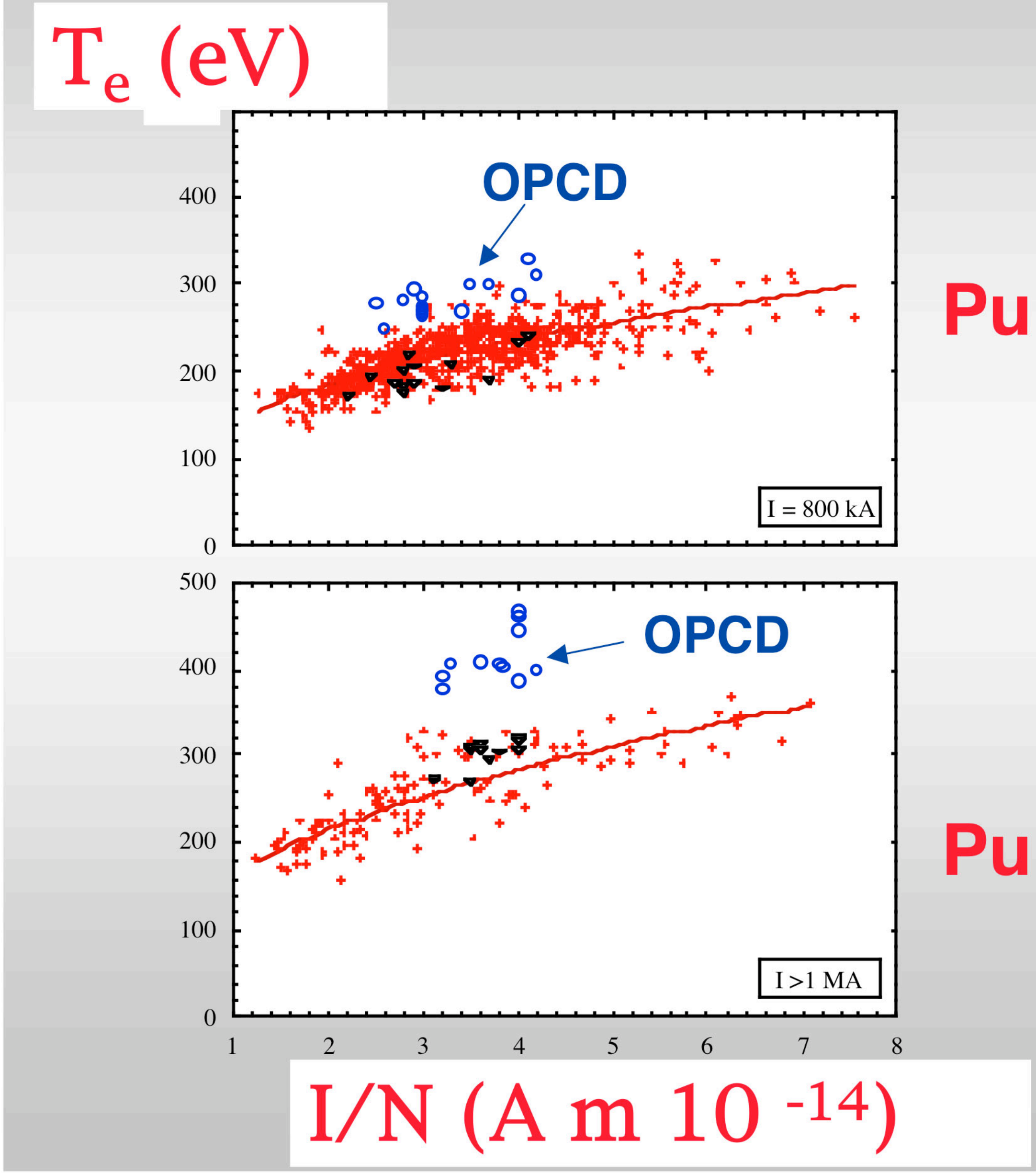
⬇

Quasi-stationary confinement improvement

(*Bolzonella et al., PRL 2001*)



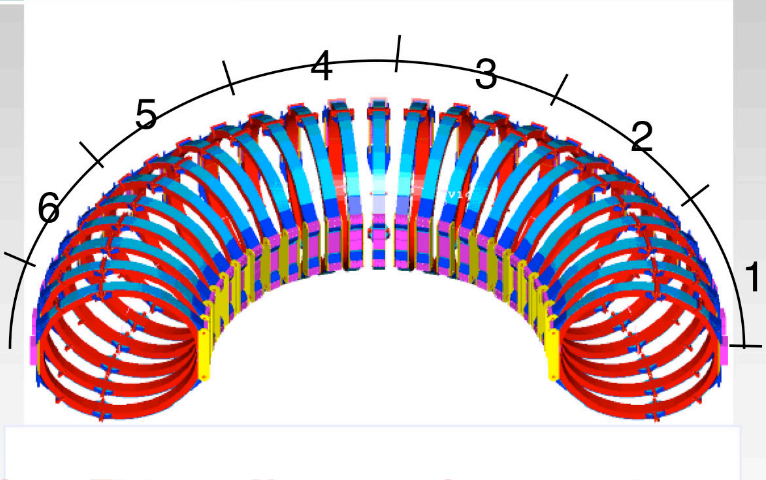
OPCD more effective at Higher Current

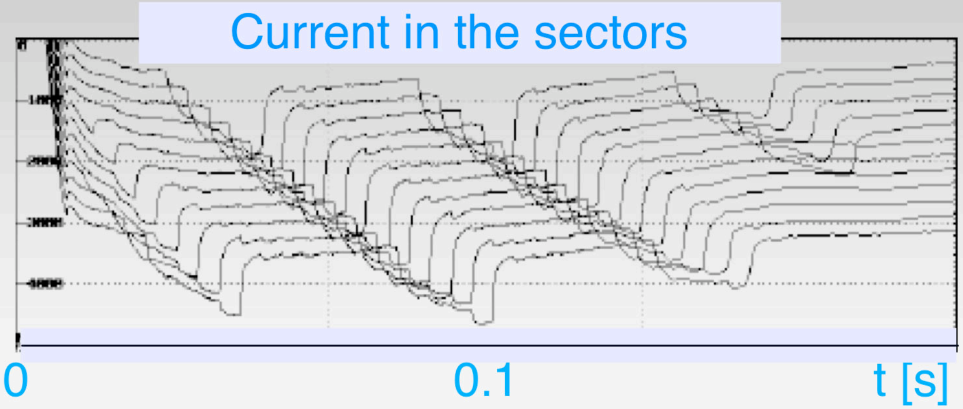


Pulses at I>800kA

Pulses at I>1MA

Rotating Toroidal Field Modulation





The Bϕ coils produce a traveling m=0 perturbation which exerts torque on q=0 island:

$$T_z^{0,1} \propto b_r^{0,1} B_r^{0,1}(r,1)\sin(\Delta\phi_{0,1})$$

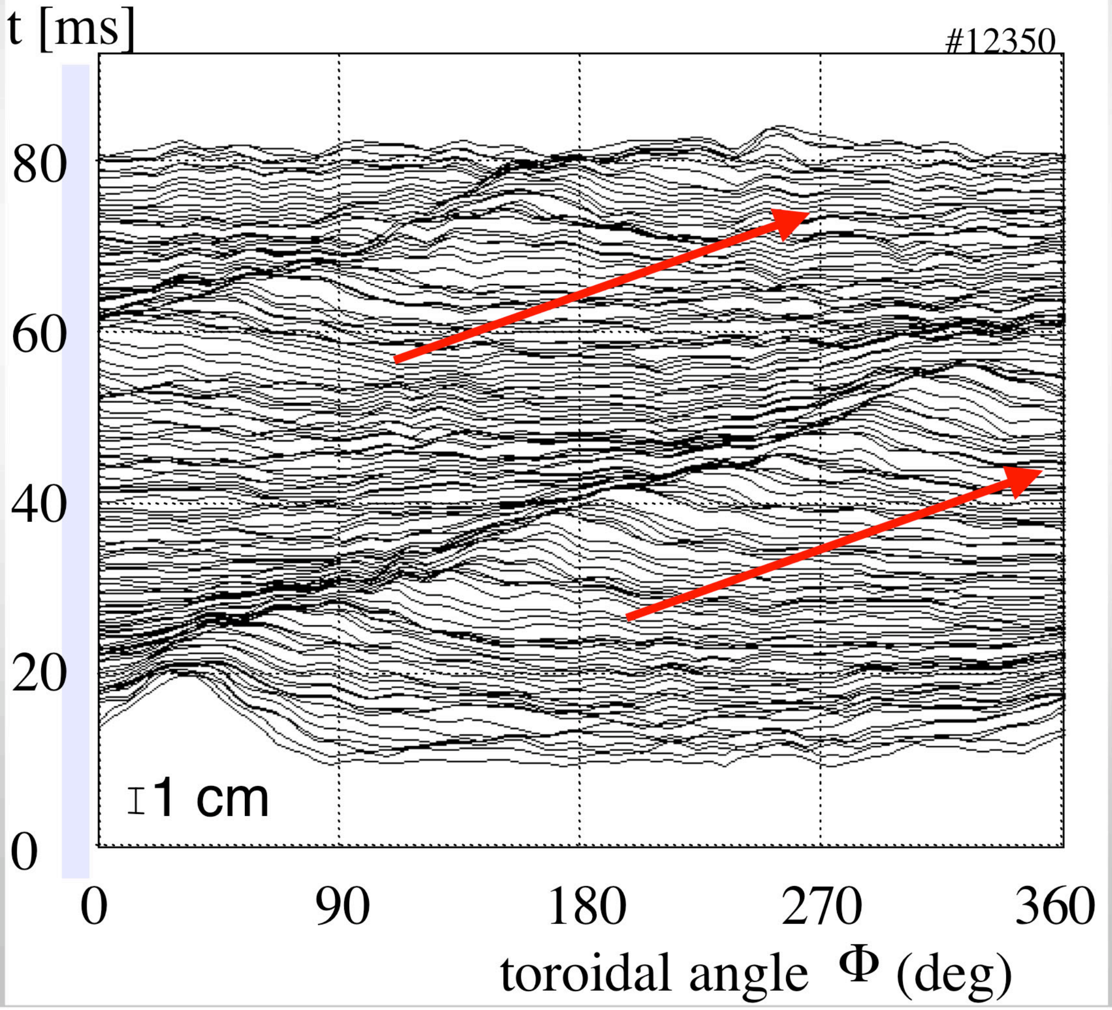
Rotation opposed by drag of eddy currents in resistive vessel → $T_{visc}^{m,n} \propto (b_r^{m,n})^2\,\omega$

A sufficiently high external field $\mathbf{B_r^{0,1}}$ overcomes the drag and **lock in phase the 0,1 mode**

Continuous Induced Rotation

Enforcing the proper phasing during the start-up phase:

→ continuous rotation for the whole discharge



Three mode interaction

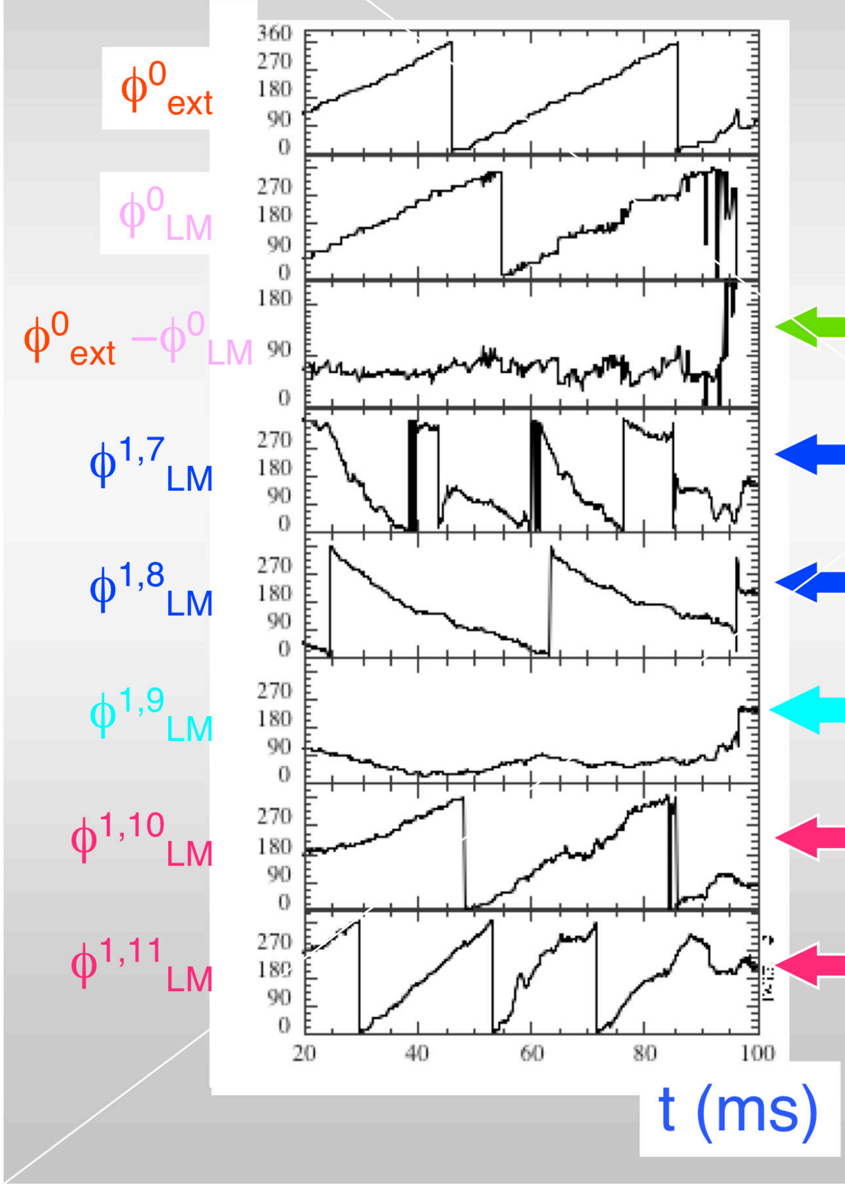
- m=1 modes experience a non linear torque:

$$T_z^{1,n} \propto C_n b_r^{1,n} b_r^{1,n+1} b_r^{0,1} \sin(\phi^{1,n+1} - \phi^{1,n} - \phi^{0,1}) +$$
$$C_{n-1} b_r^{1,n} b_r^{1,n-1} b_r^{0,1} \sin(\phi^{1,n-1} - \phi^{1,n} + \phi^{0,1})$$

for sufficiently high external field:

- high n modes will co-rotate with (0,1) ext. perturbation
- low n modes will counter-rotate
- in general => $\omega^{1,n+1} - \omega^{1,n} = \omega^{0,1}$

Dynamics of m=1 modes



phase locking of m=0 mode

harmonic generation

low n m=1 modes travel backward

most restrained m=1 is stationary

high n m=1 modes travel forward

harmonic generation

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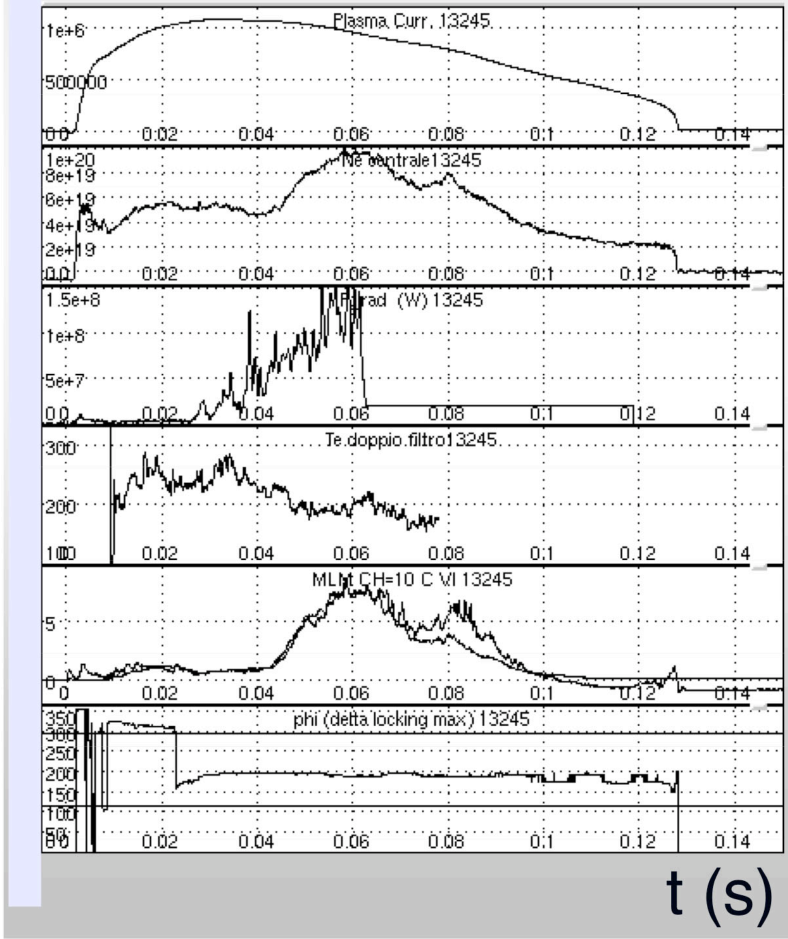
1MA Pulses with & without rotation

NO rotation



I_p (A)

n_e (m^{-3})

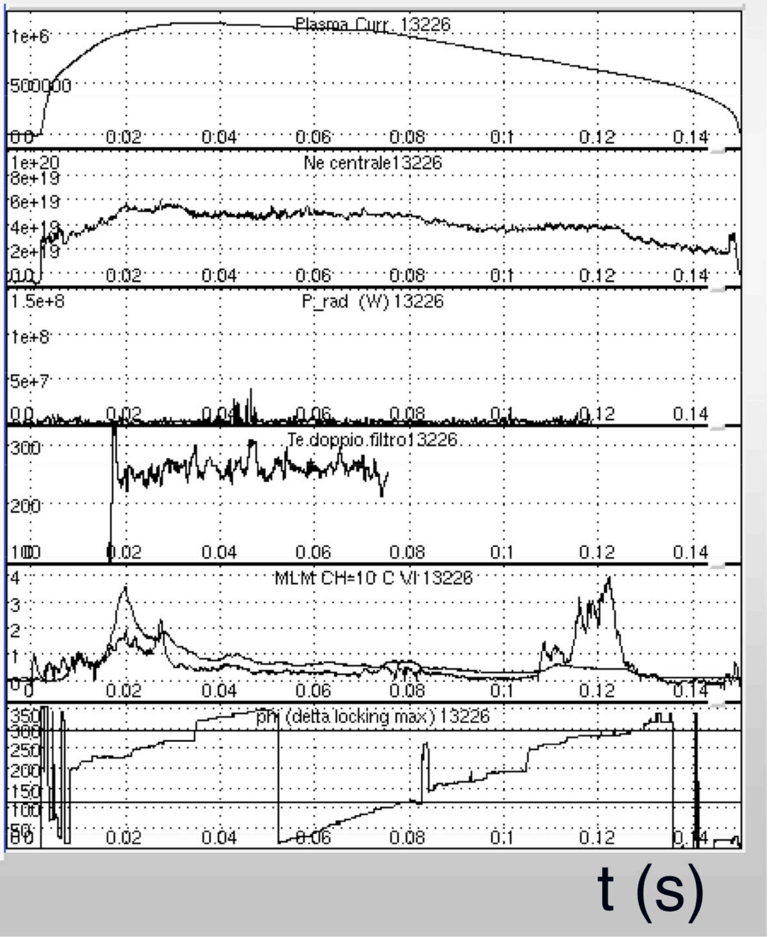
P_{rad} (W)

T_e (eV)

CVI (au)

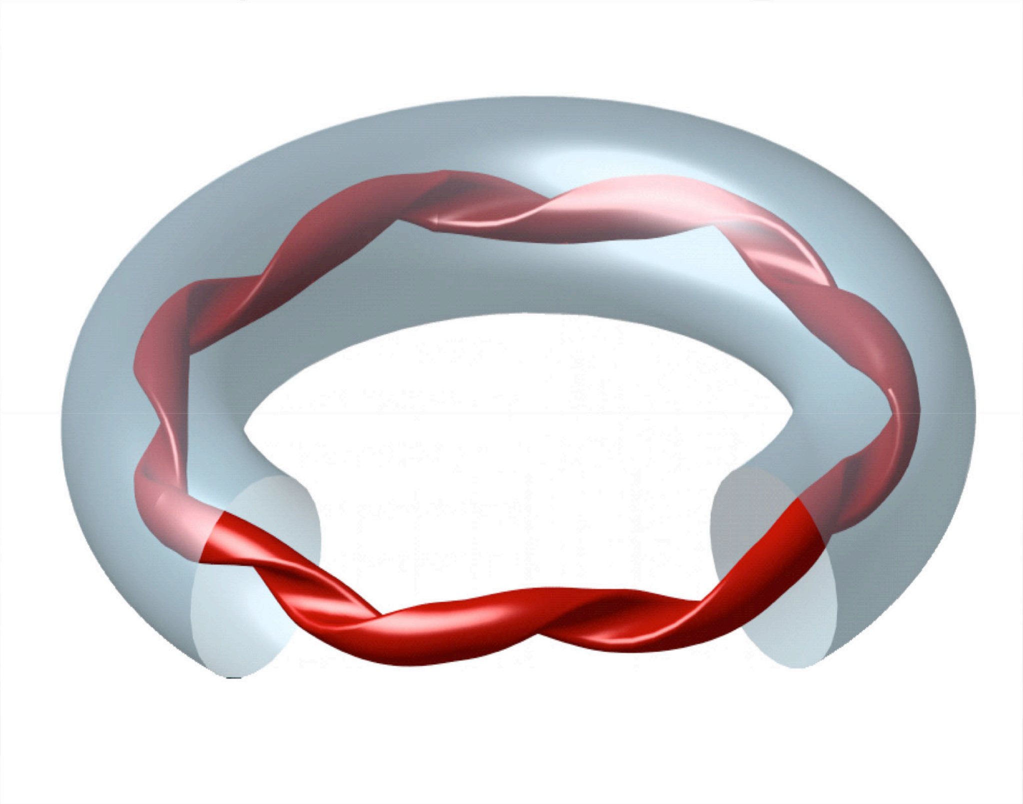
ϕ_{LM} (°)

with rotating modes



The Single Helicity (SH) dynamo

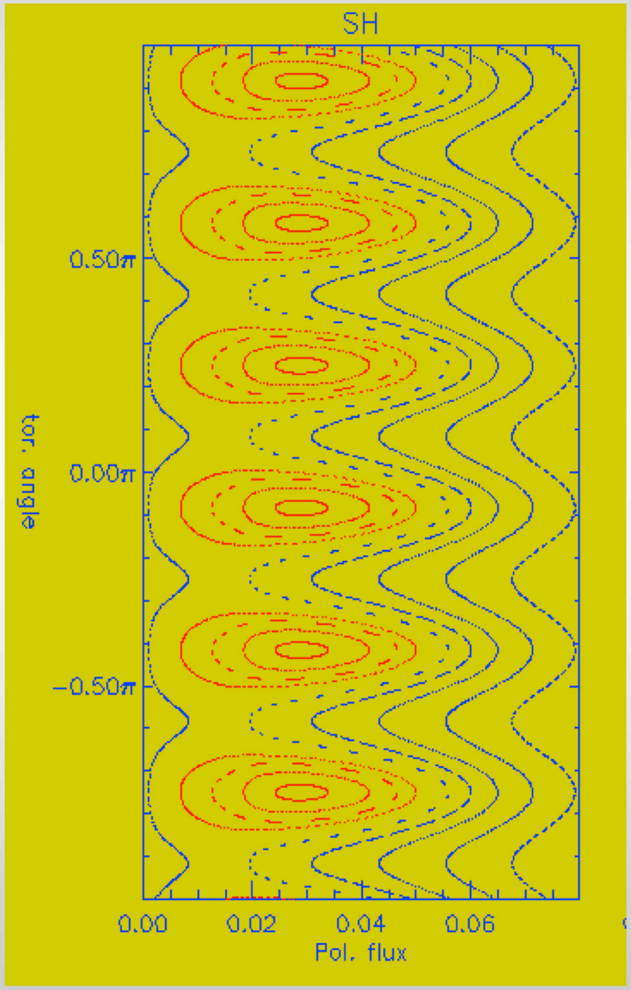
- a theoretically predicted state with a unique $m = 1$ saturated resistive kink (a pure helix wound on a torus),
- Stationary LAMINAR dynamo mechanism with good helical flux surfaces



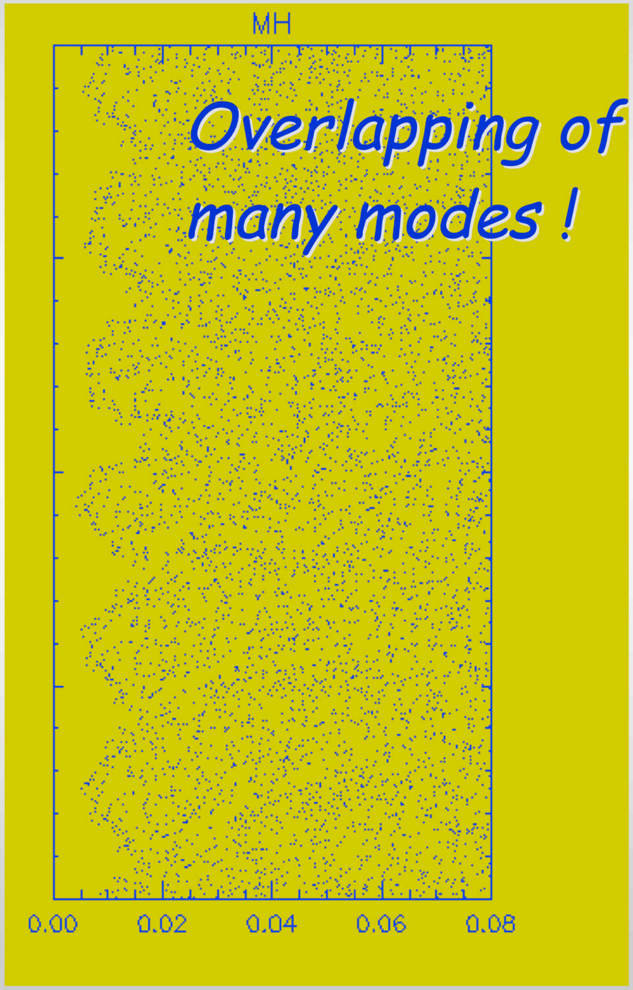
Escande et al., PRL 85 (2000)

Magnetic order with SH dynamo

Good magnetic flux surfaces in SH



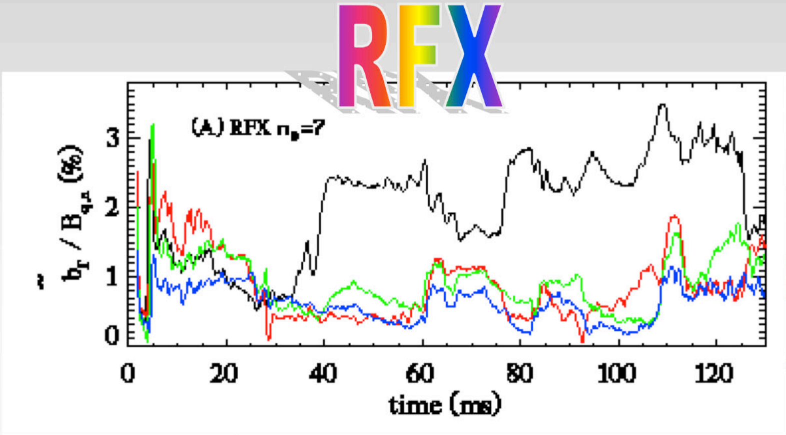
SH

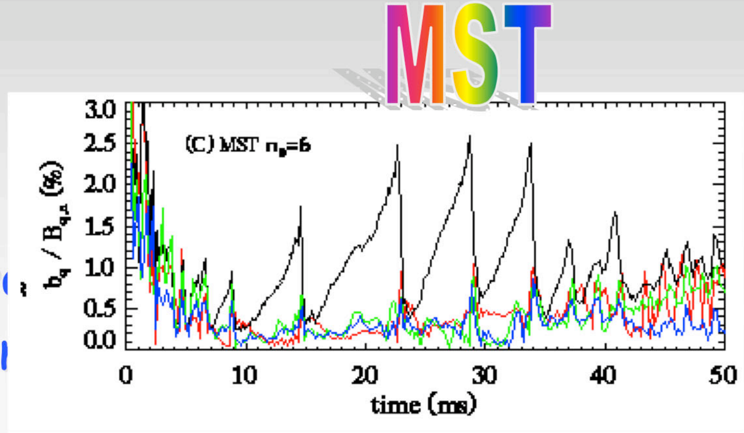


Overlapping of many modes !

Turbulent (MH)

Helical states in the experiment

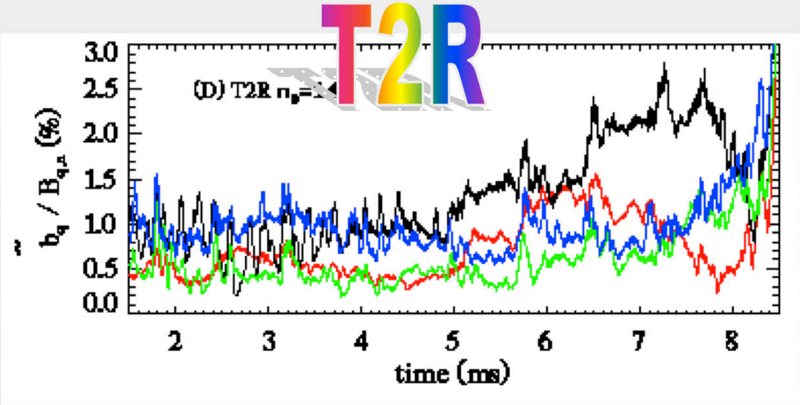




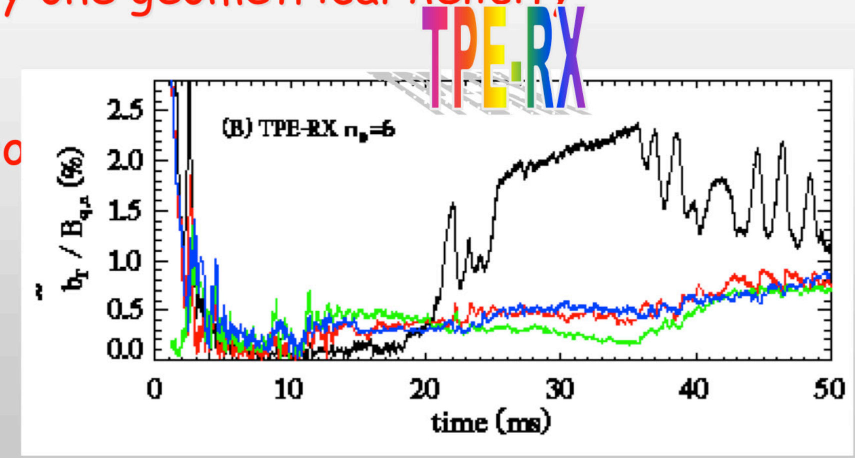
H) spectr

ty of bou

- The mode spectrum is dominated by one geometrical helicity



non-zero



Summary of old RFX results

Therefore, with the aim of making

a new step (hopefully) forward

along the path to the "good RFP"

we now have…

QSH alleviate the problems, but are not sufficient to reach the design target 2MA regime.

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RFX reloaded

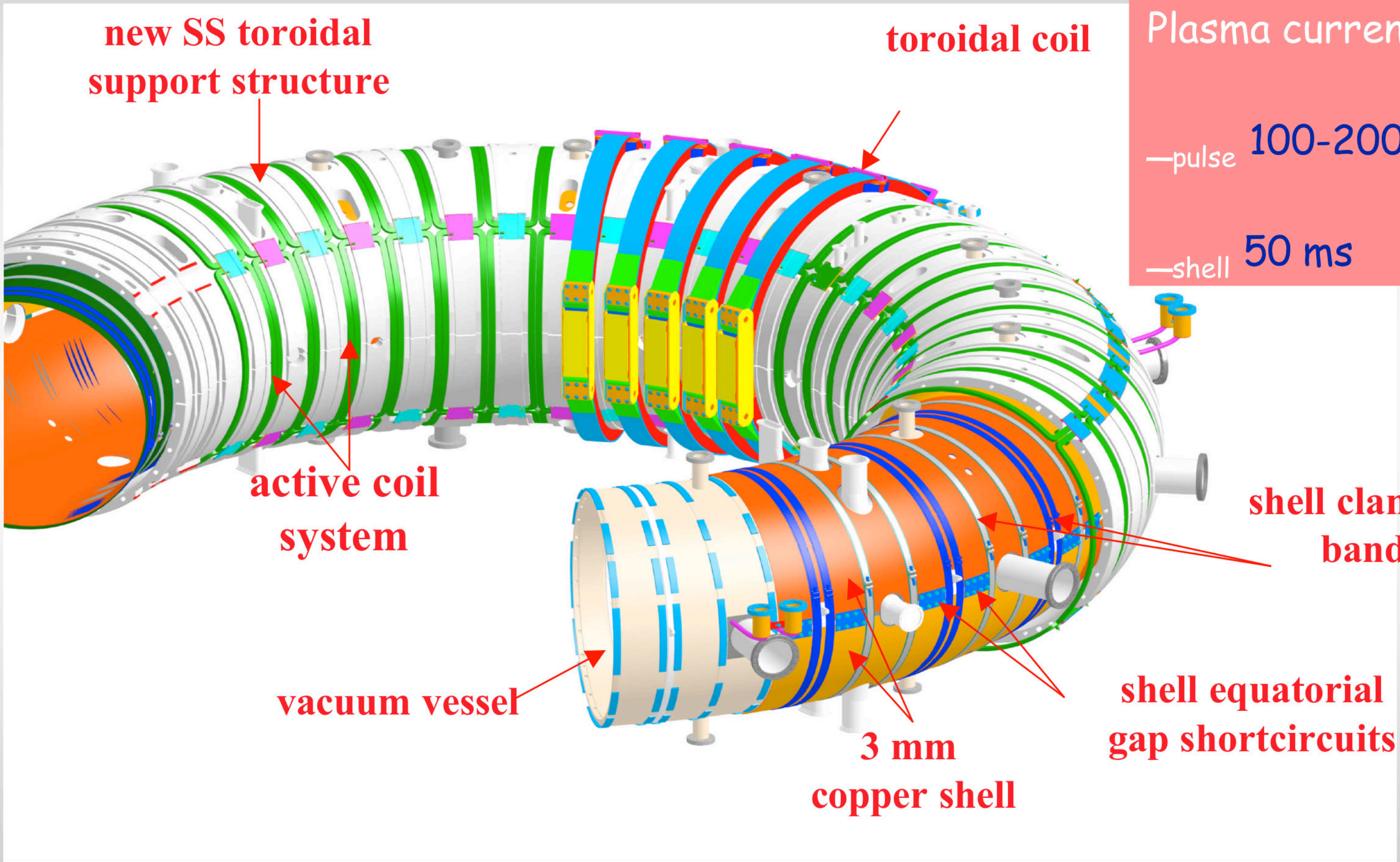
Major radius 2 m

Minor radius 0.46 m

Plasma current 0.3-1.1 MA

—$_{\text{pulse}}$ 100-200 ms

—$_{\text{shell}}$ 50 ms



48x4 active coil system 100% surface coverage

First plasma with the new assembly mid December 2004

Mode dynamics in RFPs

- Experimental evidence in several RFPs shows that the evolution of MHD modes, including the dynamo modes, depends on the magnetic boundary, and in particular on the **shell**:
  - **thickness**
  - **proximity**
  - **geometry**

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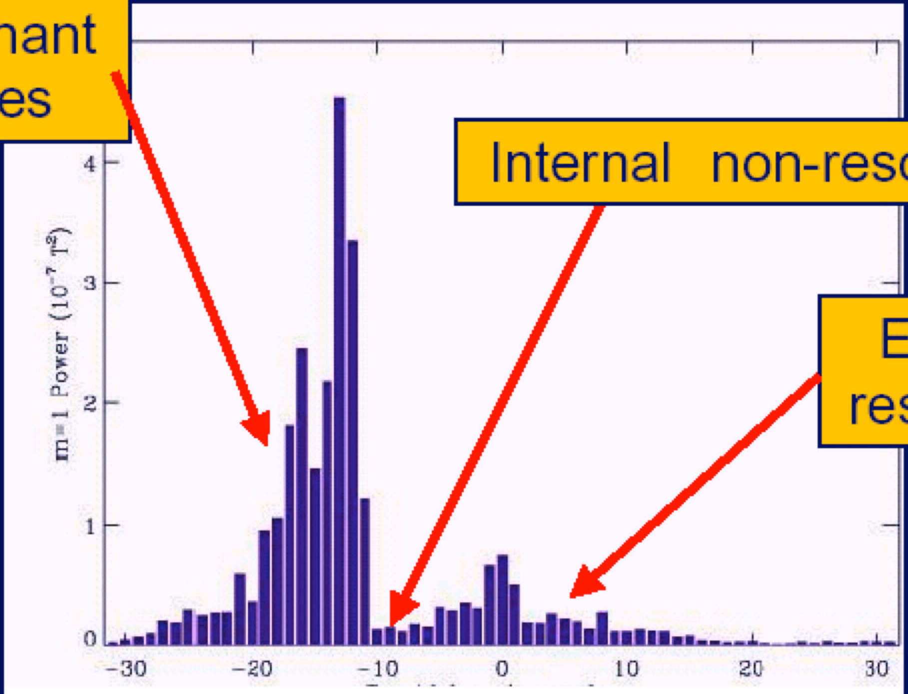
Conducting shell in RFPs

Scenarios for MHD control in the new RFX depend crucially on the effect of the modifications to shell geometry, proximity and time constant

Experiment	R/a m	b/a	τ_{shell} ms	τ_{pulse} ms	τ_{pulse}/τ_{shel}
RFX92	2/0.457	1.24	450	150	1/3
RFX new	2/0.459	1.11	50	*150 ?*	*3 ?*
MST	1.5/0.51	1.07	400	60-90	_
TPE RX	1.72/0.45	1.08 1.16	10 330	60	6 1/5
T2R	1.24/0.183	1.08	6	20	>3

Tearing mode spectrum in T2R



Internal resonant tearing modes

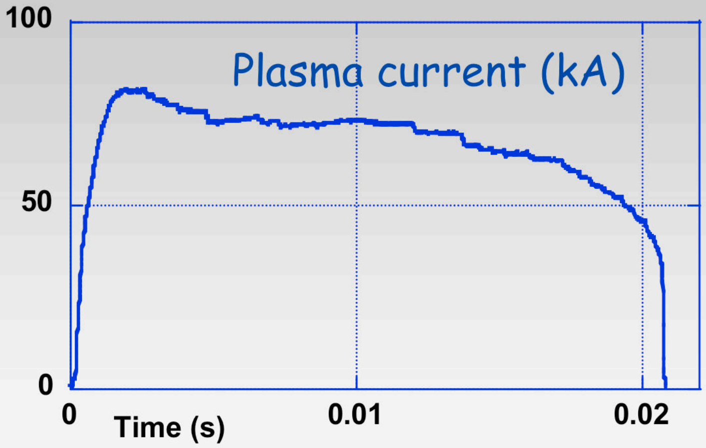
Internal non-resonant RWMs

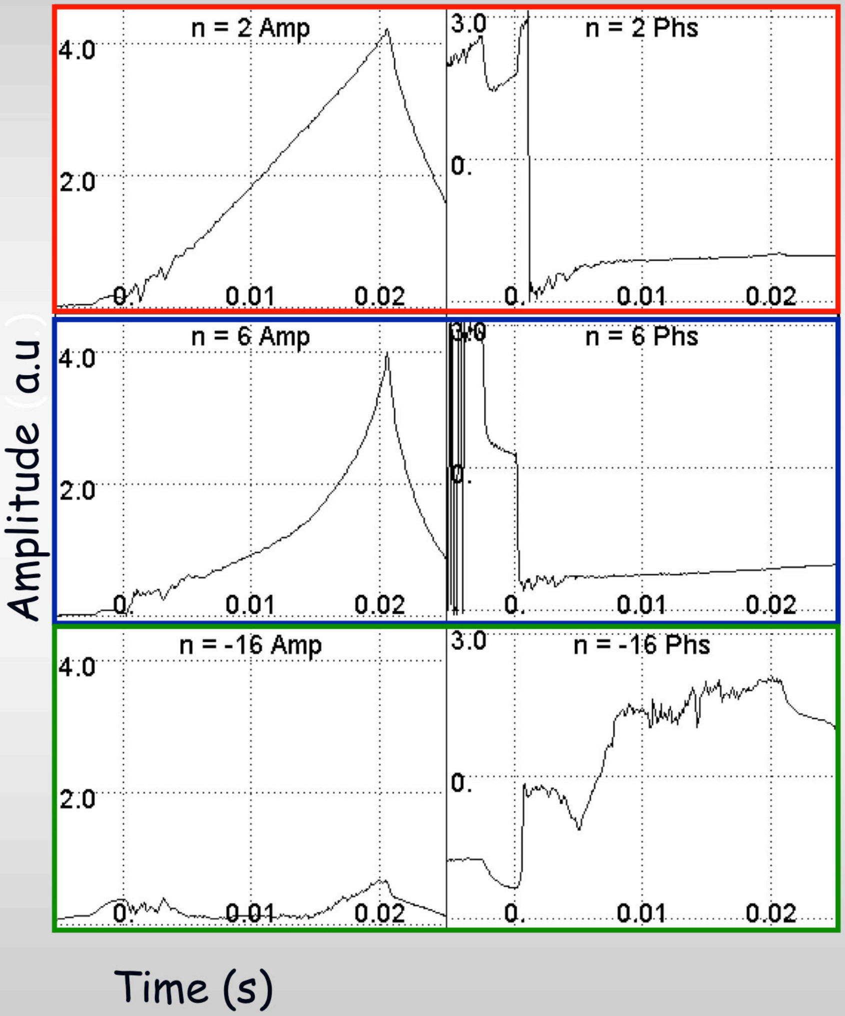
External non-resonant RWMs

Toroidal mode numbers

Based on poloidal field coil measurements

Mode behaviour in T2R





N.B.: Br component #16874

- **Error field modes (e.g. n=2):**
  - Linear growth
  - Wall locked
  - Reproducible phase
- **RWM (e.g. n=6):**
  - Exponential growth
  - Wall locked
  - Reproducible phase
- **Tearing modes (e.g. n=-14)**
  - Rotating (10-30 kHz)
  - small Br component
  - eventually wall locked

Conclusions on mode rotations

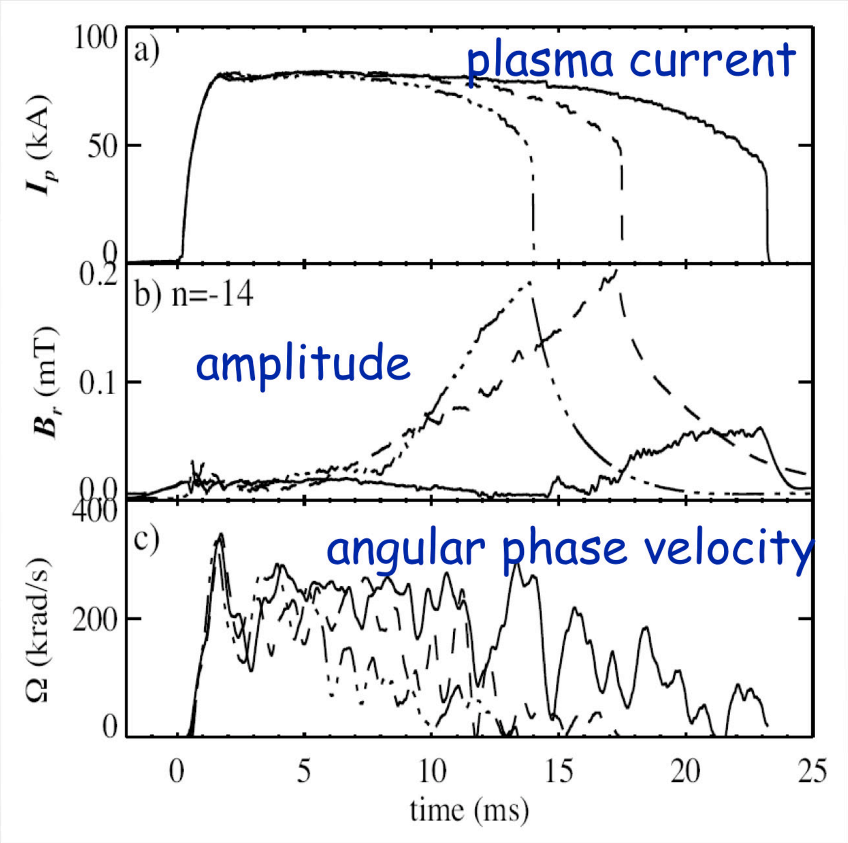
- Dynamo modes are spontaneously rotating in RFP devices with close fitting shell (even if a threshold in current might exist)
- Externally resonant RWM are seen in RFPs. Their growth time agrees with the shell time constant and they do no rotate
- There is a reasonable basis for spontaneous rotation of dynamo modes in the new RFX

Mode control experience in T2R

- As shown in previous talks by
  - Jim Drake (yesterday)
  - Roberto Paccagnella (today)
- During the last year a fruitful collaboration between the T2R and the RFX groups permitted to perform very interesting experiments on active mode control on T2R

Feedback experiments on T2R

Amplitude and angular phase velocity for resonant tearing mode m=1, n=-14.



—··· No feedback

--- Feedback all modes (intelligent shell)

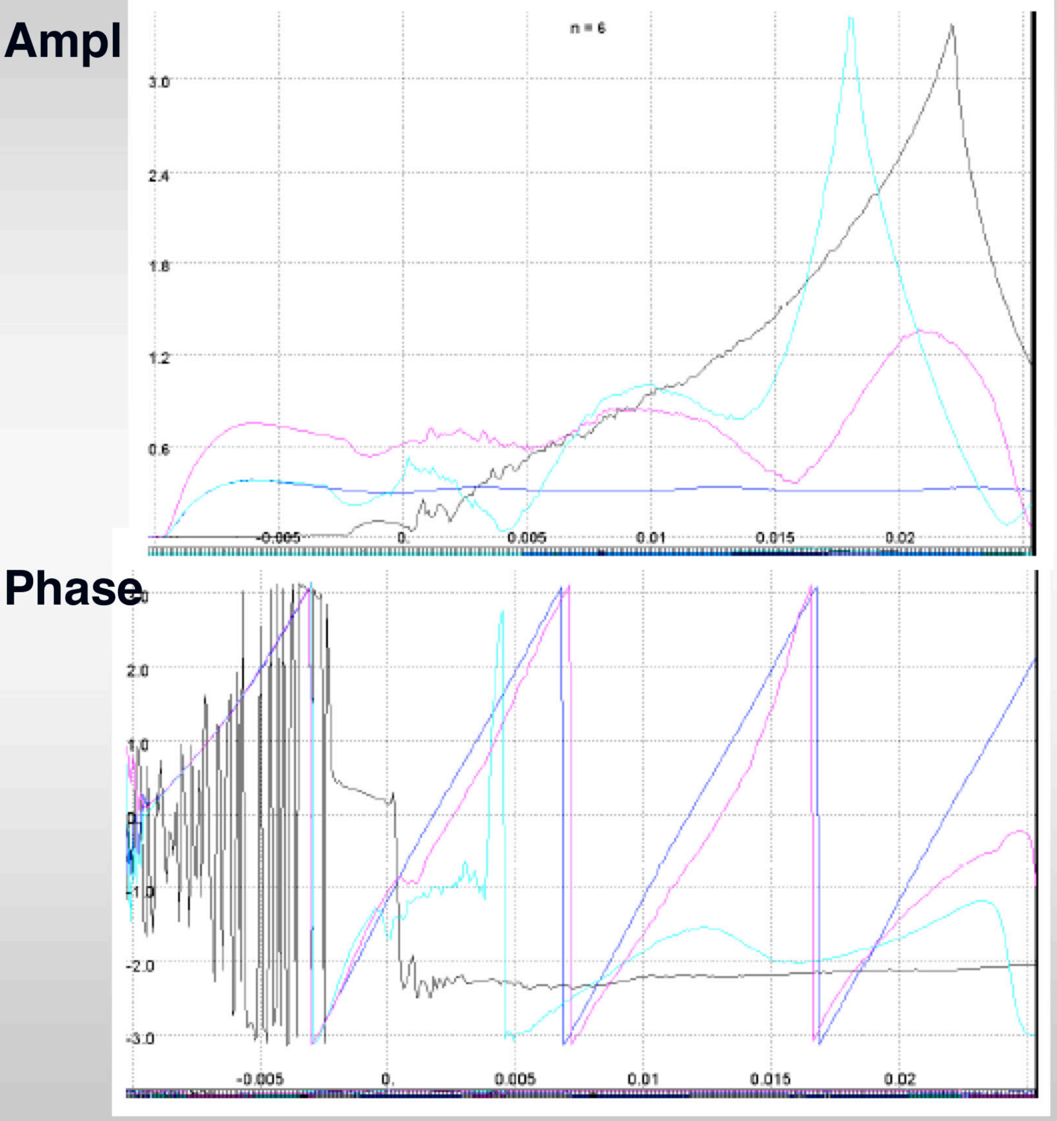
— Feedback all modes except -2 ≤n ≤+2 (wise shell)

Tearing mode rotation is maintained with feedback

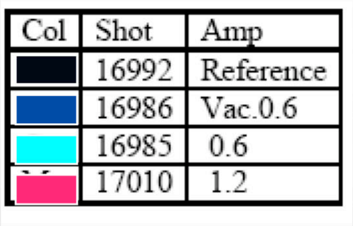
From: P. R. Brunsell, et al., "*First results from intelligent shell experiments with partial coil coverage in the EXTRAP T2R reversed field pinch*", 31st EPS, ECA Vol.28G, P-5.190 (2004)

See also: P. Brunsell et al., *Feedback stabilization of multiple resistive wall modes*, to be published on PRL

Open loop control of RWM with rotating perturbation



- With sufficient amplitude of external perturbation, RWM can be rotated
- Amplitude no longer increase with rotation



Col	Shot	Amp
■	16992	Reference
■	16986	Vac.0.6
■	16985	0.6
■	17010	1.2

Rotating n=6 perturbation:. Freq.=100 Hz, ϕ_0=0, different amplitudes.

T2R experience with mode control

- Open loop experiments[1] clearly showed intrinsic error field reduction or amplification, depending on amplitude and phase of the applied external field.
- Feedback operations have shown clear reduction of MHD mode amplitudes and beneficial effects on plasma-wall interaction.
- Intelligent shell and individual/ multiple mode control schemes successfully implemented and compared
- Active rotation of single mode demonstrated

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[1] J.R. Drake - **Open loop control experiments in EXTRAP T2R RFP, yesterday talk**

RFX reloaded

Main new components:

1. new toroidal field power supply
2. first wall with higher power handling capabilities
3. smoother and thinner shell
4. 192 saddle coils, covering the whole plasma boundary, each independently powered and feedback controlled
5. in-vessel system of magnetic and electrostatic probes

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m=0 x RTFM & PPCD/OPCD

		Modified RFX			*RFX 92*	
Control strategy	*Amplitude*	*Period (ms)*	*F (Hz)*	*Amplitude*	*Period (ms)*	*F (Hz)*
RTFM m=0, n=1: B_{twall} control	**58 mT**	**40**	**25**	10 mT	40	25
PPCD: V_{pol} control	**10 V**	**10**	**125**	9 V	10	125
OPCD: V_{pol} control	**10 V**	**3 - 8**	**125 - 333**	3 V	7	140

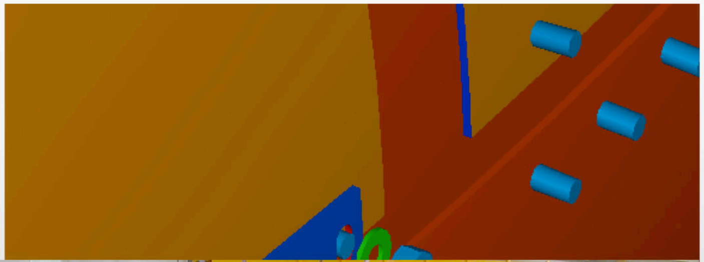
B_{tor} new ≈ 6 x B_{tor} old
at 25 Hz with 3kA

Compared to RFX 92 RTFM capability greatly enhanced, which is of utmost importance since

- **RTFM was not possible at high density in RFX92**

The new shell

- One 3 mm Cu layer:
    - 1 overlapped poloidal gap: 23° toroidal overlap
    - 1 toroidal gap on high field side



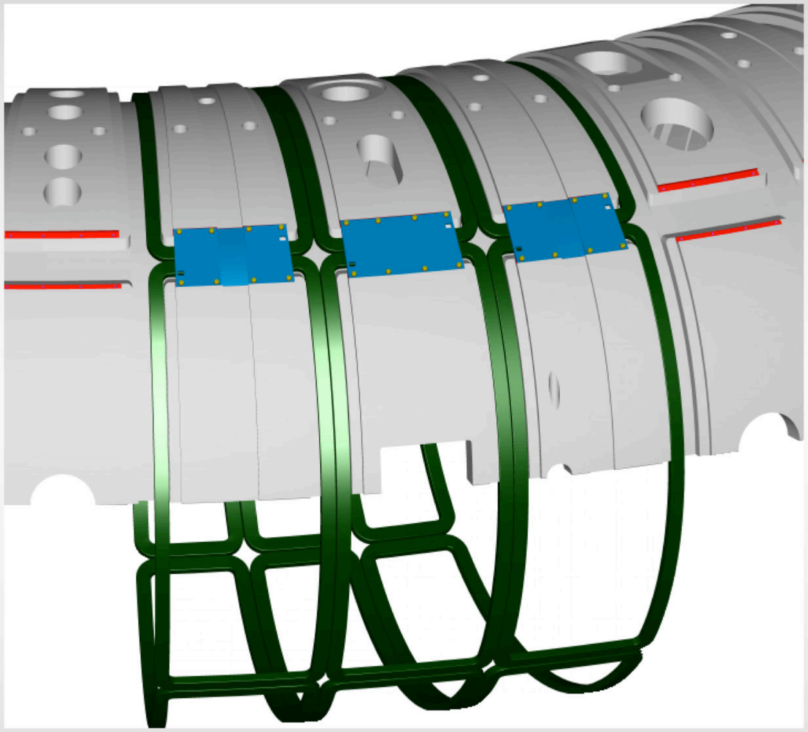
elded
gap

Shortcircuited gap: 50 bolted copper plates

New saddle coil system

- 4 poloidally: 90°
- 48 toroidally: 7.5°
- Complete toroidal coverage

each independently powered
24 kAt: 400 A x 60 turns



Wide spectrum of Fourier components :

- m=1,2
- $n \leq 24$
- DC < f < 100 Hz

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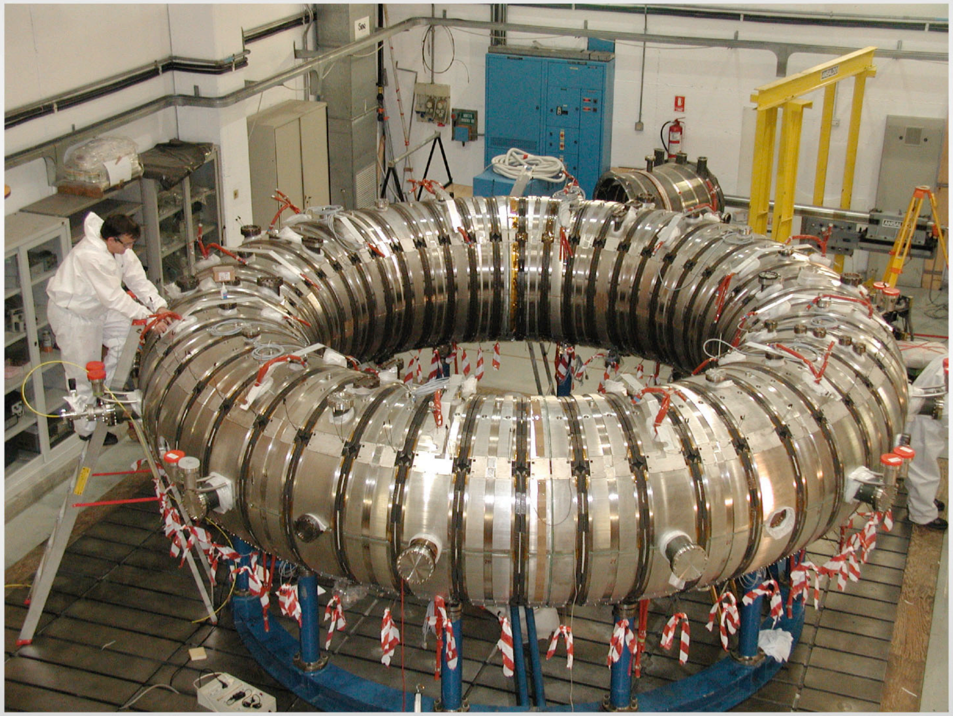
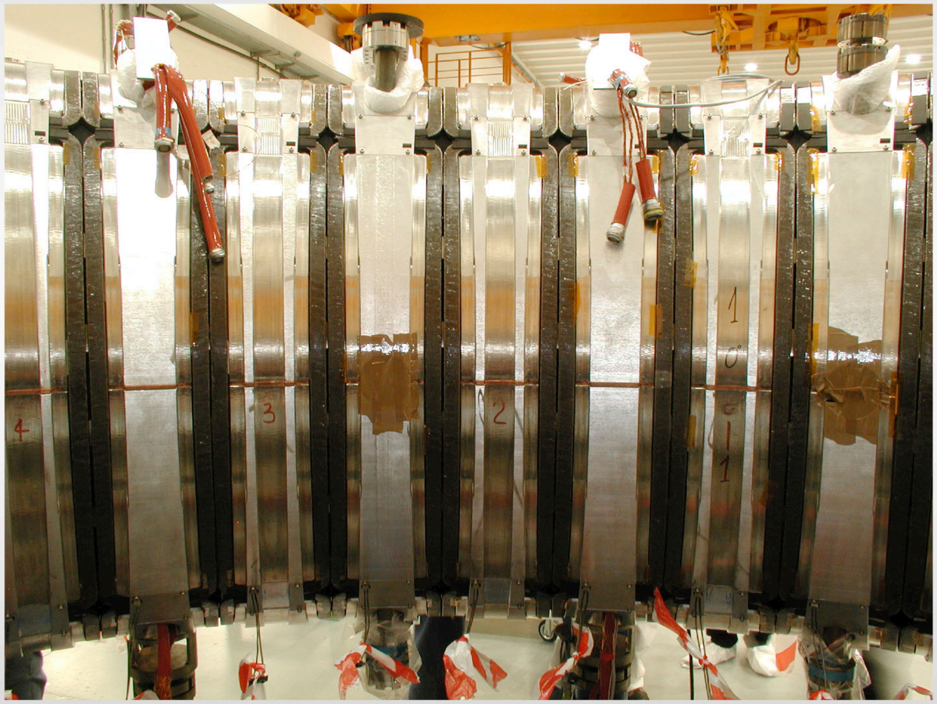
Assembly of the 192 Saddle Coils on the TSS

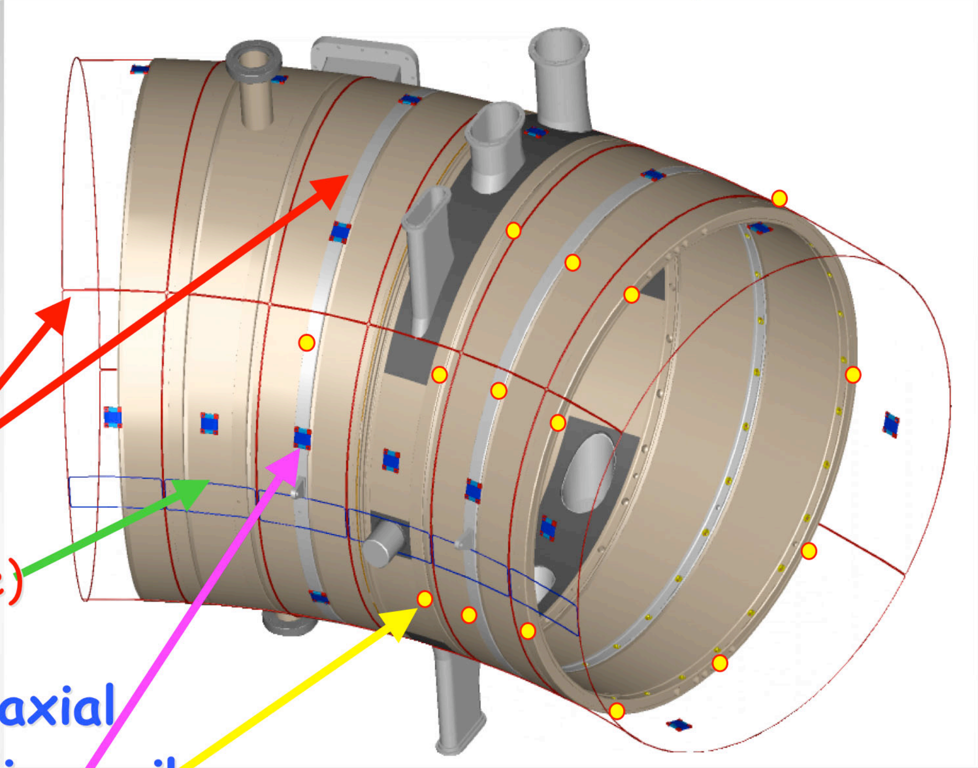




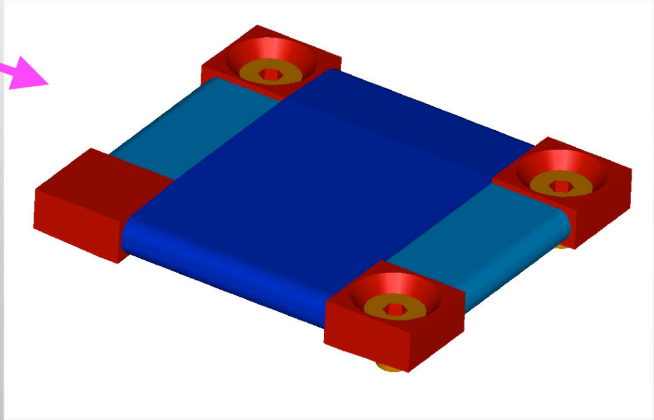
Ex-vessel magnetic and thermal probes

Probes between vessel and shell

- Integral probes:
  - 4 Rogowski coils for I_p
  - 8 toroidal voltage loops
  - 6 poloidal voltage loops
  - 32 partial V_{POL} probes for halo currents
  - 48x4 saddle probes for B_r
  - 48 saddle coils for B_r (on eq.plane)



- Pick up probes (40x36x4 mm bi-axial probe for B_T and B_P enamelled wire coils wound around single core):
  - 48 toroidal x 4 poloidal distribution
  - 2 higher resolution poloidal arrays



Magnetic probes total number ≈ 650

- Thermocouples:

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Aim of RFX modifications

- Improve the design of the plasma front end
  - First wall power handling capability;
  - Vessel wall protection;
  - Plasma breakdown;
  - Axisymmetric equilibrium control;
  - Poloidal gap field error;
  - Toroidal gap field error.

- Improve the active control of the MHD modes
  - Increase the torque applied to the plasma through the $m=0$ mode for RTFM
  - Produce $m=1$, $n= 1-20$ single o multiple mode to induce: mode rotation , *“single helicity”* and to actively control ext.& int. modes

RFX operational scenarios - 0

- Low current scenario
  - Theory (Guo, Fitzpatrick et al) and experiments (TPE-RX, EXTRAP T2R, MST) suggest that at low current RFX should see spontaneous dynamo mode rotation.
  - This is suitable to concentrate efforts on RWM control
- High current scenario (> 1 MA)
  - Better for confinement improvement techniques (OPCD) and for interaction with "dynamo" modes (but higher wall-locking probability).
  - Passive shell (and EXTRAP T2R experience) might postpone RWM issue up to ≈50-100 ms

RFX operational scenarios - 1

Benchmark and improve old RFX performance

- Actions by an applied *m*=0 mode (TF coils):
  a. RTFM (also in closed loop mode)
  b. PPCD/OPCD
  c. OPCD+ RTFM
  d. OFCD

RFX operational scenarios - 2

Active actions through 192 saddle coils:

- Apply *m* =1 magnetic perturbations
  - Work on individual modes: one at the time or several simultaneously
- Realize an intelligent shell
  - Zeroing of radial field at the edge to maintain an effective close fitting shell.
  - Interesting also for QSH studies, since a smooth magnetic boundary facilitates their onset.

RFX operational scenarios - 3

Drive of *m*=1 magnetic perturbations

- Apply a monochromatic perturbation to affect one individual mode:
  - "pumping" the mode to drive QSH states through helical fields at the plasma boundary
  - Feedback stabilization of individual modes
  - inducing rotation of a single mode

- Apply several simultaneous geometrical helicities (various *n*'s):
  - damping of main "dynamo modes"
  - feedback stabilization of RWM
  - breaking phase locking among "dynamo modes" with induction of modes differential rotations

2005 RFX program

- Plasma pulses start mid December 2004. The program for 2005 envisages 45 weeks of operation including 11 weeks of machine commissioning and 34 with plasma.
- Aim of first year is to test most of the increased flexibility of RFX covering many programs, including a first assessment of enhanced confinement regimes and active control of MHD instabilities.

Main objectives of first year

- Maximise the parameter range for spontaneous fast rotation of tearing modes.

- Establish a clear comparison with the reference passive operation of the old RFX.

- Explore scenarios for enhanced confinement.

- Active control of MHD instabilities:
    - feedback stabilisation of RWM,
    - control of single and multiple m=0,1 tearing modes
    - intelligent/wise shell.

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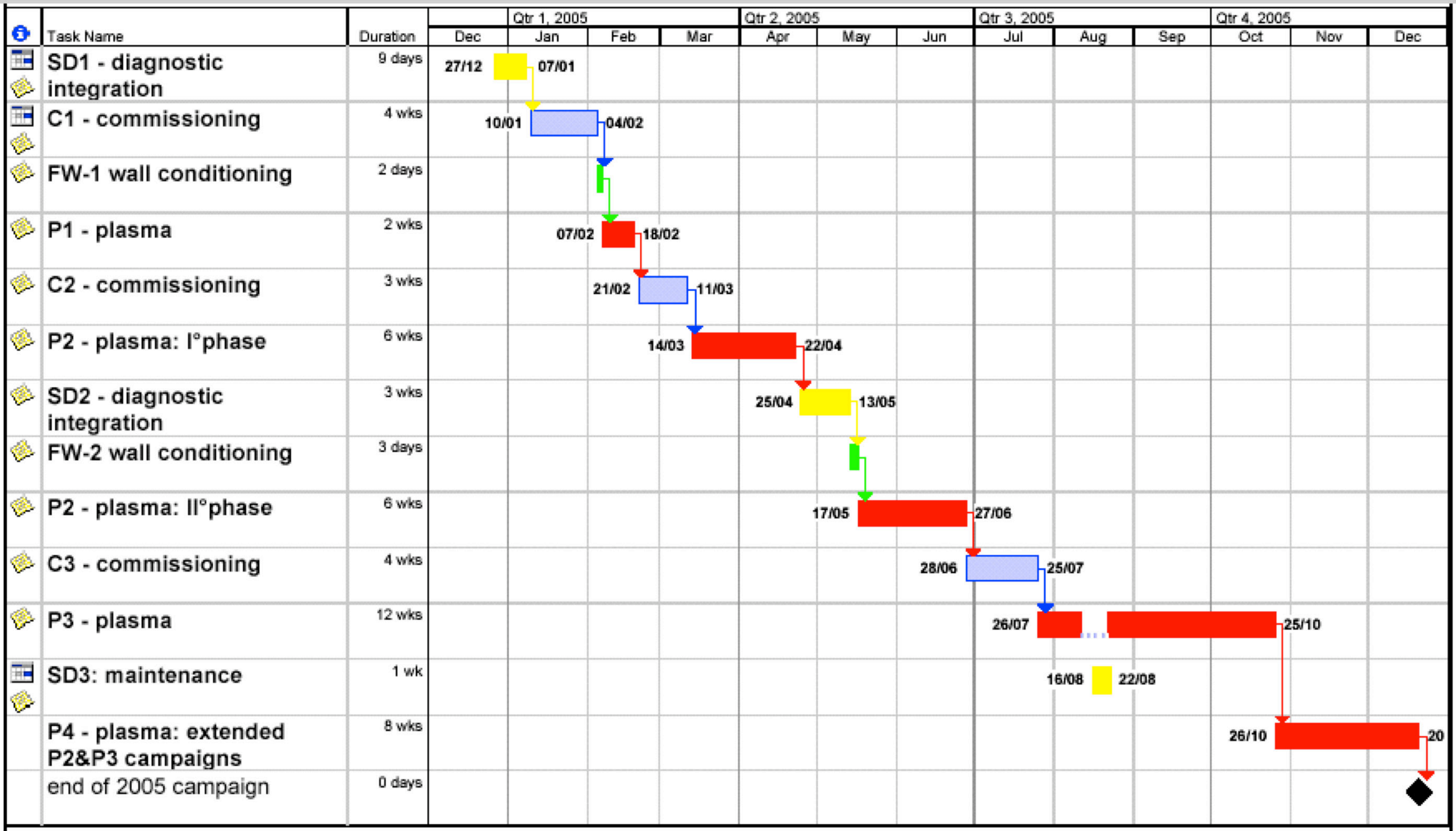
2005 planning



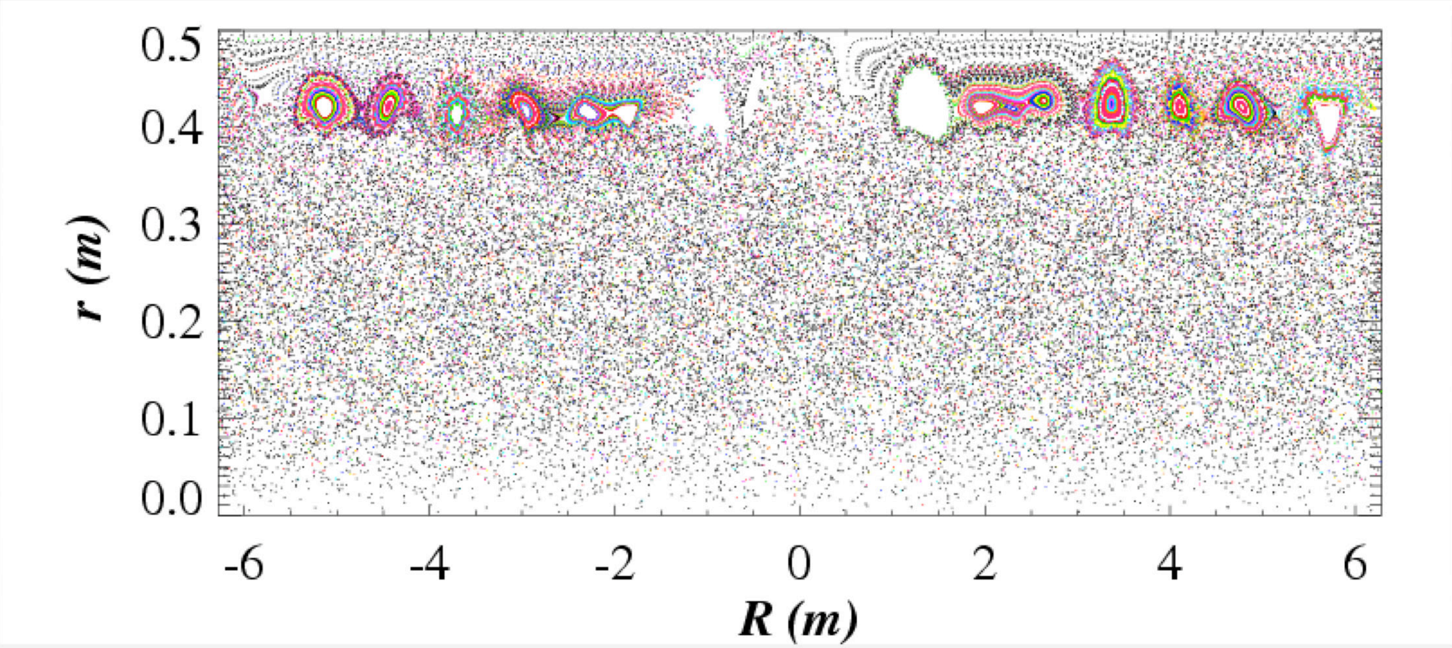
Task Name	Duration
SD1 - diagnostic integration	9 days
C1 - commissioning	4 wks
FW-1 wall conditioning	2 days
P1 - plasma	2 wks
C2 - commissioning	3 wks
P2 - plasma: I°phase	6 wks
SD2 - diagnostic integration	3 wks
FW-2 wall conditioning	3 days
P2 - plasma: II°phase	6 wks
C3 - commissioning	4 wks
P3 - plasma	12 wks
SD3: maintenance	1 wk
P4 - plasma: extended P2&P3 campaigns	8 wks
end of 2005 campaign	0 days

Thu 21/10/04

v.1

Shutdown: 6 weeks
Commissioning 11 weeks
Planned experimental campaigns: 26 weeks + 8 weeks (extension and/or maintenance)

P2 e: feedback control of m=0 modes



- Simulations show that the transport in the q=0 region is determined by amplitude and phases of m=0 and m=1 modes
- Acting on the phases of m=0 modes can influence closed structures in the reversal region
- Minimising m=0 amplitudes is important also for favouring QSH

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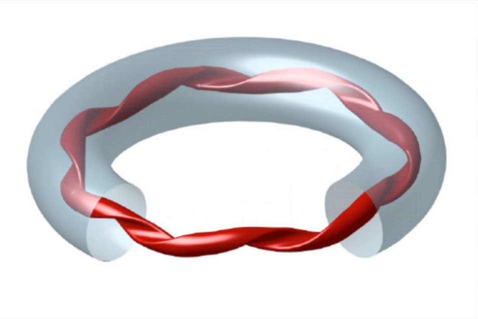
P2 g: experiments on QSH

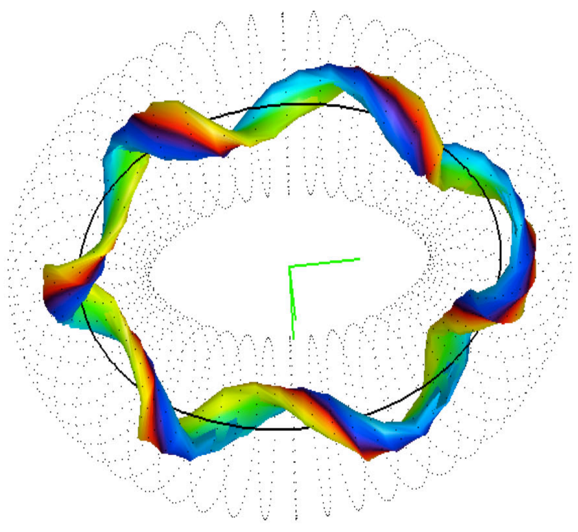


- Investigate conditions which help onset of QSH states
  - Parameter scans
  - Magnetic boundary optimization
    - Feedback controlled equilibrium
    - P/OPCD

- Diagnostic improvements will allow
  - Particle and energy confinement studies
  - Ion dynamics measurements
  - Determination of the plasma flow correlated with QSH

MAC-302

SXR isoemissive surface during a rotating n=6 QSH in MST



Based on a sequence of 2D tomographic reconstructions

P2 h: Self-similar current decay

- Aim: suppressing the dynamo and establishing the confinement and β limits for the RFP configuration
- Rationale: 3-D MHD simulations show that a stochastic plasma reaches a condition of low amplitude modes by applying proper time-dependent magnetic boundary conditions (R.A.Nebel et al, PoP 2002)
- The decay rate is about $-\gamma \approx -10/\tau R$
- In RFX a first test of this prediction will be performed

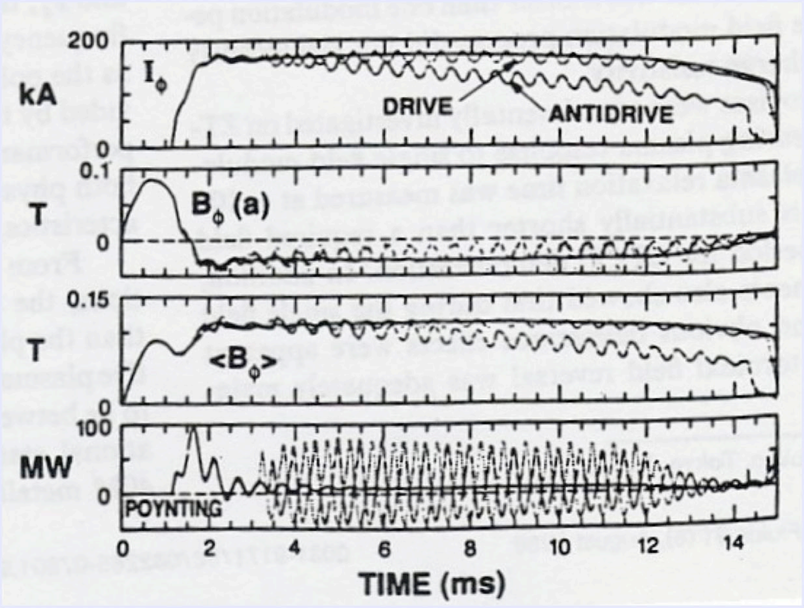
P2 i: Oscillating Field Current Drive

➢ Motivations:

- study of steady state current drive in RFP
- perturbative study of dynamo mechanism

Range of parameters:

- frequency of the 100-150 Hz
- amplitude 20 V toroidal and 25 V poloidal



Phys. Fluids, Vol. 31, No. 8, August 1988
Schoenberg *et al.*

PLANS:

- ➢ Use new power supply system to test the concept on RFX
- ➢ Optimize of plasma and power supply parameters
- ➢ Coordinate experimental plans with MST (different frequencies and plasma regimes)

P3 1b: Active Control of tearing modes

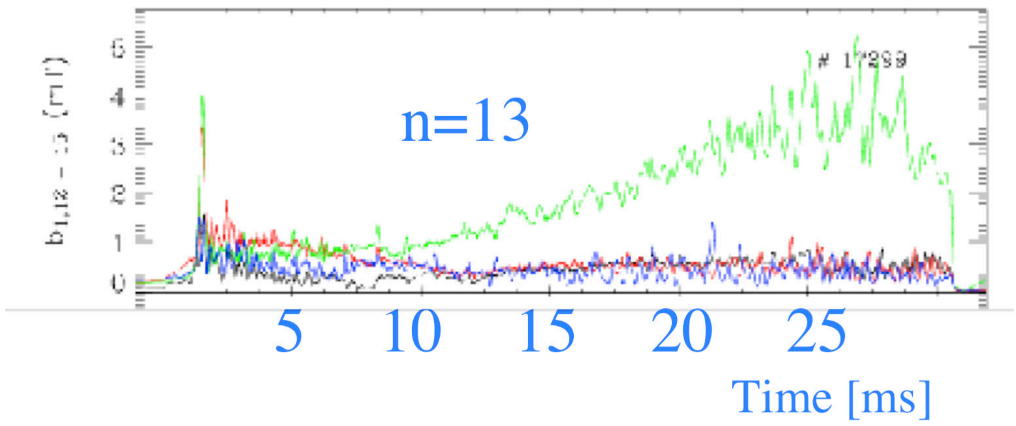
Open loop and feedback control on single/multiple dynamo modes including:

- induction of QSH regimes
- drag of locked tearing modes into slow rotation and control of their relative phases.

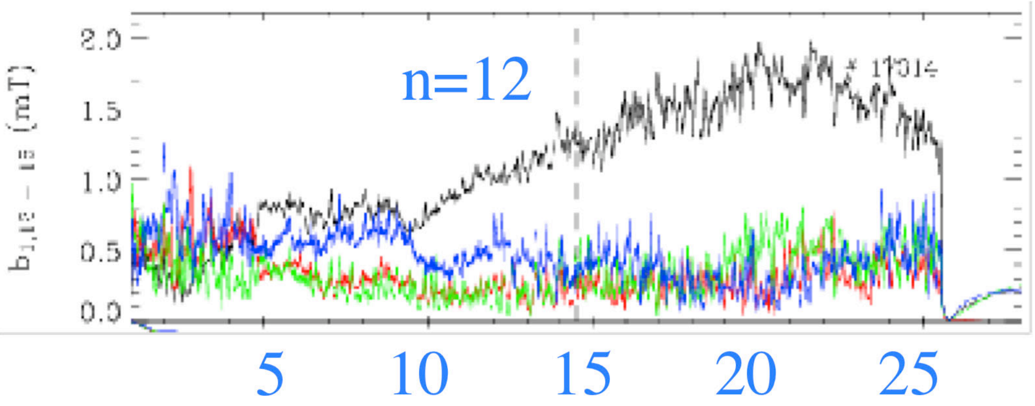
Encouraging results from T2R:

- Pre-programmed helical perturbations with resonant helicities (open-loop)
- Feedback suppression of other resonant modes (closed loop)

Open loop



Closed loop



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RFX-Tokamak operation

- With its highly flexible diagnostic and control system, RFX could contribute also to studying MHD mode control on tokamak plasmas

- A maximum Bφ = 0.6 T allows us to set up a Tokamak with:
  - I = 100 kA @ q(a)=3
  - A total flux swing of 6-7 Vs permits to sustain the plasma for times much longer than the 50 ms shell time constant

- **We are open to suggestions/proposal for collaborations also in this area!**

This is the last workshop without RFX

Hopefully this is the last workshop…

OPS…

I FORGOT A SLIDE FROM LAST YEAR WORKSHOP!

s

proposals from You

END