THE RFX MODE CONTROL PROGRAM: PHYSICS ISSUES AND PLANS

Piero MARTIN

Consorzio RFX

Associazione Euratom-Enea sulla fusione

Padova, Italy

Workshop on Active Control of MHD Stability: Extension of Performance

Columbia University, NYC - 18-20/11/2002

Contributions to this talk

RFX:

- A. Luchetta, S. Ortolani, R. Paccagnella, N. Pomaro, G. Serianni, P. Sonato,

EXTRAP T2R

- P. Brunsell, J. Drake, J.A. Malmberg

The co-authors of the IAEA 2002 paper :" *Overview of Quasi Single Helicity experiments in RFP devices*"

Outline

- Main recent MHD issues in the RFP research: the basis for our future activity
- The RFX modifications: a facility for MHD studies
- The experimental plans
- Conclusions

RFX reconstruction

RFX (Reversed Field eXperiment) is a RFP device, which is presently under reconstruction:

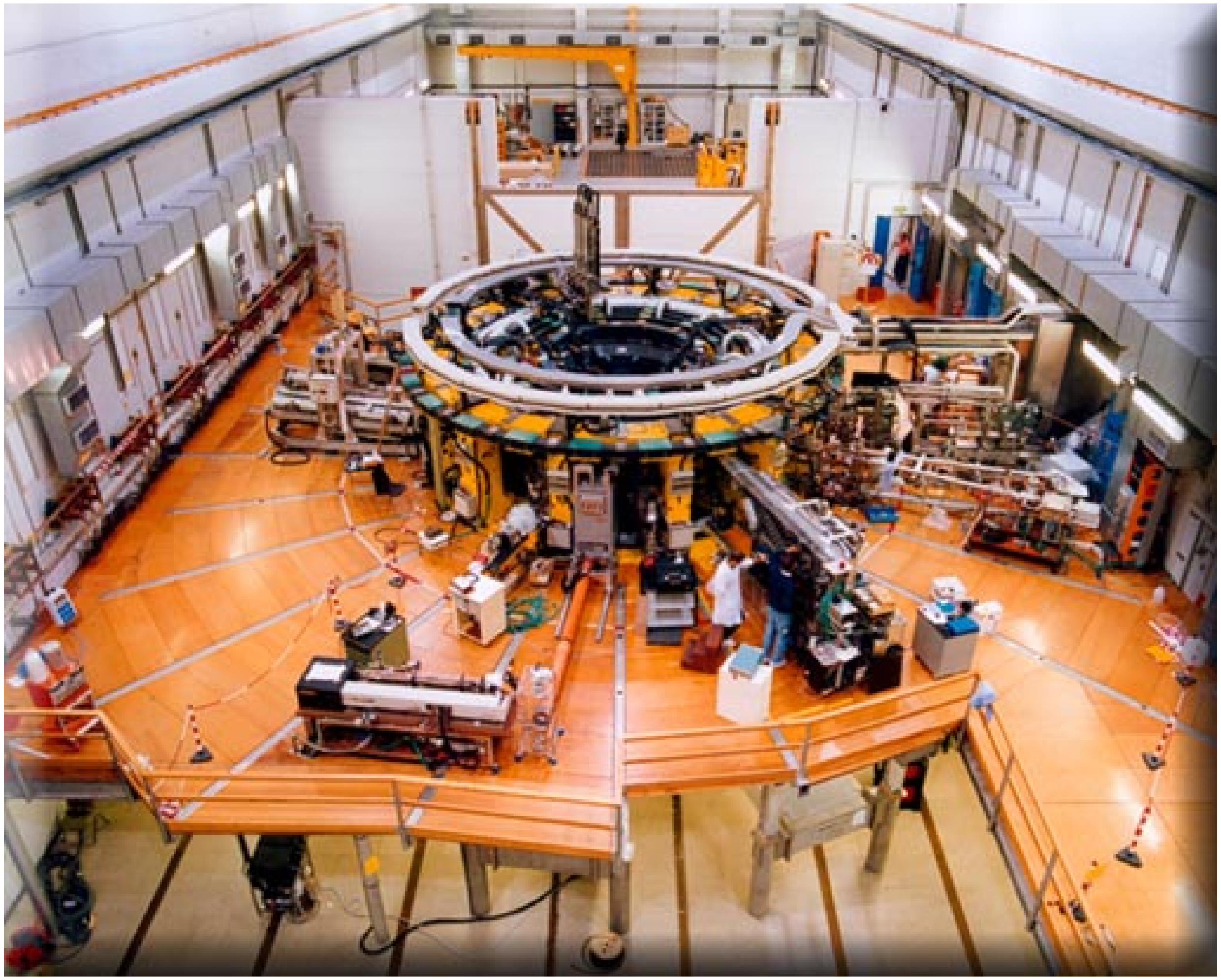
- to replace the power supplies destroyed by the fire
- to install a new magnetic front-end:
  - shell, feedback system, sensor system

This will allow a significant expansion of the research program, mostly to exploit:

- RFP physics and confinement at high current (2 MA)
- active control of MHD modes through an advanced feedback system

The RFX device

R= 2 m, a=0.46 m

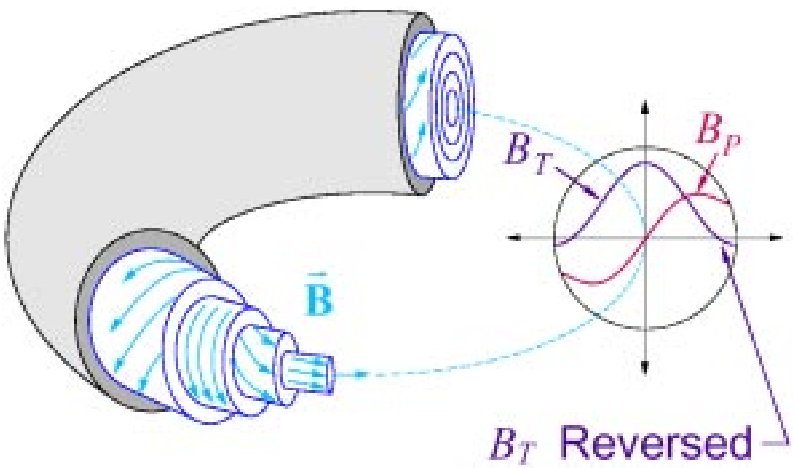


The Reversed Field Pinch (RFP)

The RFP belongs to the class of PINCH configurations (like the tokamak)

It has **TOROIDAL and POLOIDAL** magnetic field components:

- whose amplitudes are **SIMILAR**
- which are mainly produced by **CURRENTS** flowing inside the plasma.
- Plasma currents, through a magnetic **SELF-ORGANIZATION** process, are responsible for the reversal of the toroidal field at the edge.



The external magnetic field is WEAK (≈0.4 T for 1 MA in RFX)

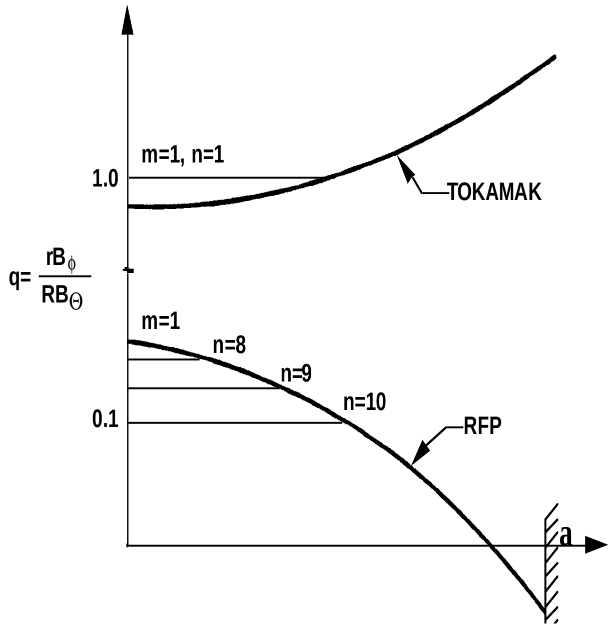
The modes we have to deal with

m=0

- various *n*: resonant at the B_t reversal surface

m=1

- ***|n| ≥ 2R/a,*** resonant inside the B_t reversal surface (resistive kink, “dynamo modes”)
- ***|n| ≤ 2R/a,*** internally non resonant from above (RWM, with the same helicity as the “dynamo” modes and the same handedness as the core **B**)
- ***|n| ≤ R/a,*** externally non resonant (RWM, with opposite helicity)



m=1 "dynamo" modes internally resonant

reduce their impact on transport

magnetic chaos, wall-locking

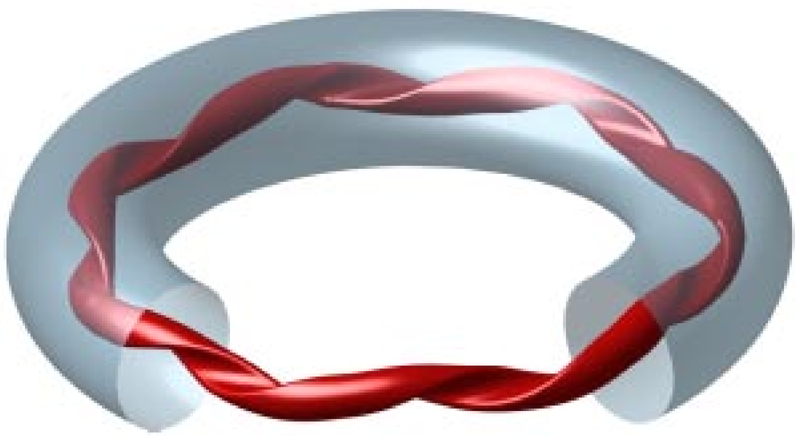
Spontaneous self-organization towards helical states

SINGLE HELICITY

The RFP Single Helicity state: why it is appealing?

Single Helicity (SH):

- a state with a unique *m*=1 saturated resistive kink (a pure helix wound on a torus), theoretically predicted.
- SH is the result of a chaos-order spontaneous transition in a complex system
  - ***shares a lot of physics with other natural systems***
- Stationary LAMINAR dynamo mechanism with good helical flux surafaces



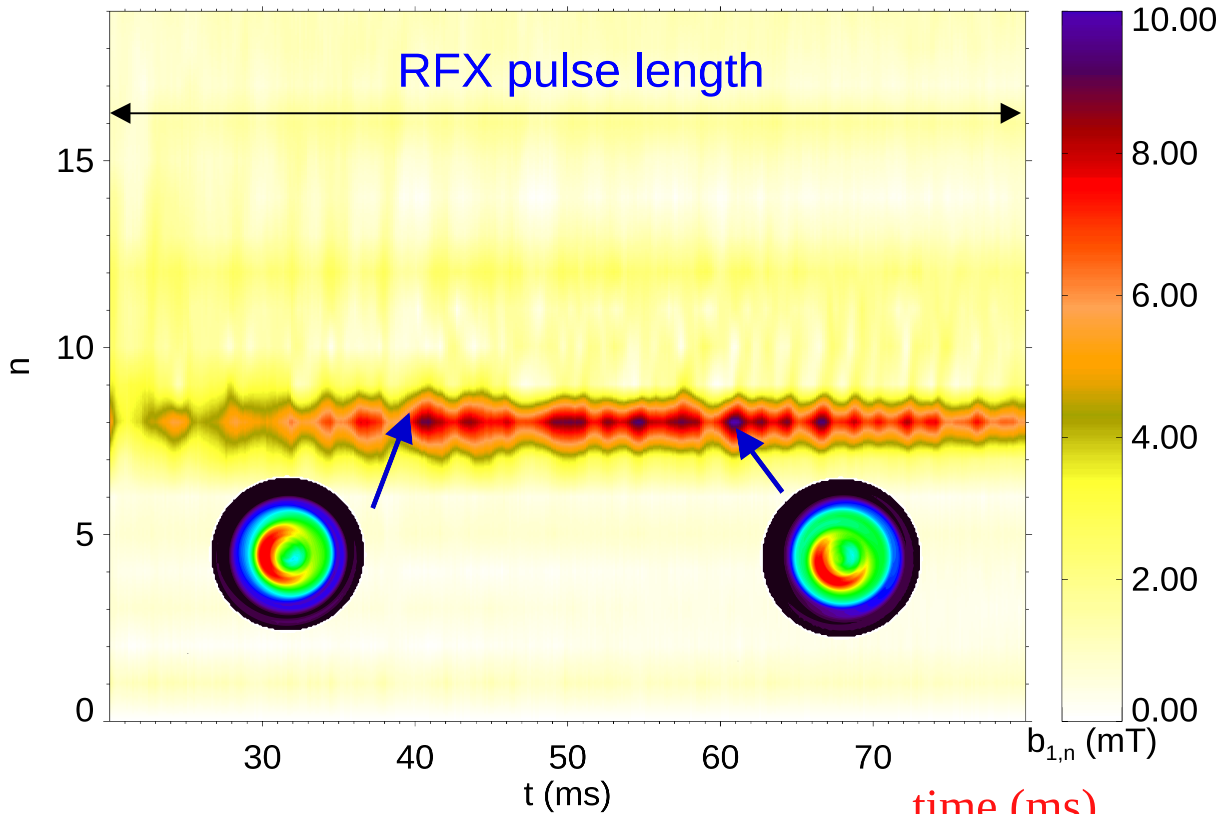
Setting the RFP in the SH state might lead to extremely significant confinement improvement.

Quasi Single Helicity (QSH) in the experiment

Stationary Quasi Single Helicity spectra have been observed in RFX (**IAEA 2000**)

- **with an helical coherent structure emerging from magnetic chaos in the plasma core.**
- **The spectrum is not pure: secondary modes have non-zero amplitude, the dominant kink is smaller than in SH.**

Toroidal mode number *n*



time (ms)

RFX

Escande et al., PRL 2000)

The tools

EXPERIMENTAL DEVICES

– RFX	(EU)	R/a = 2.0 / 0.46	(m)	I =1.1 MA
– MST	(USA)	R/a = 1.5 / 0.52		I =0.5 MA
– TPE RX	(J)	R/a = 1.72 / 0.45		I =0.5 MA
– EXTRAP T2R	(EU)	R/a = 1.24 / 0.18		I =0.1 MA

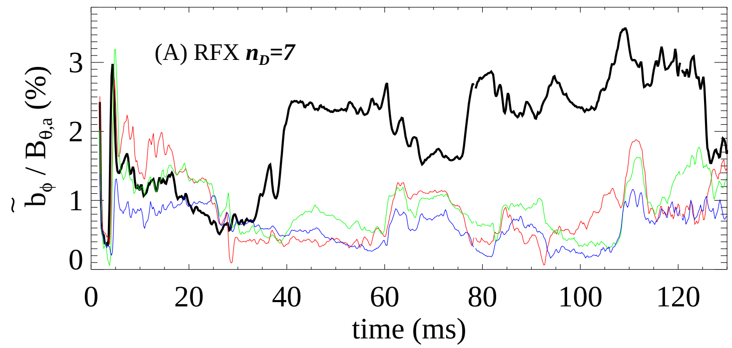
NUMERICAL CODES

– ORBIT	hamiltonian guiding center Montecarlo code	(USA)
– NIMROD	3-d MHD - toroidal and cylindrical geometry	(USA)
– SPECYL	3-d MHD - cylindrical	(EU)
– DEBS	3-d MHD - cylindrical	(USA)

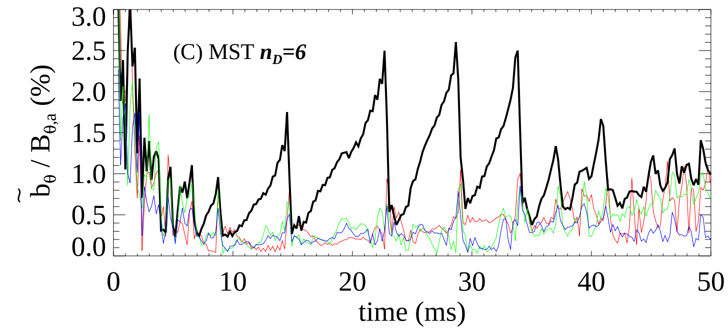
QSH: a robust phenomenon

M=1 modes evolution

RFX



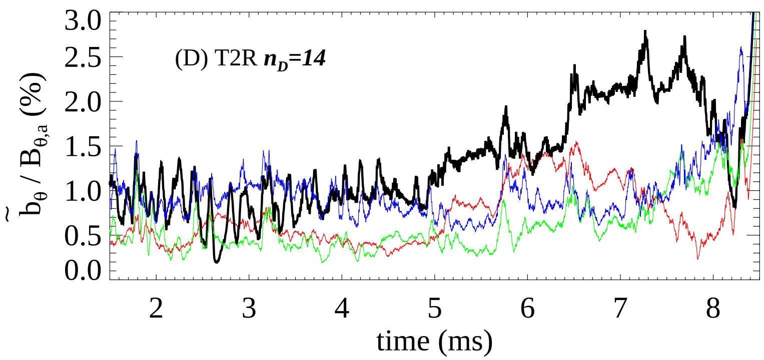
MST



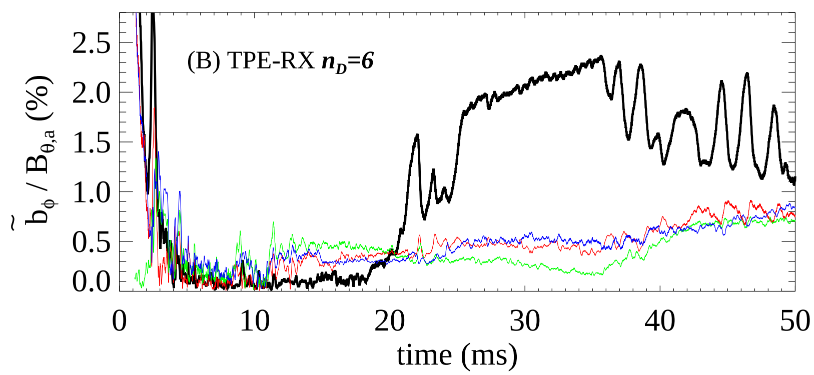
QSH SPECTRA ARE FOUND IN ALL THE DEVICES, IN A WIDE SET OF EXPERIMENTAL CONDITIONS

More frequent at high current

EXTRAP T2R



TPE-RX



QSH: a selection process

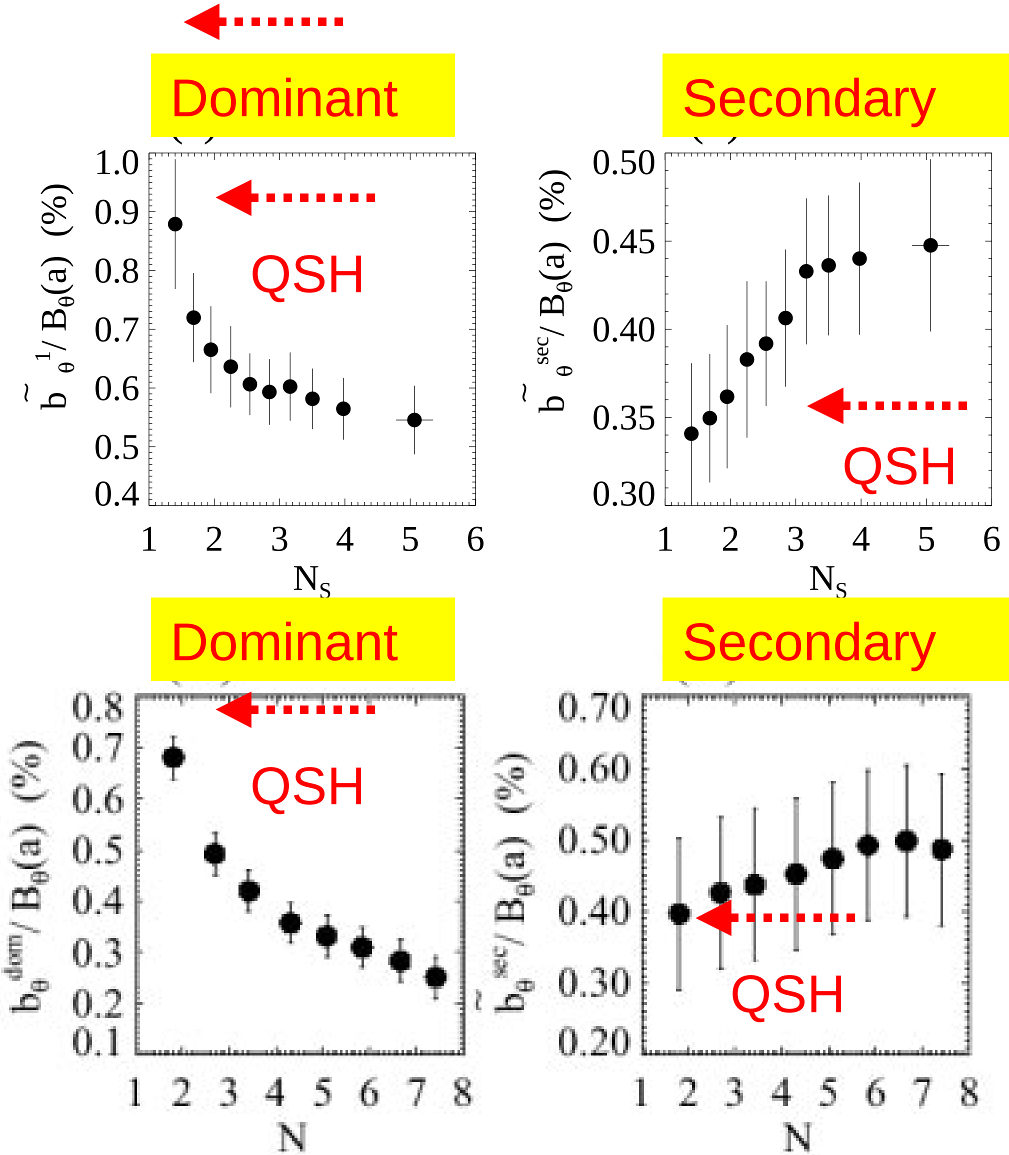
MST

The dominant mode takes the energy at the expense of the others (secondary)

Secondary modes strongly responsible for magnetic chaos and spoiling confinement

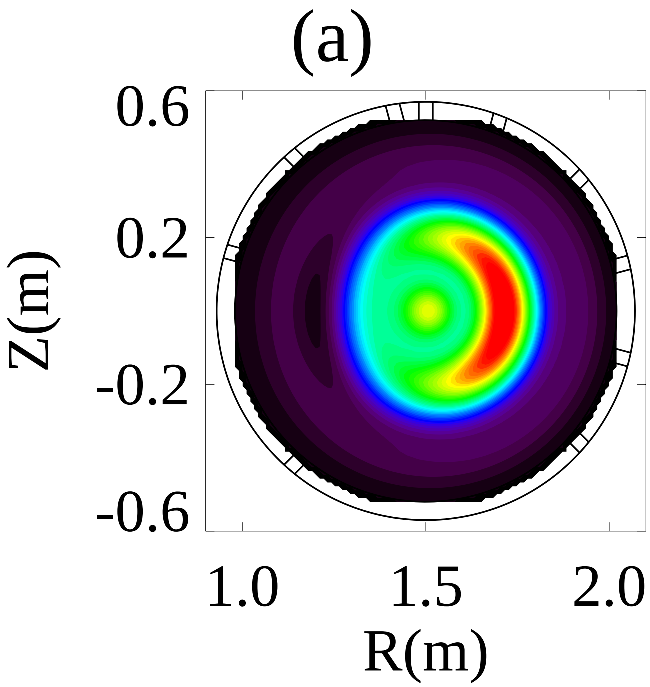
(*Sarff, this morning*)

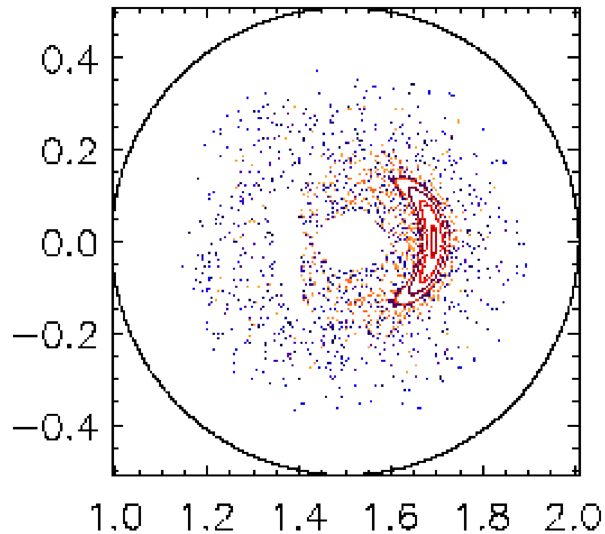
TPE RX



Magnetic flux surfaces theoretical reconstruction

From experimental magnetic fluctuations measurements we reconstruct magnetic field lines trajectories with the ORBIT code





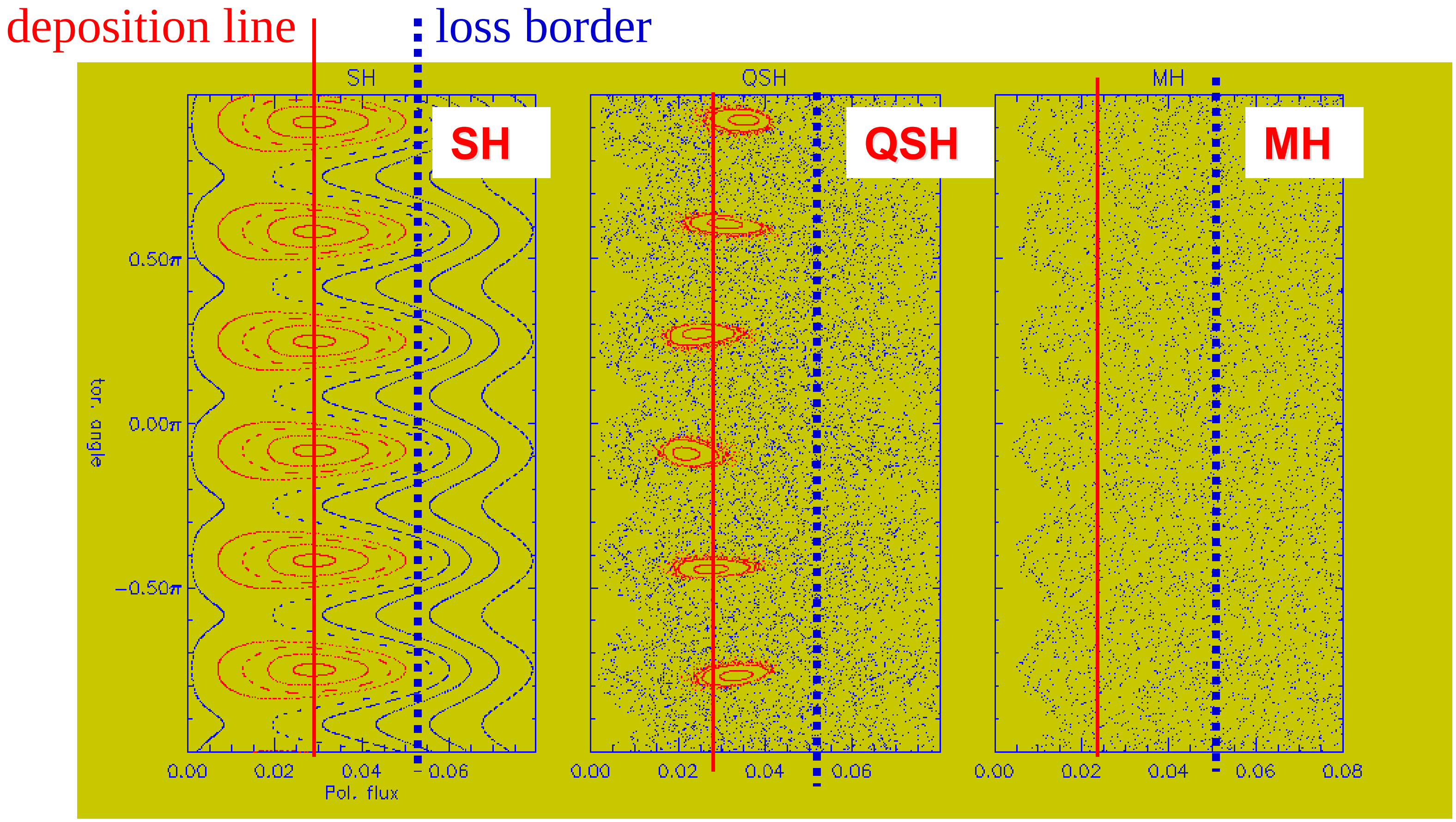
The measured magnetic perturbation is consistent with the observed helical structure

Particle transport studies: SH-QSH *vs.* MH

Particle loss time has been studied with ORBIT (R.White, PoF 90).

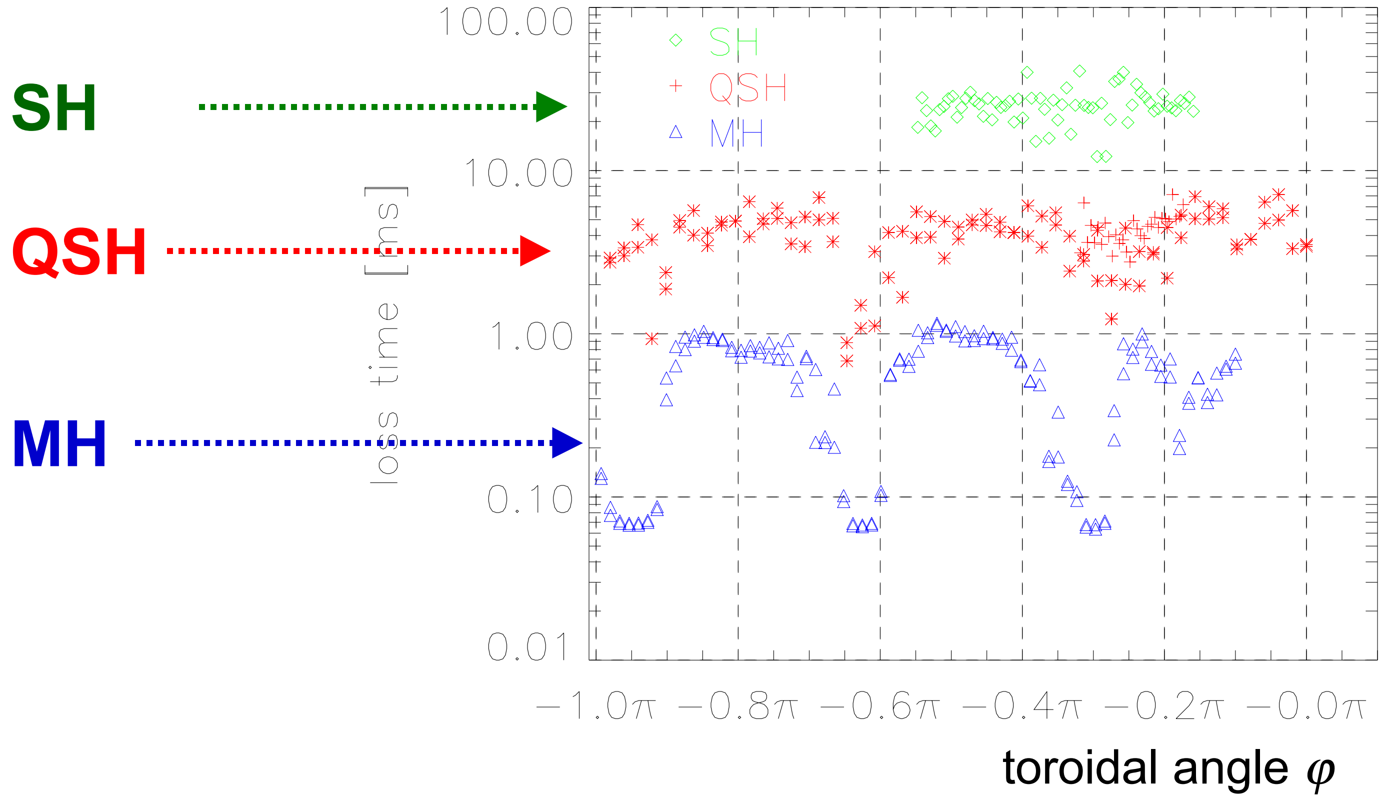
Population of test particles deposited in the plasma core.

Their diffusion outside a fixed border is monitored



Transport and helical states

Comparison between loss times as a function of initial toroidal position of the particle population with ORBIT
(I=400 kA, Bwall=0.16 T)



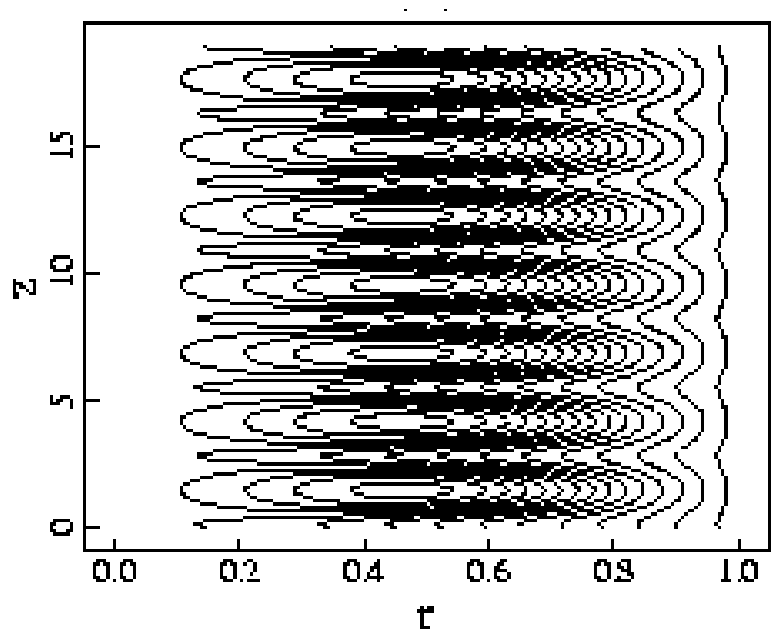
SXR emission is higher when the spectrum is narrower

Simulation of finite β SH with NIMROD

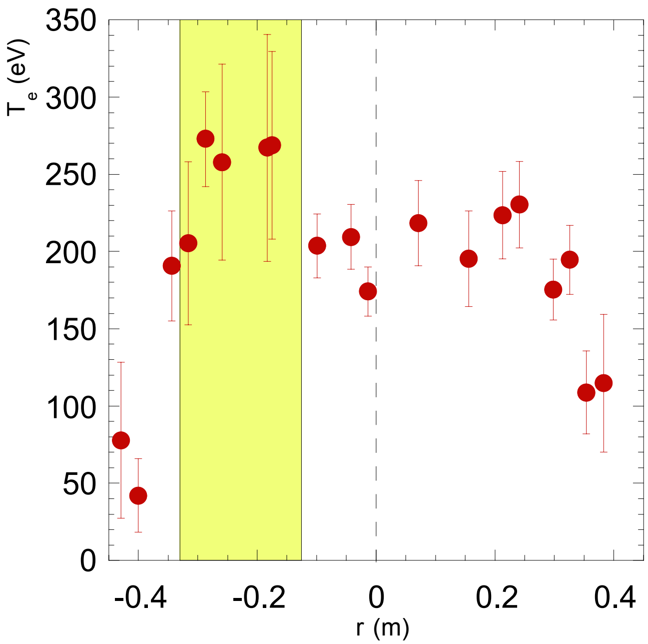
- SH RFP simulations performed at finite β (≈12%) to investigate pressure-driven mode stability

- The computed temperature distribution resembles experimental measurements

Nimrod Te contour plot



RFX Te(r) profile



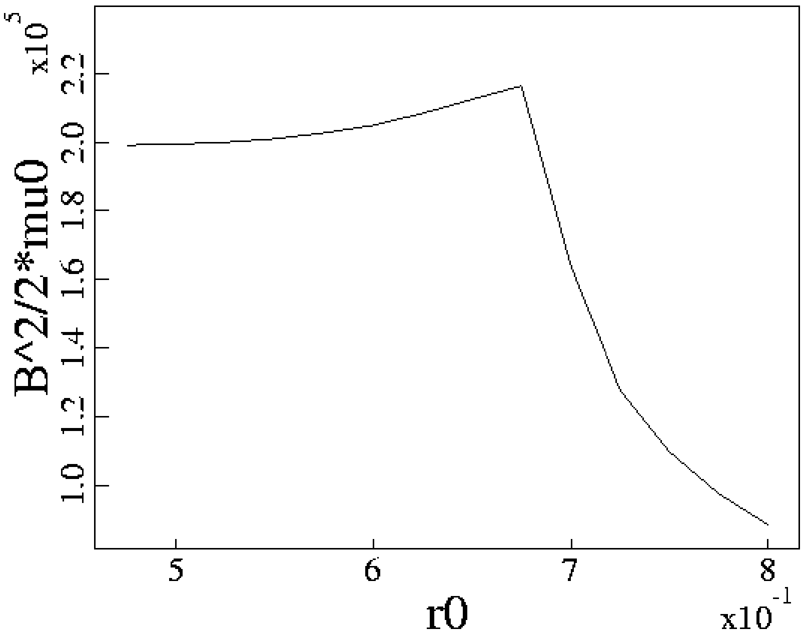
Magnetic well in the SH RFP

The helical flux surfaces in SH have distinct topology that resemble stellarator-like configurations

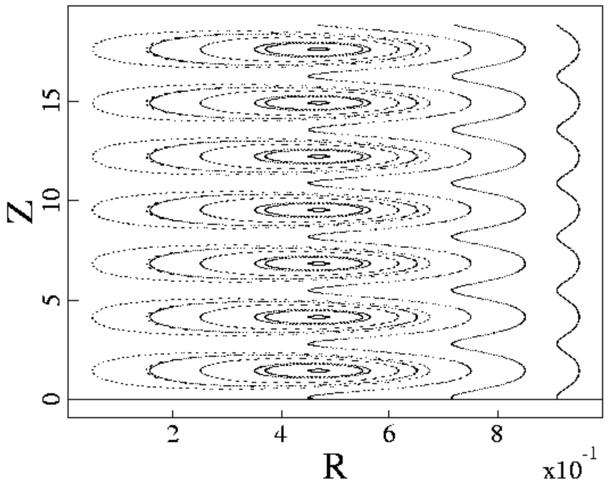
- (different from standard axisymmetric RFP)

a <u>magnetic well</u> exists from the helical magnetic axis to the separatrix

(Consistent with Miller theoretical predictions, PoF 1983)



NIMROD

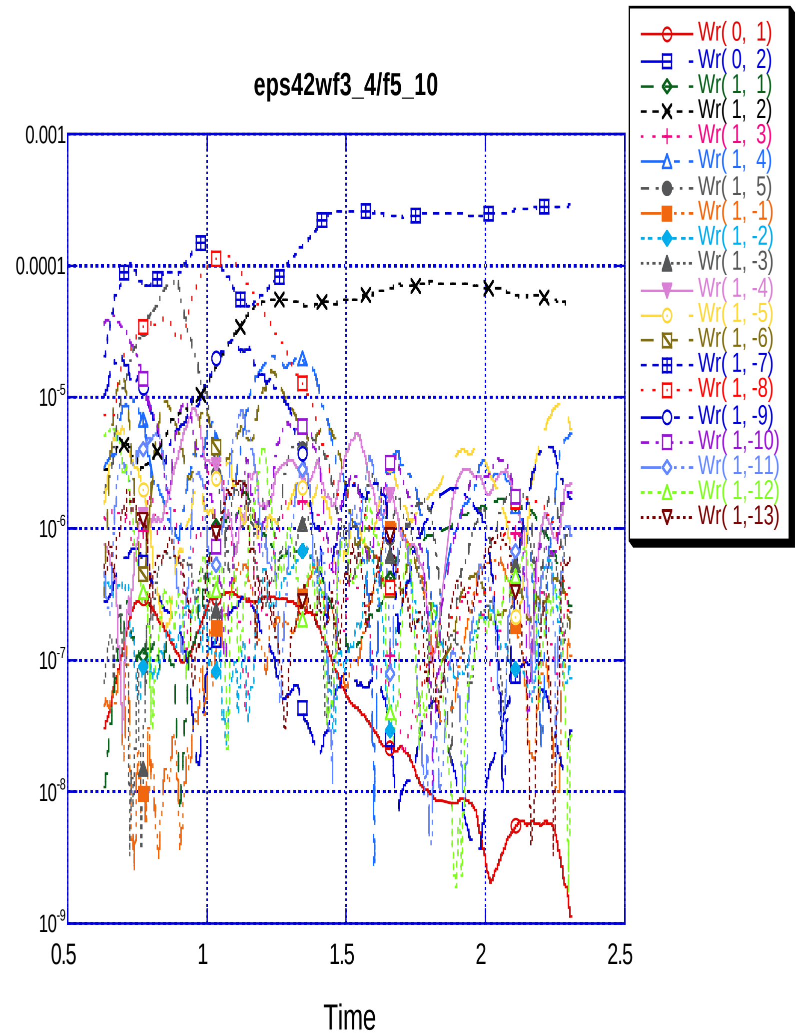


Active drive of SH: numerical results

Numerical simulations of the feedback of MHD modes, performed with the cylindrical DEBS code, show that

the drive and control of a SH spectrum, with a dominant mode, is possible (even starting from a MH base plasma)

R. Paccagnella, this workshop



Conclusions on helical states

- Long lasting self-organized QSH states have been found in several experiments.
- Good agreement with theory
- Experimental hints of a more steady dynamo action provided by the dominant mode during QSH: suggestive signatures of a path towards SH laminar dynamo
- Numerical simulations show that good particle confinement properties and the existence of a magnetic well are distinctive features of helical RFPs.
- The formation of states with one dominant helical mode (Ohmic Single Helicity state) is an approach complementary to active control of magnetic turbulence to improve confinement in a steady state RFP.
- Clear plans on what needs to be investigated in the future (and tools available)

A TASK WHICH UNIFIES THE RFP EFFORTS AND CAN PROVIDE CONTRIBUTIONS TO THE FUSION AND PHYSICS COMMUNITIES

Active damping of dynamo modes

Pulsed Poloidal Current Drive (PPCD)

(S. Prager's talk, APS)

Oscillating Poloidal Current Drive (OPCD)

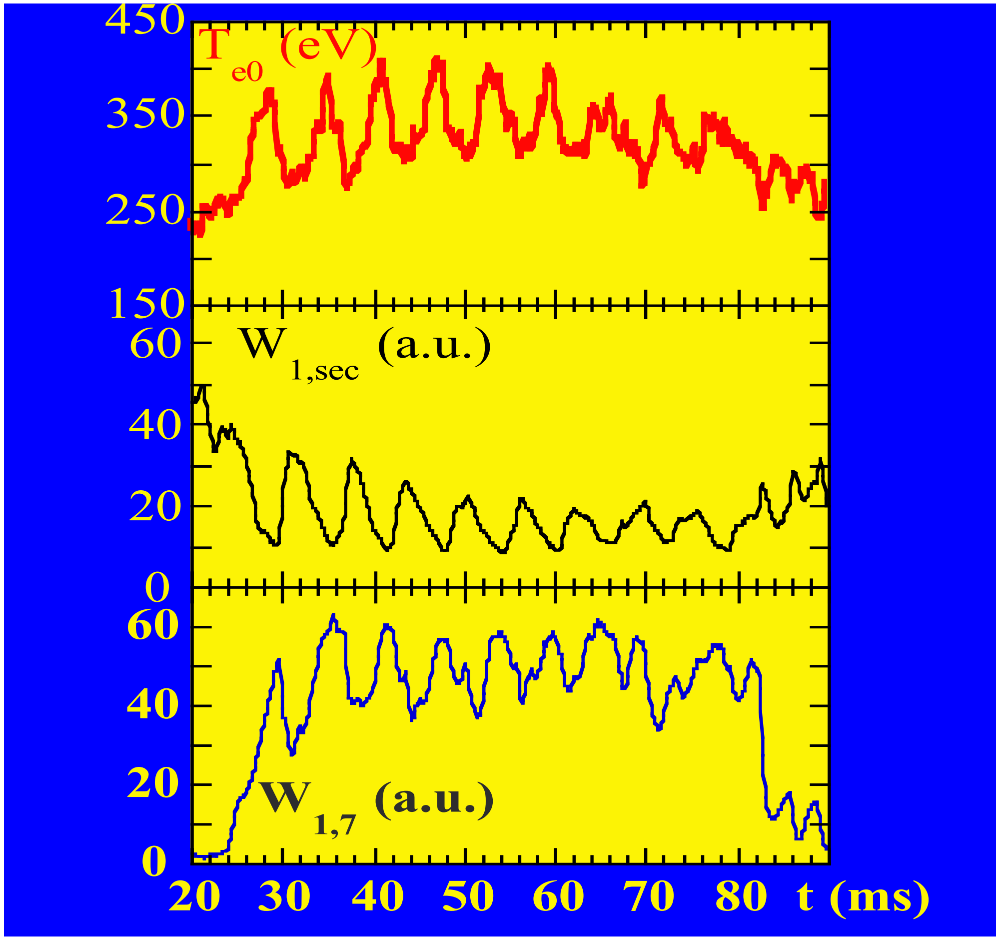
Overcomes the transient nature of PPCD

Oscillating Poloidal Current Drive (OPCD)

Periodic (oscillating) applied inductive variations of the poloidal electric field allows to extend the PPCD benefits in a stationary fashion

stationary average improvement of confinement obtained with OPCD in RFX

(*Bolzonella et al., PRL 2001*)



Induced rotation of wall-locked dynamo modes

allows high current operation

CONTINUOUS ROTATION OF LOCKED MODES

The continuous rotation of locked modes obtained by applying to the plasma through the TF coils a **(*m*=0,n=1) rotating magnetic perturbation B_r^{01}.**

B_r^{01} induces a sheet current at m=0 resonant surface and produces a torque on (0,1) mode

$$T_{ext}^{0,1} \propto b_r^{0,1} B_r^{0,1} \sin(\Delta\varphi)$$

The applied torque is transferred to *m*=1 modes via non-linear coupling

(1,n)

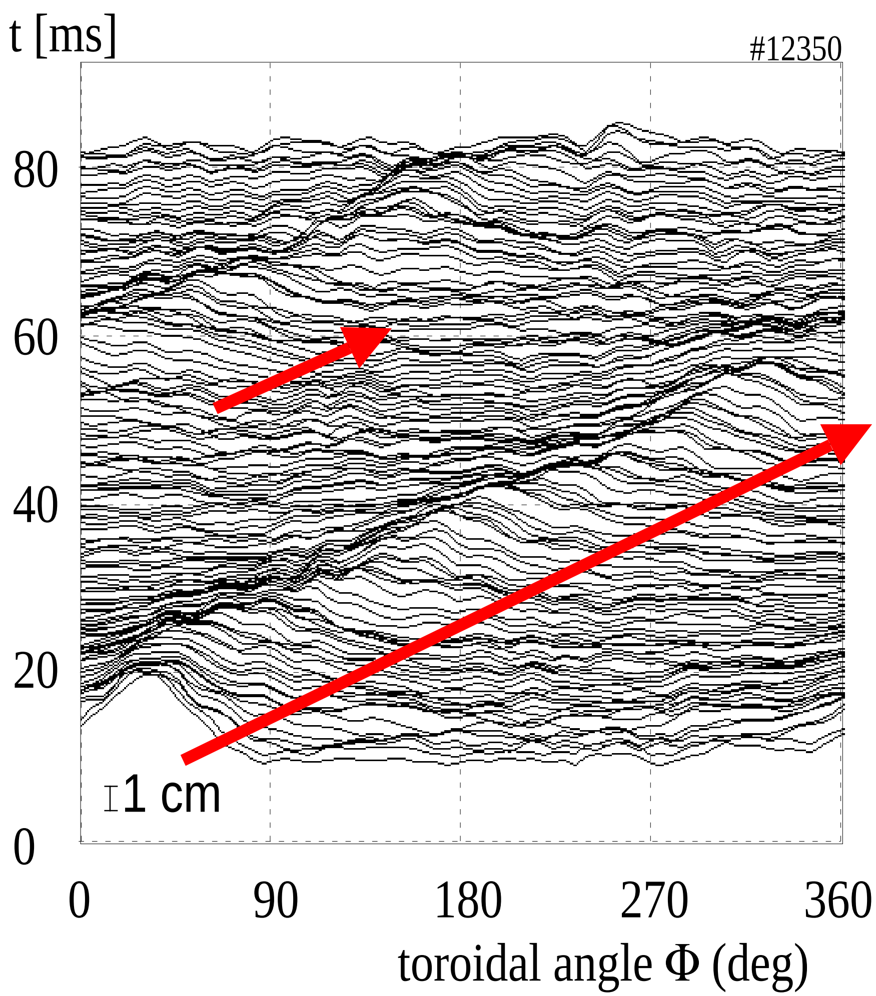
(1,n+1) → **(0,1)**

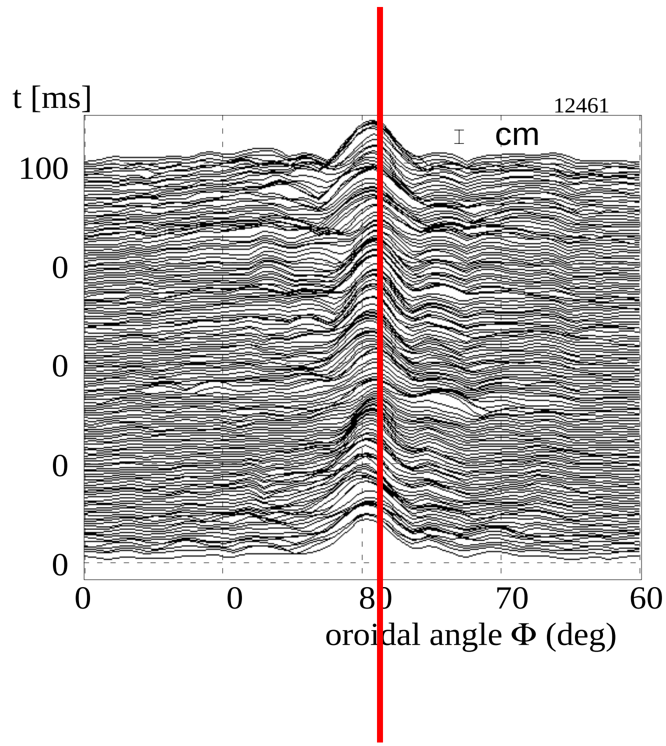
$$T_z^{1,n}$$

Bartiromo et al., Phys. Rev. Lett. 82, 1462 (1999)

Active rotation of MHD modes

T
i
m
e





Resistive Wall Modes

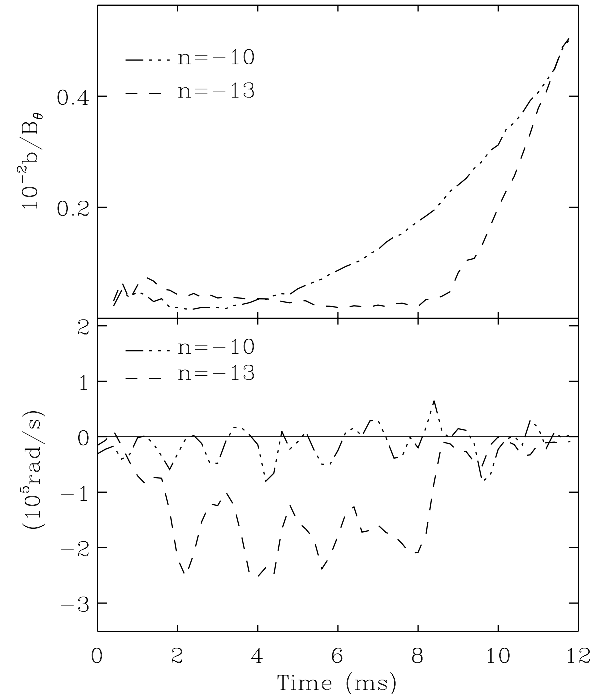
RWM in EXTRAP T2R

Resistive wall instabilities and tearing mode dynamics have been studied in the Swedish EXTRAP T2R device

(Malmberg, Brunsell, PoP 2002)

EXTRAP T2R (rebuild version of the OHTE device) is a metal wall thin shell device ($\tau_w \approx 6$ ms): a unique device to build an experimental background on RWMs in the RFP

- Discharges as long as ≈3 τ_w have been produced
- RWM linear growth rates have been measured and they agree with theoretical estimates
- RWM characterization as a function of plasma global parameters



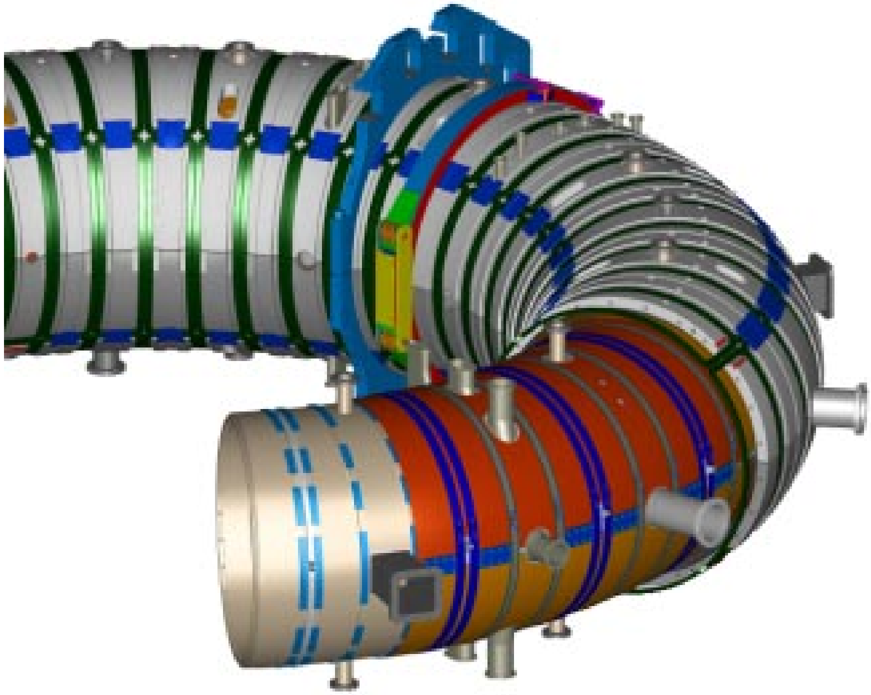
J.A. Malmberg's talk on T2R results-this workshop

The RFX device modifications

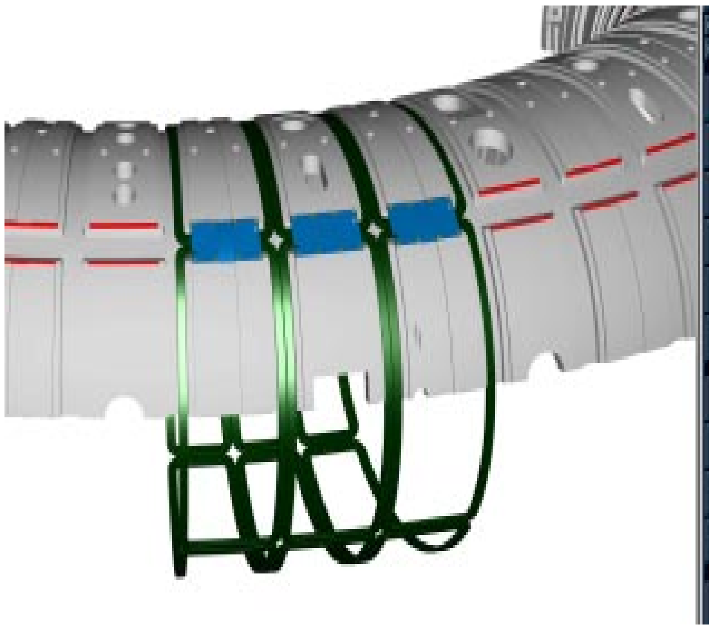
Main new components of the experiment (MHD relevant):

- thinner and closer shell (**τ_s≈50 ms**, *b*/*a*≈1.1, compared to the old τ_s≈400, *b*/*a*~1.2)
- high spatial resolution active coil array (**4 poloidal x 48 toroidal coils**) and power supplies
- ex-vessel magnetic and thermal trasducers:
  - **650 magnetic probes**
  - **≈200 thermocouples**
- in-vessel system of sensors:
  - **140 pick-up coils**
  - **100 electrostatic probes**
- smoother and thinner graphite first wall

The new RFX load assembly



- *48 x 4 = 192 active coils*
- *each independently powered*
- *24 kAt: 400 A x 60 turns*



- *New power supply for the TF coils*

Applied *m*=0

The new TF power supply allows for upgraded performance when a *m*=0 perturbation is applied

	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

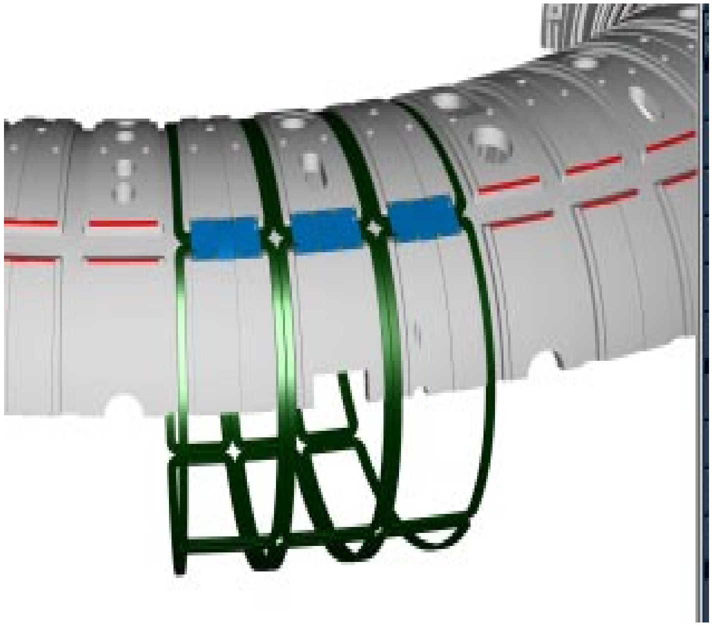
B_{tor} new ≈ 6 x B_{tor} old
at 25 Hz with 3kA

Active saddle coils

192 indpendent saddle coils covering the whole plasma surface

Wide spectrum of Fourier components can be produced:

- m=1,2
- n ≤ 24
- DC < f < 100 Hz



Example: edge b_r for (1,8) mode:

- 20 mT@10 Hz
- 1.3 mT @100 Hz

Relevant MHD time scales

The new RFX magnetic front end (passive shell + active coils) allows

- for clear separation between relevant MHD time scales and
- for decoupling of the control strategies.

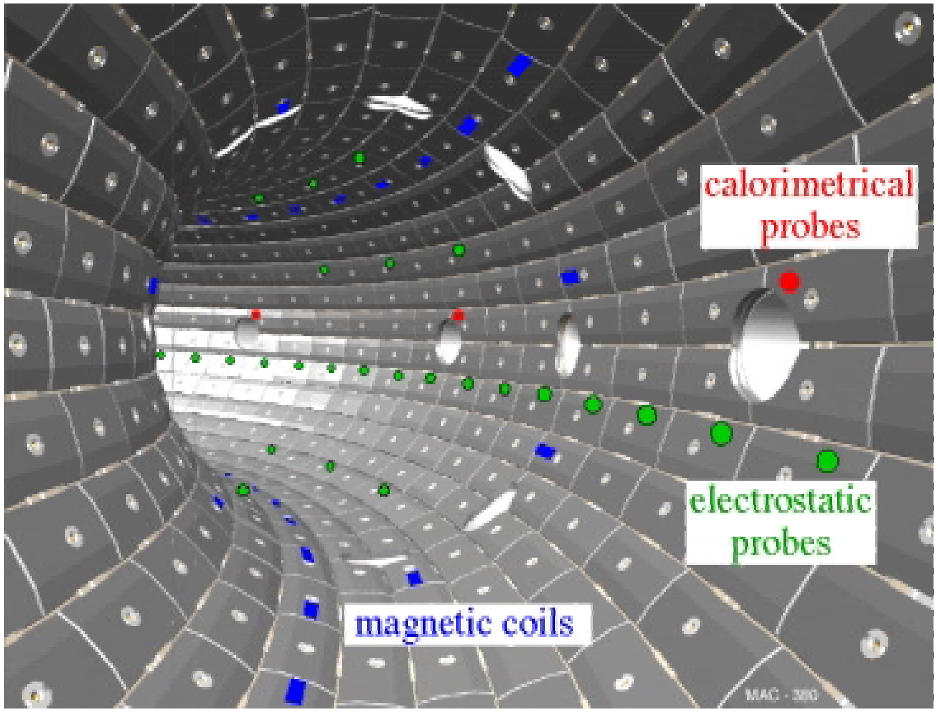
Pulse lengthe > 100 ms

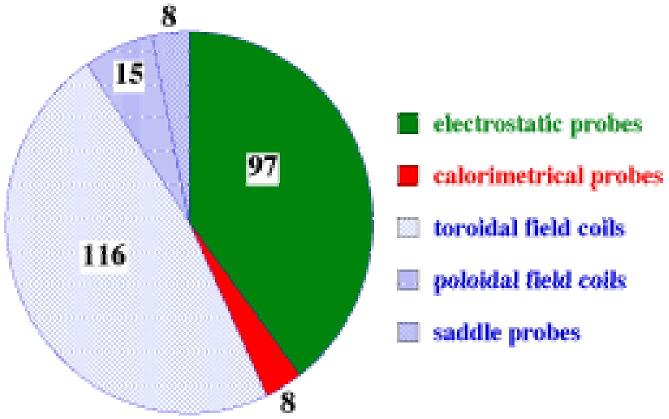
The shell passively stabilizes RWM on time scales ≈ 50 ms

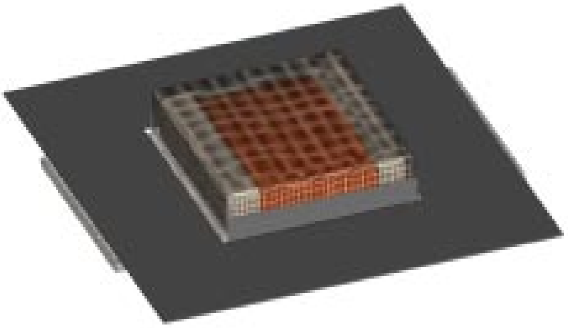
- In this time lag we can concentrate on problems related with internal “dynamo modes”, where we can work with time scales ≥10 ms
- RWM time scales are of the order of τ_{shell}

Facilitates initial operation

Integrated system of internal sensors







Pomaro, Serianni, to appear in RSI (2002)

Control strategies and plans - 1

Actions through an applied *m*=0 mode (TF coils):

- Synchronous driving torque for mode rotation (non linear coupling) also in closed loop mode
- PPCD
- OPCD

Benchmark and improve old performance

Control strategies and plans - 2

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 B_r at individual coils

Control strategies and plans - 3

m=1 magnetic perturbations

Apply one well defined helicity 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 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

Thanks to the flexibility of the coils system, different actions can coexist in the same pulse

Control strategies and plans - 4

“intelligent shell” operation

– Zeroing of radial field at the edge to maintain an effective close fitting shell.

– Might be interesting for QSH studies, since we have evidence that a smooth magnetic boundary facilitates their onset.

ITER relevance

– **Feedback stabilization of RWMs and schemes where simultaneous control of axisymmetric equilibrium, radial helical fields and m=0 perturbations will be experimentally studied.**
– **This will be relevant for tokamaks and in particular for ITER where, for example, the Error Field Correction Coils are planned to be used both for static error field compensation and for feedback stabilization of RWMs in advanced scenarios operation.**

Control strategies and plans - 5

Low current scenario

- Theoretical work (Guo, Fitzpatrick et al) and experimental data (TPE-RX, EXTRAP T2R, MST) suggest that low current operation could allow for spontaneous dynamo mode rotation.
- If dynamo modes rotate, this scenario is more suitable to concentrate efforts on RWM control

High current scenario

- Better for confinement improvement techniques (OPCD) and for interaction with "dynamo" modes (but higher wall-locking probability).
- Passive shell (and EXTRAP T2R experience) allows to forget about RWM up to ≈50-100 ms