THE RFX MODE CONTROL PROGRAM: PHYSICS ISSUES AND PLANS

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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”
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 (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

\[ R = 2 \text{ m}, \ a = 0.46 \text{ m} \]
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** ($\approx 0.4$ T for 1 MA in RFX)
The modes we have to deal with

$m=0$
- various $n$: resonant at the $B_t$ reversal surface

$m=1$
- $|n| \geq 2R/a$, resonant inside the $B_t$ reversal surface (resistive kink, “dynamo modes”)
- $|n| \leq 2R/a$, internally non resonant from above (RWM, with the same helicity as the “dynamo” modes and the same handedness as the core $B$)
- $|n| \leq R/a$, 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.**
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.
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

QSH spectra are found in all the devices, in a wide set of experimental conditions.

More frequent at high current.
QSH: a selection process

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)

P. Martin – Consorzio RFX
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.

deposition line

loss border
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 $\beta$ SH with NIMROD

- SH RFP simulations performed at finite $\beta$ ($\approx 12\%$) to investigate pressure-driven mode stability

- The computed temperature distribution resembles experimental measurements
The helical flux surfaces in SH have distinct topology that resemble stellarator-like configurations
- (different from standard axisymmetric RFP)

A magnetic well exists from the helical magnetic axis to the separatrix
(Consistent with Miller theoretical predictions, PoF 1983)
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
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.

The applied torque is transferred to \(m=1\) modes via non-linear coupling:

\[
T_{ext}^{0,1} \propto b_r^{0,1} B_r^{0,1} \sin(\Delta \phi)
\]

\(B_{r,01}\)

\((1,n)\)  \(\rightarrow\)  \((0,1)\)

\((1,n+1)\)

\[T_{z}^{1,n}\]

*Bartiromo et al., Phys. Rev. Lett. 82, 1462 (1999)*
Active rotation of MHD modes
Resistive Wall Modes
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 $\approx 3 \tau_w$ 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 ($\tau_s \approx 50 \text{ ms}$, $b/a \approx 1.1$, compared to the old $\tau_s \approx 400$, $b/a \sim 1.2$)

- high spatial resolution active coil array (4 poloidal x 48 toroidal coils) and power supplies

- ex-vessel magnetic and thermal trasducers:
  - 650 magnetic probes
  - $\approx 200$ 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
The new TF power supply allows for upgraded performance when a $m=0$ perturbation is applied.

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Modified RFX</th>
<th>RFX 92</th>
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<tbody>
<tr>
<td></td>
<td>Amplitude</td>
<td>Period (ms)</td>
</tr>
<tr>
<td>RTFM $m=0$, $n=1$: $B_{twall}$ control</td>
<td>58 mT</td>
<td>40</td>
</tr>
<tr>
<td>PPCD: $V_{pol}$ control</td>
<td>10 V</td>
<td>10</td>
</tr>
<tr>
<td>OPCD: $V_{pol}$ control</td>
<td>10 V</td>
<td>3 - 8</td>
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$B_{tor}$ new $\approx 6 \times B_{tor}$ old at 25 Hz with 3kA
Active saddle coils

192 independent 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 length \( > 100 \text{ ms} \)

The shell passively stabilizes RWM on time scales \( \approx 50 \text{ ms} \)

- In this time lag we can concentrate on problems related with internal “dynamo modes”, where we can work with time scales \( \geq 10 \text{ ms} \)
- RWM time scales are of the order of \( \tau_{\text{shell}} \)

Facilitates initial operation
Integrated system of internal sensors

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
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
$m=1$ 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
“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.
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 $\approx 50-100\, \text{ms}$.