Lessons from the RFP on magnetic feedback control of plasma stability

Piero Martin

Consorzio RFX
Associazione EURATOM-ENEA per la fusione, Padova, Italy

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Acknowledgments

- Results from:
  - and the EXTRAP T2-R, MST, RELAX, RFX-mod, CREATE, DIII-D, JT-60 SA teams
Outline of the talk

• Introduction: the RFP, and why an RFP at the ITER school
• Lessons learned from the RFP on feedback control of MHD stability and their application to tokamak and ITER
• Conclusions
Introduction:
what is an RFP, and why we talk about it here
The RFP configuration is similar to a tokamak:

- it is *toroidal*
- a toroidal electrical current is driven in a plasma embedded in a toroidal magnetic field: **pinch effect**.
- *but the applied toroidal field is 10x weaker than in a tokamak*
RFP advantages

• No need for large and superconducting magnetic coils
• In principle ignition achievable with ohmic heating only
• Easier technology involved

• ....and an essential piece of diversity on the path to FUSION.
The Great Green Walls

- The Green Wall of China, also known as the **Green Great Wall** started in 1978 and will be a series of human-planted forest strips in PRC, designed to hold back the Gobi Desert.

- Plans are to complete it around 2070, at which point it is planned to be **2,800 miles (4,500 km)** long.

- Possibly the **largest proposed ecological project** in history

- A similar effort started in Africa
Are this huge efforts enough? Certainly they are very useful, but...

- In 2005 the Food and Agriculture Organization (FAO) of the United Nations, which monitors the state of the world's forests every few years, reported that 13 million hectares of global forests are lost annually, including 6 million hectares of what are described as primary forests-some of the most biologically diverse ecological systems in the world.

- Monoculture plantations are not enough. They are not places where birds want to live." The lack of diversity also makes the trees more susceptible to disease...

Nature needs diversity...

...and fusion too!
The RFP worldwide community
Consorzio RFX, Padova, Italy

\(a=0.459\ m, R=2\ m,\) plasma current up to 2 MA
Madison Symmetric Torus (MST)

University of Wisconsin, Madison

$a=0.52$ m, $R=1.5$ m, plasma current up to 0.6 MA
Kyoto Institute of Technology, Kyoto, Japan

\( a=0.25 \text{ m}, \ R=0.51 \text{ m}, \text{ plasma current up to } 0.1 \text{ MA} \)
EXTRAP T2-R

Royal Institute of Technology, Stockholm, Sweden

\( a=0.18 \, \text{m}, \, R=1.24 \, \text{m}, \) plasma current up to 0.3 MA
Ancient Chinese philosophy “Let a hundred schools of thought contend” (BC 770)

Improve the understanding of toroidal confinement in general

Test bed for diagnostics development
Low safety factor

- Safety factor $q$ is **low**, and negative at the edge.
- $m=1$ and $m=0$ resonant surfaces in the plasma
Why controlling MHD stability in the RFP?

- Two main kinds of global, current driven, MHD instabilities may be present in a RFP with a resistive wall:

  - **Resistive kink/tearing modes**: resonant in the plasma, intrinsically linked to the sustainment of the configuration through a self-organization process (current transport)

  - **Resistive Wall Modes**: non resonant ideal modes, slowed down by the resistive wall, present also at low beta (current driven)
Low safety factor

RFX-mod

RWMs
(m=1, n=-6, -5, -4..)

Tearing/Resistive kink

RWMs
(m=1, n=2, 3..)
RFX-mod has the best system of feedback control coils ever built for a fusion device.

192 independently feedback controlled coils covering the whole torus. Digital Controller with Cycle frequency of 2.5 kHz.
RFPs at the leading edge of feedback control

- 64 independent feedback controlled coils in EXTRAP T2-R
- advanced controller design
Control system architecture in RFX-mod

- **ACTUATORS**: 192 saddle coils, covering the whole plasma surface
- **SENSORS**: 576 measurements of magnetic field and currents in the saddle coils
- **PLASMA**: 192 reference values for the currents in the control coils
- **DIGITAL CONTROLLER**: 7 computing nodes, 2 Gflop/s, cycle frequency 2.5 kHz

192 power amplifier to drive the control coils
A step back in history: 1989

- First evidence of RWM in RFP in **HBTX-1C** (Culham)
- First experiments on **feedback stabilization**

Alper et al., PPCF (1989) PPCF 31 205
• **No-wall**: ideal mode evolves on Alfvénic time scale

• A **perfectly conducting** wall stabilizes the mode

  - where “perfect” means \( t_{\text{wall}} \gg t_{\text{plasma}} \)
A grid of saddle coils, feedback controlled, zeroes the local $b_r$ at the plasma edge measured by an identical grid of sensor loops.

4. THE INTELLIGENT SHELL

Consider a toroidal pinch surrounded by a grid as shown in Fig. 6. Each plaquette in the grid is constructed like the single loop described in Section 2 and independently freezes the total flux through that plaquette. The overall effect is equivalent to a perfectly conducting mesh for frequencies greater than $\omega_{\text{min}}$. Modes with wavelengths

![Diagram of a toroidal pinch surrounded by an Intelligent Shell.](image-url)
Lesson #1: simultaneous feedback control of many modes achieved
First stabilization of multiple RWMs

- **Multiple RWMs** have been simultaneously stabilized in EXTRAP T2-R and RFX with the intelligent shell scheme.

- Discharge sustained for many wall times (basically limited by available power).

- Proves that a thick shell is not necessary for an RFP.

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*Brunsell et al., PRL 93, 225001 (2004)*

*Paccagnella et al., PRL 97, 075001 (2006)*
RWM vs. tearing in the RFP

- Intelligent shell successfully suppresses RWM and reduces tearing mode edge amplitudes
- One (or more, depending on the regime) non-linearly saturated tearing modes are required to maintain the RFP configuration through a self-organization process.
- These TMs would exist also in presence of a perfectly conducting shell.
- A feedback system cannot suppress a non-linear TM in the RFP: at the best can keep its edge values low
Lesson #2:
controller design and implementation
Intelligent shell issues: aliasing

- Virtual Shell **CAN ONLY cancel the measurement of a mode**, not the mode itself.
- This implies that all discrete fourier transforms (DFT) of the $b_r$ measurements are ZERO...
- ...but: DFT harmonics correspond to Fourier harmonics (plasma modes) **only if no aliasing occurs**..
Sideband aliasing

- **UNAVOIDABLE** problem: the discrete nature of the MxN coils produces **high periodicity sidebands harmonics**.

\[ I_{DFT}^{m,n} \rightarrow b_{r,c}^{m+lM,n+kN} \quad l,k \in \mathbb{Z} \]

- If we have MxN sensors, higher sidebands harmonics are aliased in the measurements of the tearing modes.
**GOAL:** we want to cancel a mode with toroidal mode number $n$

- The spectrum of the field with toroidal mode number $n$ generated by $N$ saddle coils contains many harmonics (sidebands)...
- ... which are aliased into the spectrum measured by the array of $N$ sensors.
Zeroing the aliased measurements does not imply that the harmonics produced by the plasma are cancelled.

\[ b_n^{\text{plasma}} - \left( b_n^{\text{ext}} + \sum_k b_n^{\text{ext}_{n+kN}} \right) = 0 \]

\[ b_n^{\text{plasma}} - b_n^{\text{ext}} \neq 0 \]

RFX-mod
• Sidebands are unavoidable, but aliasing can be removed real-time from measurements.

• The “clean” Fourier harmonics $b_{n}^{\text{ext}}$ are available real-time by subtracting from the DFT harmonics the sidebands.

\[
b_{n}^{\text{plasma}} - \left( b_{n}^{\text{ext}} + \sum_{k} b_{n+kN}^{\text{ext}} \right) = 0
\]
Feedback at the desired radius

- There is normally a difference between the radial position of the sensor coils and the plasma edge
  - in RFX $r_c=0.507 \text{ m}$, $r_p=0.457 \text{ m}$

- Even a perfect cancellation of the clean Fourier harmonics at the sensor radius would not imply a zero field at the plasma edge

Using not only the 48x4 radial field measurements, but also the 48x4 toroidal field measurements, the **extrapolation to the plasma edge is performed real-time** with a further improvement of the feedback control.

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Zanca, Marrelli, NF 47 1425 (2007)
Marrelli et al., PPCF 49 B359 (2007)
Consorzio RFX
From intelligent shell to clean mode control

- **Clean Mode Control (CMC)**: to each mode is assigned its own PID regulator with individual *COMPLEX* gains

\[ b_{m,n}^{\text{coil}}(t) = -K_p e_{m,n}(t) - K_I \int_0^t dt e_{m,n}(t) - K_D \frac{d}{dt} \mathcal{H}(e_{m,n}(t), f_{cut}) \]

- Each mode can be controlled separately
  - sidebands eliminated
  - action at the desired radius
  - gains optimized for each mode (different modes required different gains due to different penetration of the field through passive structures)
  - non-zero reference for individual modes may be imposed (helical boundary conditions)
  - ....
RFX-mod feedback control architecture

\[ B_{r, \text{ref}}^{m,n} \rightarrow R \rightarrow \mathcal{F}^{-1} \rightarrow I_{\text{ref}}^{i,j} \rightarrow P \rightarrow \mathcal{F} \rightarrow B_r \rightarrow \mathcal{F} \rightarrow B_{r, \text{raw}}^{m,n} \rightarrow + \rightarrow C \rightarrow \Delta B_r^{m,n} \rightarrow + \rightarrow B_r^{m,n} \]

- **CONTROLLER**
- **MODE CLEANER**
Active control means performance improvement

- RFX-mod reliably operates at plasma current close to 2 MA thanks to feedback control of magnetic boundary
**Significant plasma improvement with CMC**

- Smoother plasma boundary
- High performance helical state

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Plasma control system based on mode identification in EXTRAP T2-R

Olofsson et al., to appear in PPCF (2010), special issue on “MHD mode control in toroidal devices”
• **MHD spectroscopy** involves active probing of the plasma by applying external fields using the control coils.

• On EXTRAP T2R a **closed-loop identification** method is used:
  - The response to external perturbations of unstable RWM is measured while simultaneously maintaining stabilizing feedback.
  - A pseudo-random dithering signal is applied to all coils.

![Wall penetration time constant](image1.png)

![RWM growth rate](image2.png)
Lesson #3:
what you do may not be exactly what you think you are doing
Three dimensional effects

- Feedback coils and passive front-end structure are complex, non-uniform, three dimensional structures.
- In RFX-mod wall has 1 poloidal gap, 2 toroidal gaps, portholes, …
Only **ONE** out of 4x48 coils is energized at 20 Hz

\[ B_r \] measurements at the 4x48 sensors
3D structures to cause e.m. coupling

Only **ONE** out of 4x48 coils is energized at 20 Hz

Br measurements at the 4x48 sensors

2 vertical gaps (180° apart): coupling of $n$ harmonics

1 equatorial gap: coupling of $m$ harmonics
Dynamic Decoupling

All the e.m. couplings in the system are represented by a matrix of transfer functions $M(f)$ between the 192 active coils and the 192 $B_r$ sensors.

The $B_r$ at the sensors produced by arbitrary currents in the active coils can be thus computed:

$$I_{c\text{,}i,j} \rightarrow M(f) \rightarrow b_{r\text{,}i,j}$$

$i = 1$ to $4$; $j = 1$ to $48$

A dynamic pseudo-decoupler has been built by inverting the $M$ matrix with SVD and pseudo-inversion techniques:

$$b_{r\text{,}i,j} \rightarrow M^{-1}(f) \rightarrow I_{c\text{,}i,j}$$

Porting the experience to tokamaks: AC decoupling in DIII-D

- Feedback sensors in DIII-D sense not only $n=1$ plasma field but also spurious AC field produced by various coils.
  - Spurious B field must be subtracted from the measurement to have clean feedback.
  - These effects depend on frequency, couplings described by complex transfer functions

- An algorithm to compensate the sensor signals including these frequency dependent effects has been implemented in real time and tested in Ohmic plasmas
AC compensation spares significant feedback coil current for dynamic error field correction

- #141242 with DC compensation
- #141243 with AC compensation
Lesson #4: think broad
RFP: versatile devices

- RFX-mod can be run as a tokamak
Active control of a (2,1) mode in RFX tokamak with $q_{\text{edge}} \approx 2$

Inspired by an experiment in DIII-D by In, Okabayashi, et al, with RFX participation (Okabayashi et al., NF 2010 Nucl. Fusion 50 042001)

- no feedback
- plasma current
- (2,1) amplitude
- $q_{\text{edge}}$
- SXR emission
Active control of a (2,1) mode in RFX tokamak with $q_{\text{edge}} \approx 2$

with feedback on the (2,1) mode is stabilized and the plasma is run with $q_{\text{edge}} \approx 2$

- Plasma current
- (2,1) amplitude
- $q_{\text{edge}}$
- SXR emission

Piovesan et al., 14th IEA - RFP Workshop (Padova, 2010)
Lesson #5: output tracking control for RWM and tearing modes
• A design for general output tracking is devised, implemented and experimentally verified to be capable of sustaining MHD modes in EXTRAP-T2R.

• In principle, by active feedback, the plasma column boundary is forced to ‘user-specified’ helicities of prescribed amplitudes and phases.
Tracking a reference spectrum in EXTRAP T2-R

Note that some features of the reference spectrum (seen in sensor signal) can be recognized in the spectrum of the actuator coil currents, but it is clear that the controller provides a “broader” spectrum to the actuator in order to reproduce the sharp reference spectrum.
High performance helical equilibria in RFX

- At high current plasma spontaneously self-organizes in a helical state ($m=1, n=-7$)
- Helical equilibria come with electron transport barriers
Tracking a non-zero reference for the (1,-7) mode

Imposing a non-zero static or rotating reference for the (1,-7) resistive kink mode favors long-lasting helical equilibria.
Lesson #6: grasp & pull
Forcing RWM rotation

- **2 control time windows:**
  - **FIRST:** the mode is not controlled
  - **SECOND:** the mode is feedback controlled with a pure real proportional gain.

- **Gain scan performed**
  - to obtain constant RWM amplitude
Options for controlling individual modes

Plasma field
- Total field = 0
- External field

Perfect control

Plasma field
- Total field ≠ 0
- External field

Incomplete control

m=1, n=6

(a)
Complex gains \((k_R + ik_i)\) to impose phase shift

- **Plasma field**
  - Total field = 0
  - External field

- **Plasma field**
  - Total field ≠ 0
  - External field

**Perfect control**

**Incomplete control**

**Incomplete control with phase shift**

**Total field ≠ 0**

**External field**
Active rotation of non-resonant wall-locked RWM is induced by applying complex gains (keeping the mode at the desired constant amplitude).
Lesson #7: codes for ITER need benchmarking. We are here for it.
• Codes designed to predict ITER stability and feedback need:
  
  - to take into account three-dimensional features of the magnetic front-end (portholes, non-uniformity, asymmetries...etc)
  
  - to be validated against experimental data
• CarMA (MARS-F + Cariddi) is a MHD ideal code (MARS-F) coupled with an arbitrary 3D magnetic boundary (Cariddi) used to predict MHD in ITER

• Used to assess role of 3D effects for stability predictions (holes, extensions..) and compare with 2D predictions

• RFX-mod data (n=- 6 RWM) used to validate the code, which was adapted to RFX-mod conditions (including its 3D features)
RFX-mod provides data for benchmarking

RFX-mod experimental growth rates allow for benchmarking CarMA and showing its superiority wrt two-dimensional codes

<table>
<thead>
<tr>
<th></th>
<th>ETAW</th>
<th>MARSF</th>
<th>CarMa</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n=4$</td>
<td>5.27</td>
<td>5.07</td>
<td>7.30</td>
<td>≈ 6</td>
</tr>
<tr>
<td>$n=5$</td>
<td>8.63</td>
<td>8.55</td>
<td>12.8</td>
<td>≈ 12</td>
</tr>
<tr>
<td>$n=6$</td>
<td>14.5</td>
<td>14.4</td>
<td>22.6</td>
<td>≈ 22</td>
</tr>
</tbody>
</table>

Villone et al., PRL 100, 255005 (2008)
RFX-mod control architecture

\[ B_{r, \text{ref}}^{m,n} \]

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\[ B_{r, \text{raw}}^{m,n} \]

\[ B_{r}^{m,n} \]

\[ \Delta B_{r}^{m,n} \]

\[ I_{\text{ij}} \]

\[ I_{\text{ref,ij}} \]

\[ \mathcal{F} \]

\[ \mathcal{F}^{-1} \]

\[ R \]

\[ P \]

\[ C \]

\[ \text{MODE CLEANER} \]
• **FULL closed loop simulator** of the whole plant/controller system successfully implemented based on the integration of CarMa with RFX boundary conditions and controller model.
Experimental (red) and model (blue) growth rates vs. controller proportional gain.

A portable tool
Lesson #8: more is better than less...but sometimes you have to live with less....
From full to partial coverage

- RFX-mod and EXTRAP T2-R plasma boundary is **fully covered** by active coils, each individually driven.

- This may not be the case in present tokamaks and in ITER

A reduced number of actuators is easier to implement but influences feedback efficiency.
From full to partial coverage

- A complete set of individual coils can be by purpose downgraded to study the effect of partial coverage

- Feedback downgrading experiment performed in RFX-mod by the JT-60SA team to gather information for the JT-60SA coil design
  - simplicity vs. efficiency threshold

RFX downgraded coil configurations

Bolzonella, Takechi et al., JT-60SA TCM 8 (2010) & EPS 2010
Baruzzo et al., 14th IEA - RFP Workshop (Padova, 2010)
Partial coverage experiments in RFX

JT-60SA plans: 6.8% coverage

- $48 (\phi) \times 4 (\theta)$: 100%
- $48 (\phi) \times 1 (\theta)$: 25%
- $16 (\phi) \times 1 (\theta)$: 8.3%
- $12 (\phi) \times 1 (\theta)$: 6.25%
- $8 (\phi) \times 1 (\theta)$: 4.2%
- $3 (\phi) \times 4 (\theta)$: 6.25%

Bolzonella, Takechi et al., JT-60SA TCM 8 (2010)
From full to partial coverage

- With proper selection of proportional gains full stabilization of the most unstable RWM with 48x1 coils (25% coverage)
**Lesson #9:**

tearing amplitude is affected by controlling the current density profile
Pulsed Poloidal Current Drive

- Tearing Modes responsible for anomalous transport in standard RFP are driven by the current density J profile gradient.

- **Tayloring the J profile** with external means allows for controlling TM and reducing their amplitudes.

- Current profile transiently modified by applying a pulsed poloidal electric field.
- Mostly poloidal current drive.
Tearing Modes responsible for anomalous transport in standard RFP are driven by the current density \( J \) profile gradient.

Tayloring the \( J \) profile with external means allows for controlling TM and reducing their amplitudes.

Current drive “replaces” dynamo
Mostly poloidal current drive
PPCD strongly improves confinement

- Control of core resonant tearing modes reduces transport

\[ I_p = 0.5 \text{ MA}, \quad n/n_G = 0.13 \]
\[ \tau_E = 12 \text{ ms}, \quad \beta = 10\% \]
Conclusions

- RFPs are equipped with very advanced experimental and numerical tools for active control of MHD stability.
- The RFP is providing an important, integrated and unique contribution to the physics and technology of MHD stability feedback control, in particular to ITER.
- RFP, together with other alternative concepts, directly contribute to the success of ITER.
Conclusions:
what is an RFP, and why we talk about it here
Feedback at the desired radius

- There is normally a difference between the radial position of the sensor coils and the plasma edge.
  - In RFX, $r_c = 0.507$ m, $r_p = 0.457$ m.

- Even a perfect cancellation of the clean Fourier harmonics at the sensor radius would not imply a zero field at the plasma edge.

Using not only the 48x4 radial field measurements, but also the 48x4 toroidal field measurements, the extrapolation to the plasma edge is performed real-time with a further improvement of the feedback control.
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<th>Outputs</th>
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<tbody>
<tr>
<td>No sideband corrections</td>
<td>4x48 radial field signals</td>
</tr>
<tr>
<td></td>
<td>4x48 reference values</td>
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<tr>
<td>Clean measurements</td>
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<td>4x48 currents flowing in the coils</td>
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<td>Clean and Closer measurements</td>
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