Lessons from the RFP on magnetic feedback control of plasma stability

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Acknowledgments

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  - and the EXTRAP T2-R, MST, RELAX, RFX-mod, CREATE, DIII-D, JT-60 SA teams

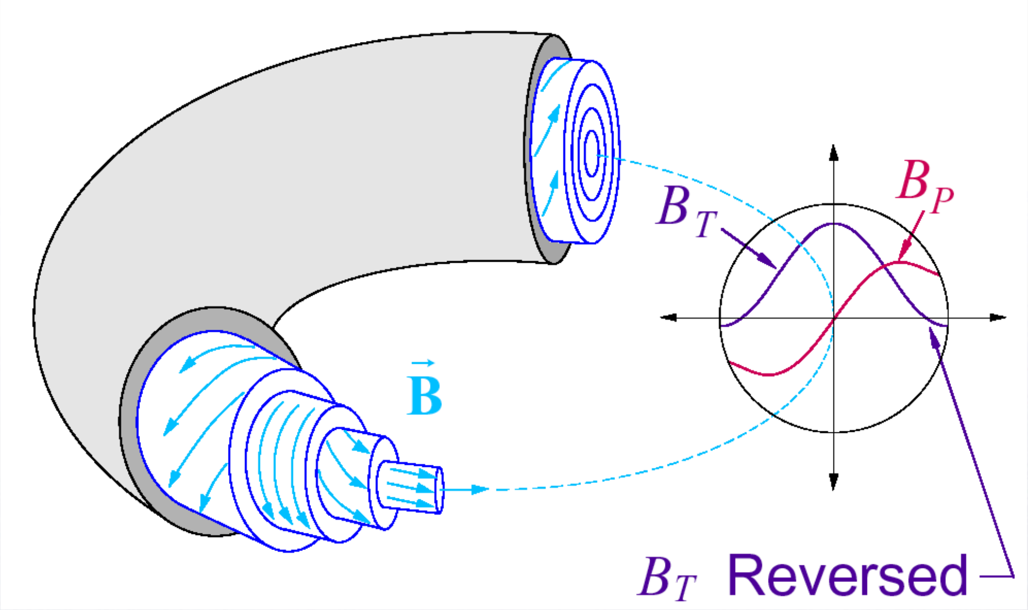
Outline of the talk

- 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

RFP: the low field approach to magnetic fusion

- 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

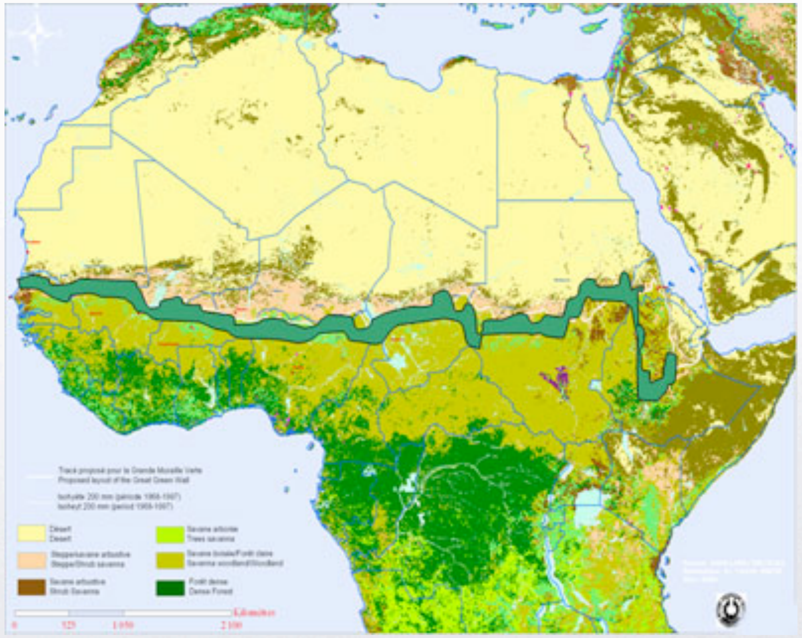
- No need for large and superconducting magnetic coils
- In principle ignition achievable with ohmic heating only
- Easier technology involved

- ....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



..but...diversity counts...

- 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!

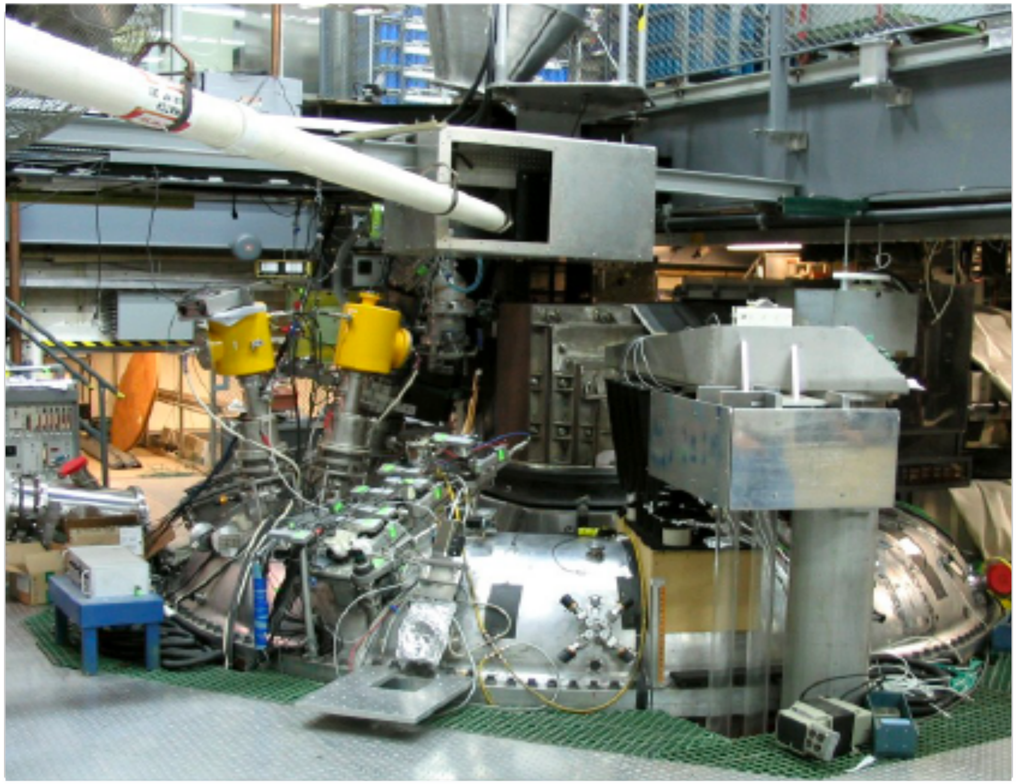
The RFP worldwide community

RFX-mod

Consorzio RFX, Padova, Italy

a=0.459 m, *R*=2 m, plasma current up to 2 MA

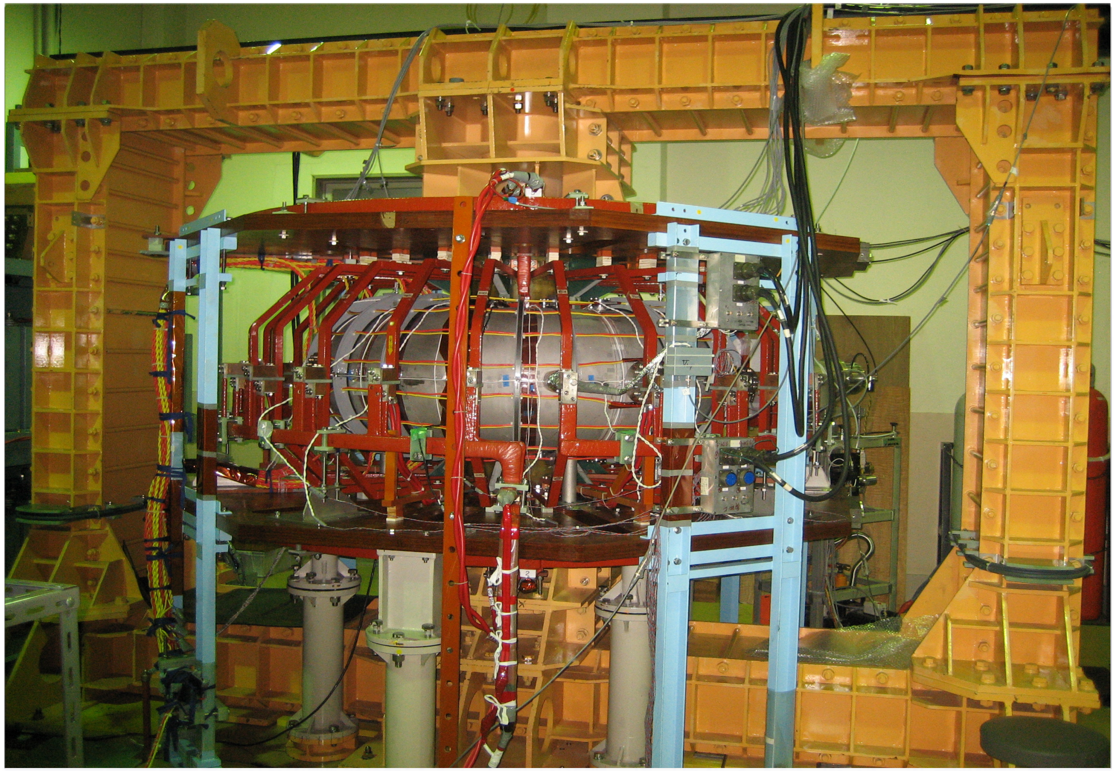
Madison Symmetric Torus (MST)



University of Wisconsin, Madison

a=0.52 m, R=1.5 m, plasma current up to 0.6 MA

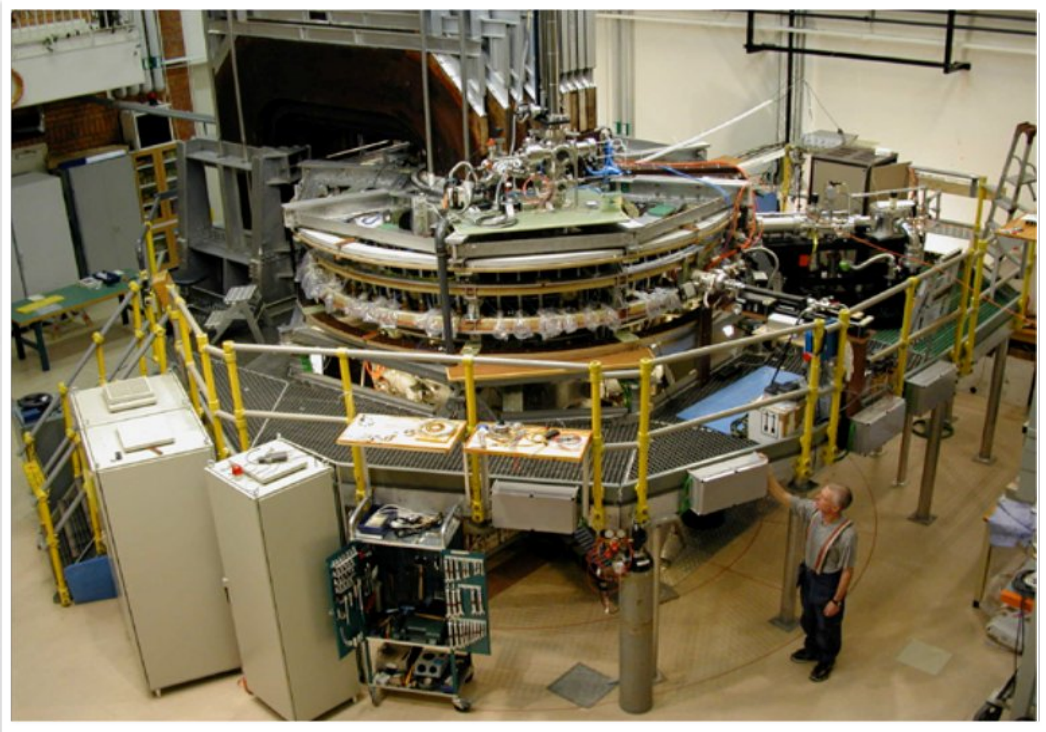
RELAX



Kyoto Institute of Technology, Kyoto, Japan

a=0.25 m, R=0.51 m, plasma current up to 0.1 MA

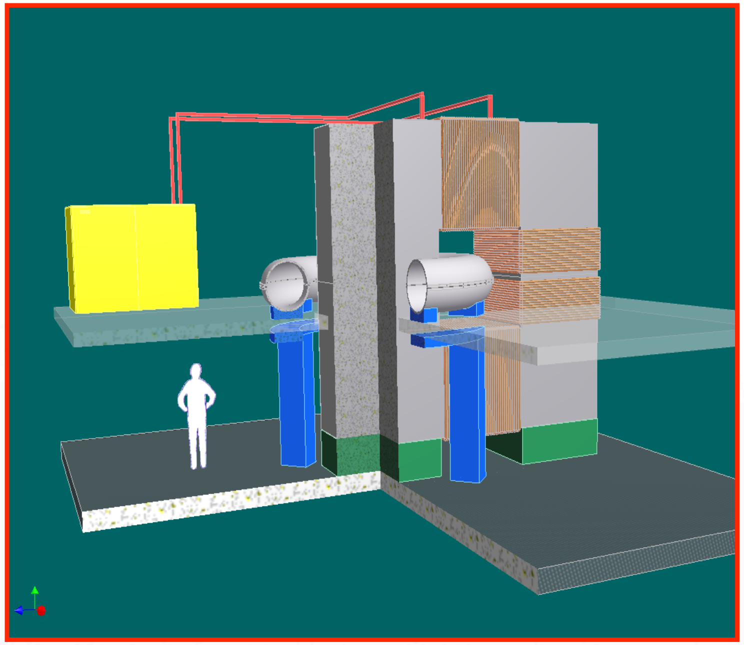
EXTRAP T2-R

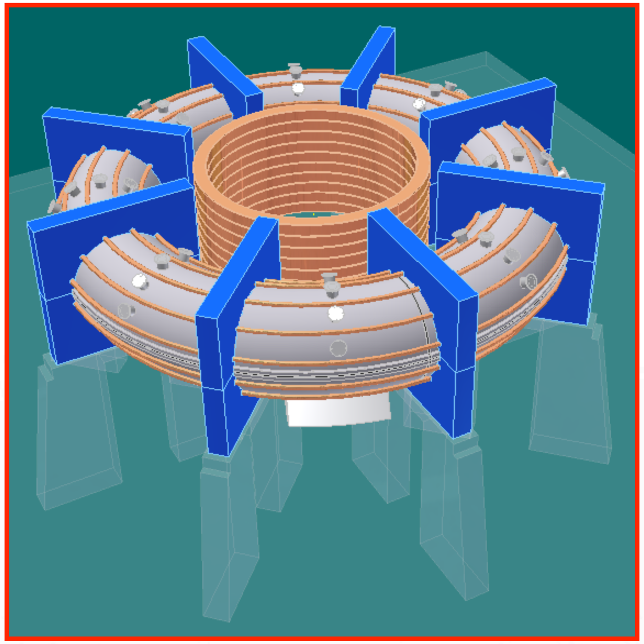


Royal Institute of Technology, Stockholm, Sweden

a=0.18 m, *R*=1.24 m, plasma current up to 0.3 MA

Hefei (PRC) ?



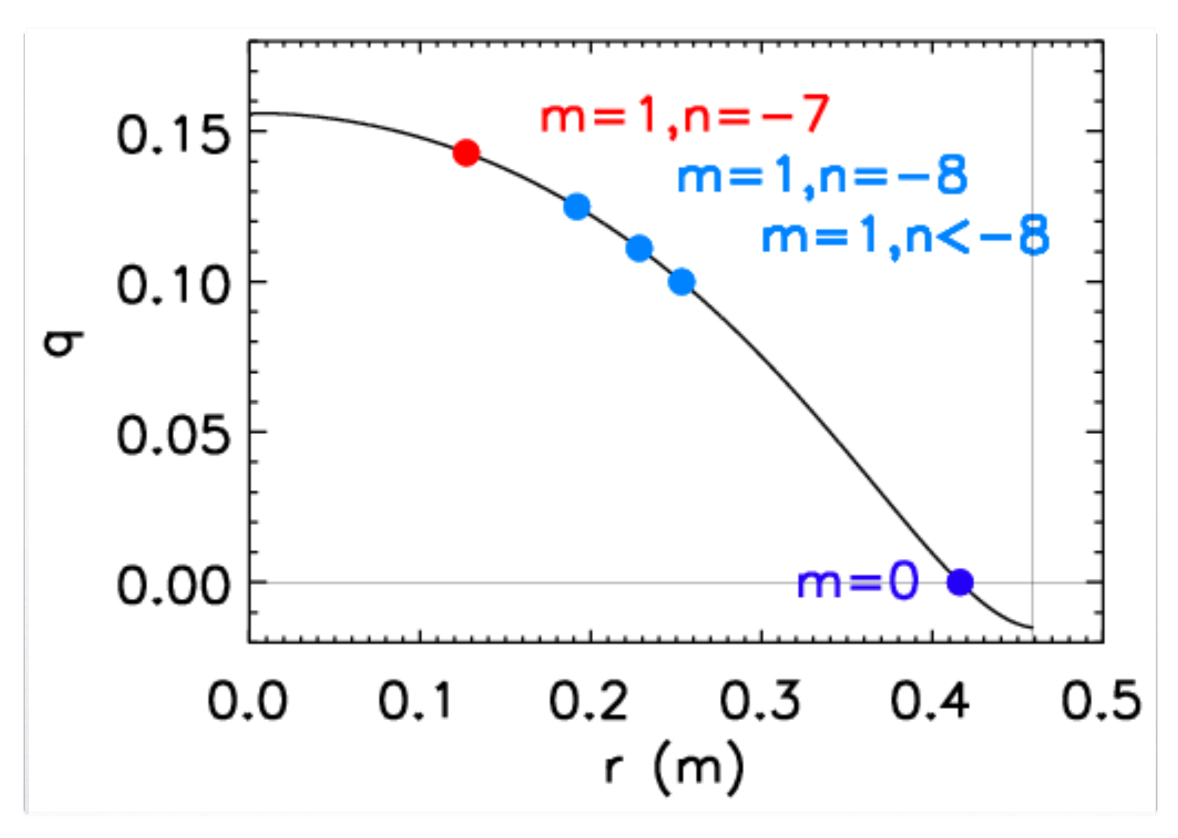


- Ancient Chinese philosophy "Let a hundred schools of thought contend" (BC 770)
- Improve the understanding of toroidal confinement in general
- Test bed for diagnostics development

Liu, 2010 IEA RFP Workshop (www.igi.cnr.it)

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 ?

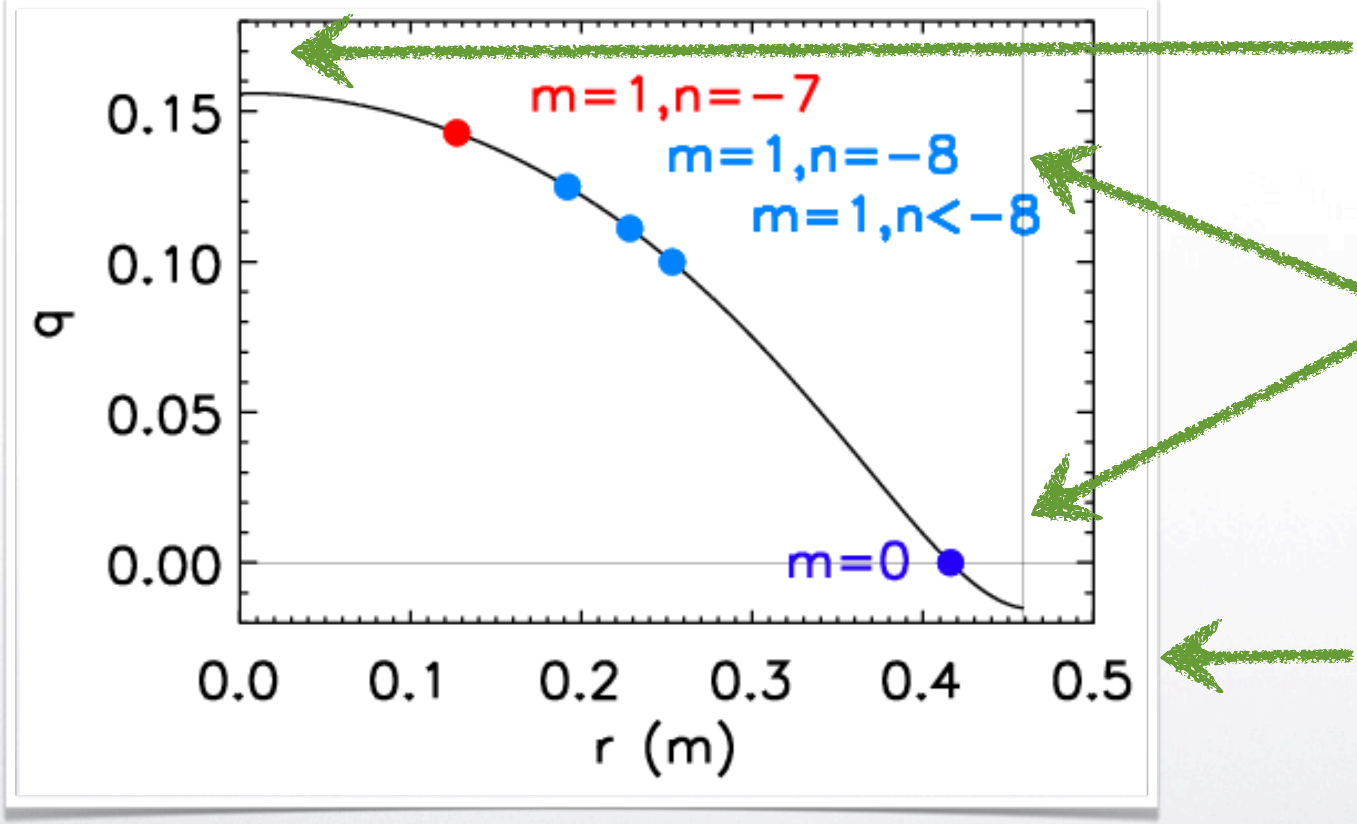
- Two main kinds of global, current driven, MHD instabilities may be present in a RFP with a resistive wall:

  - **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..)

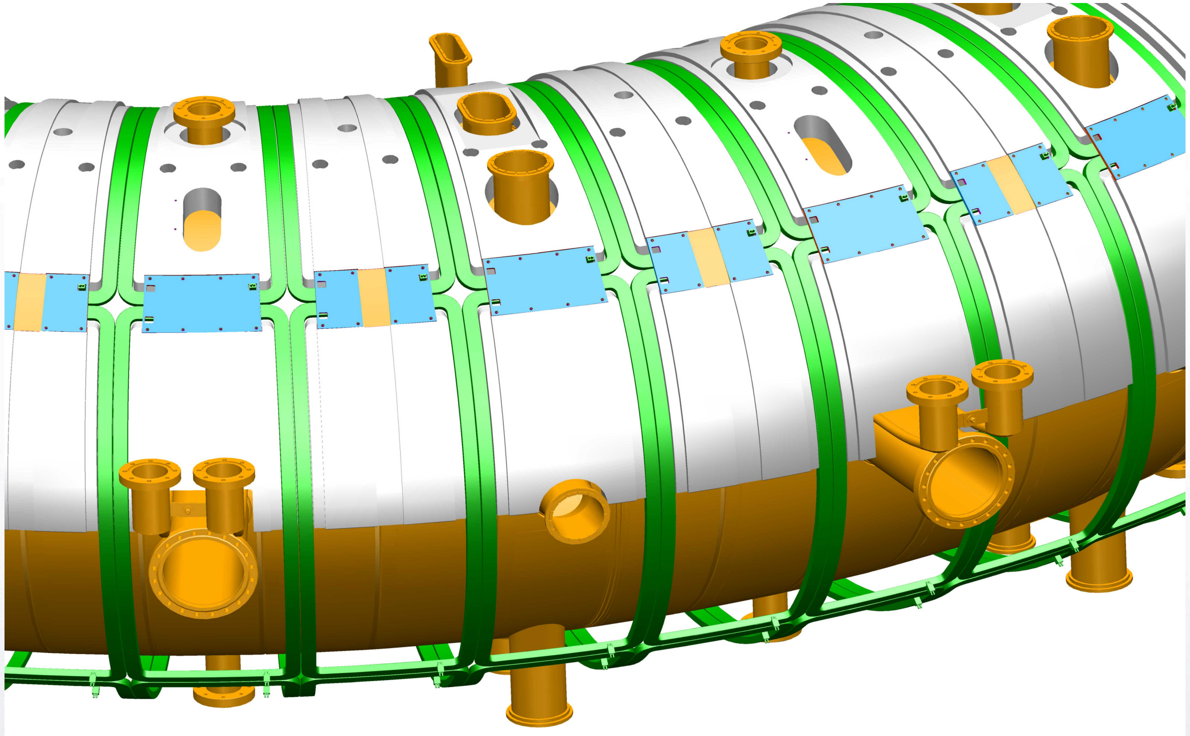
Tearing/Resistive kink

RWMs

(m=1, n=2, 3..)

RFPs at the leading edge of feedback control

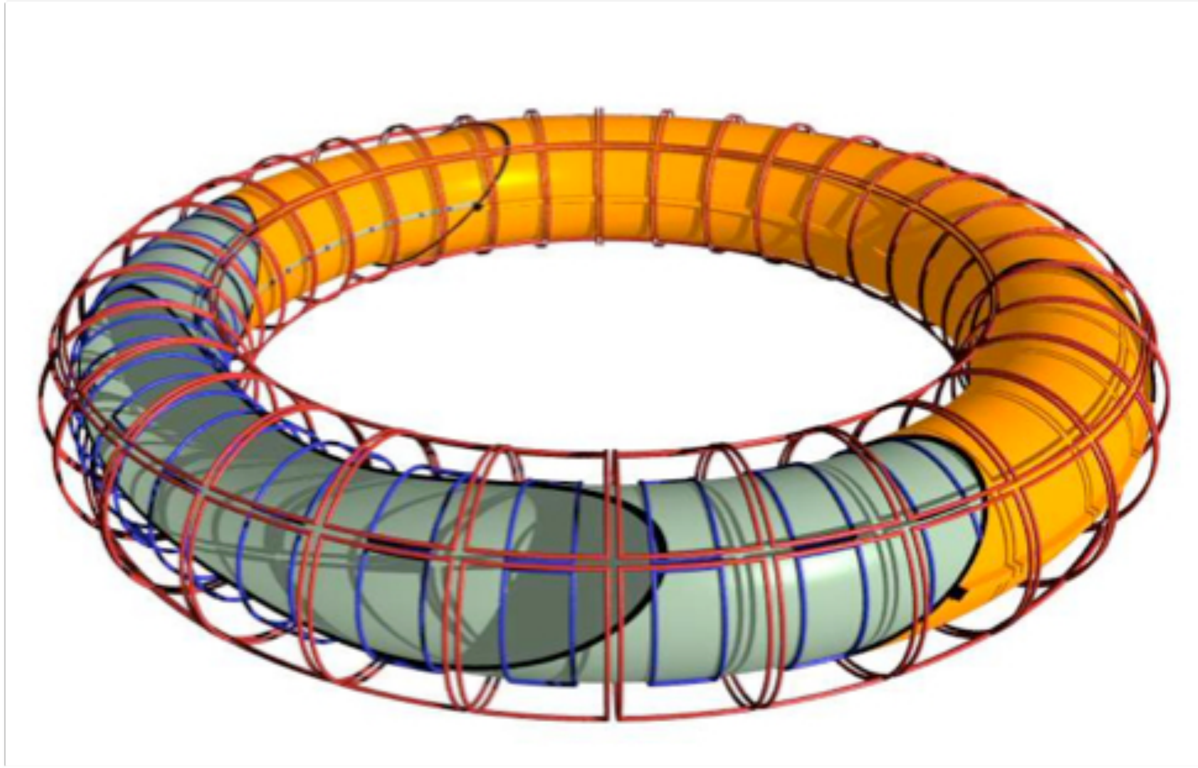
RFX-mod has the best system of feedback control coils ever built for a fusion device



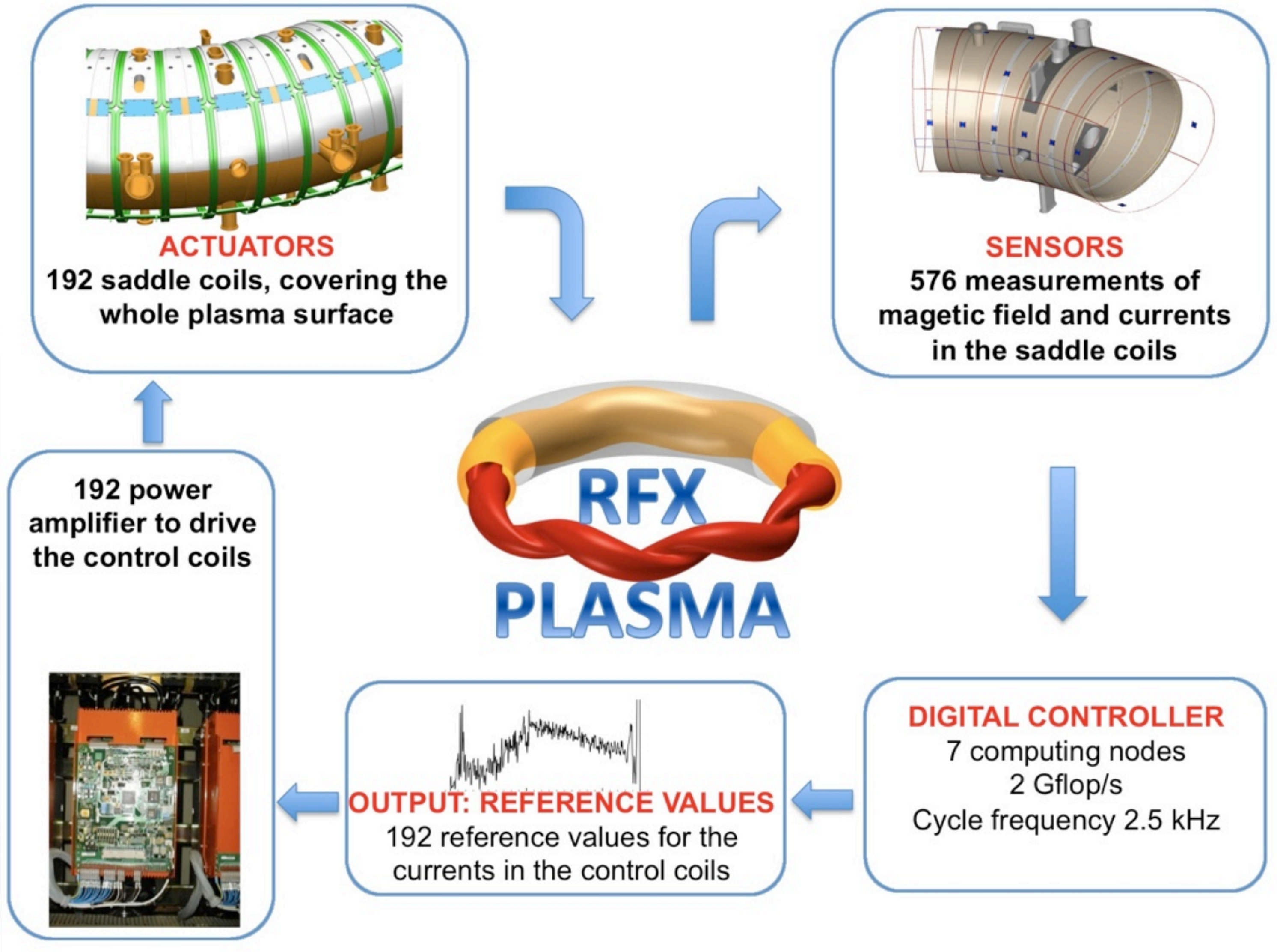
192 independently feedback controlled coils covering the whole torus.
Digital Controller with Cycle frequency of 2.5 kHz

RFPs at the leading edge of feedback control

- 64 independent feedback controlled coils in EXTRAP T2-R
- advanced controller design

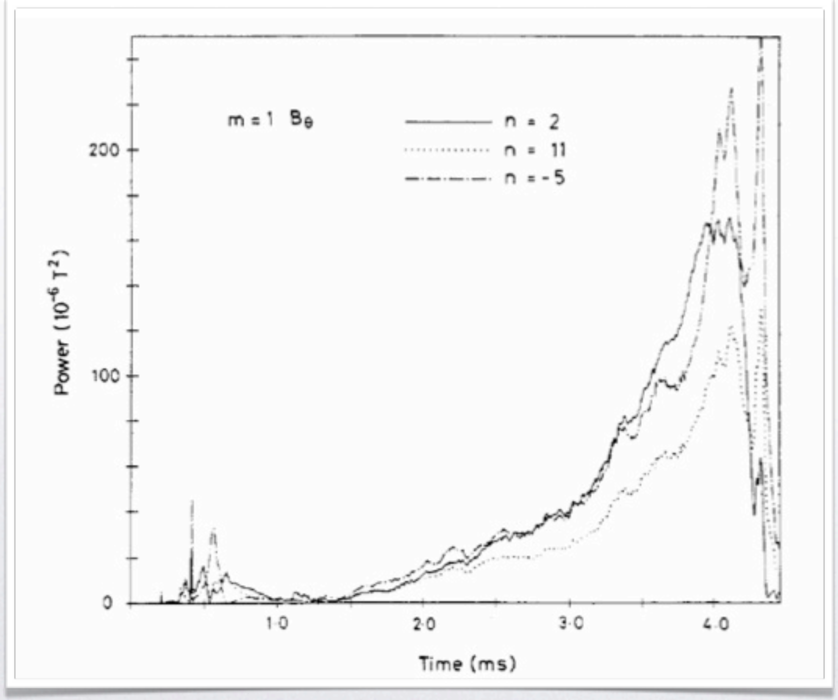


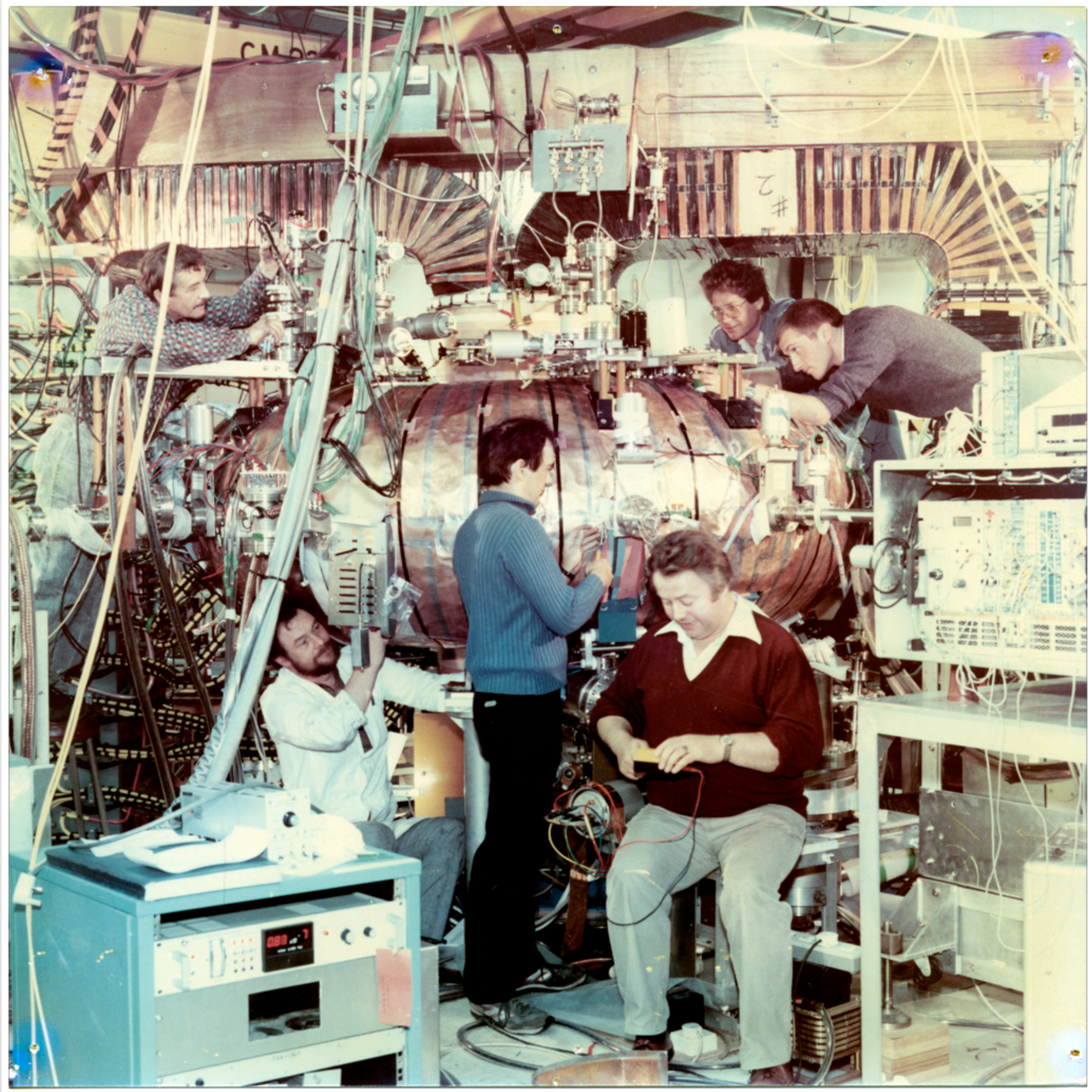
Control system architecture in RFX-mod



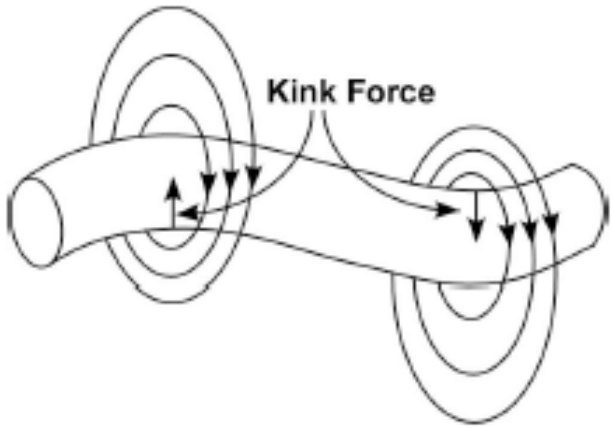
A step back in history: 1989

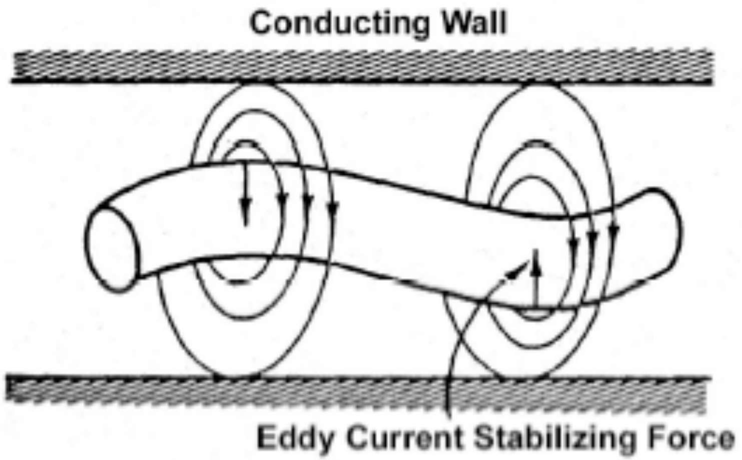
- First evidence of RWM in RFP in **HBTX-1C** (Culham)
- First experiments on **feedback stabilization**





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 $t_{wall} >> t_{plasma}$

...to the INTELLIGENT shell

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 ω_{min}. Modes with wavelengths

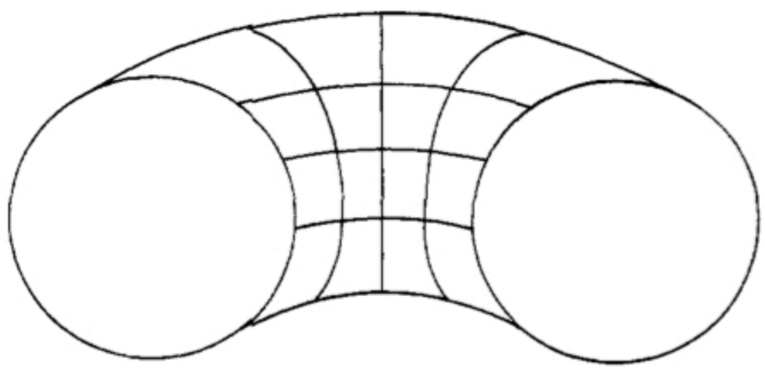


FIG. 6.—A toroidal pinch surrounded by an Intelligent Shell.

Bishop, PPCF (1989) PPCF **31** 1179

Lesson #1:

simultaneous feedback control of many modes achieved

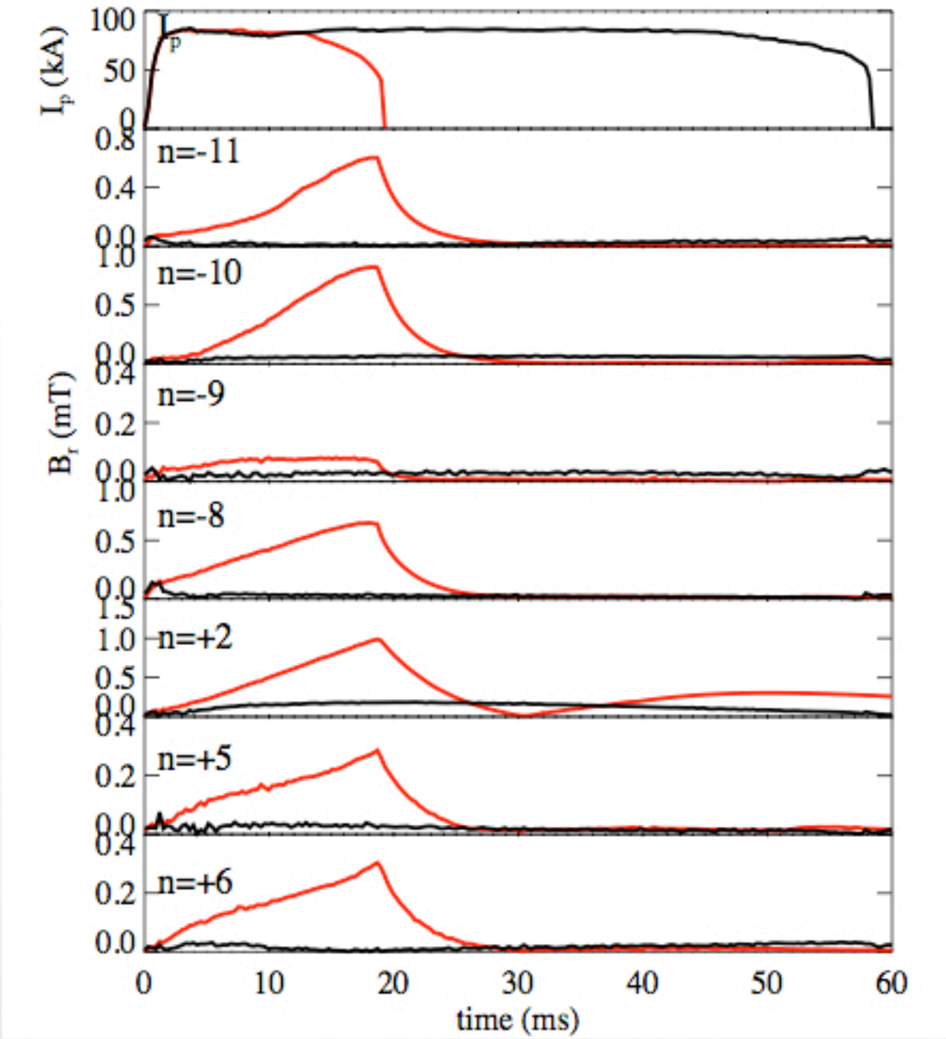
First stabilization of multiple RWMs

- 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

EXTRAP T2-R



Brunsell et al., PRL **93** 225001 (2004)
Paccagnella et al., PRL **97,** 075001 (2006)

RWM vs. tearing in the RFP

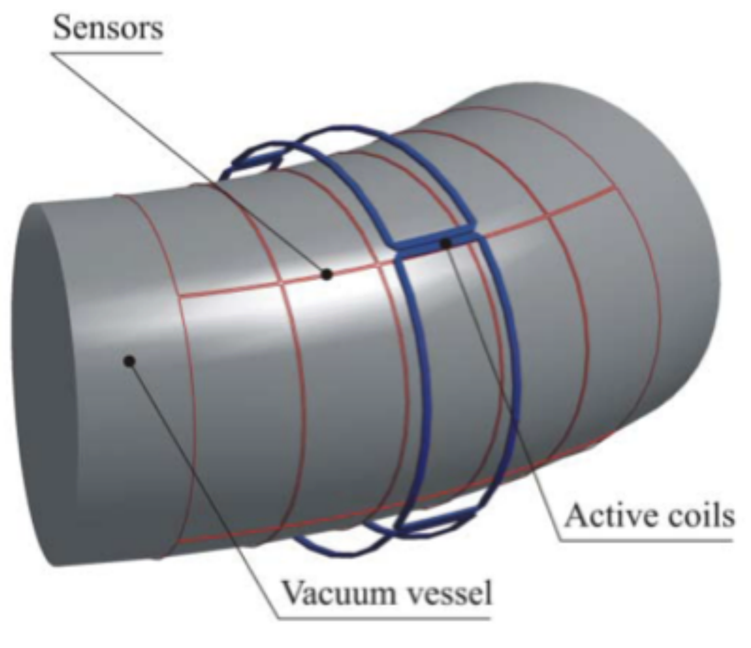
- Intelligent shell successfully suppresses RWM and reduces tearing mode edge amplitudes
- One (or more, depending on the regime) non-linearly saturated tearing modes are required to maintain the RFP configuration through a self-organization process.
- These TMs would exist also in presence of a perfectly 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

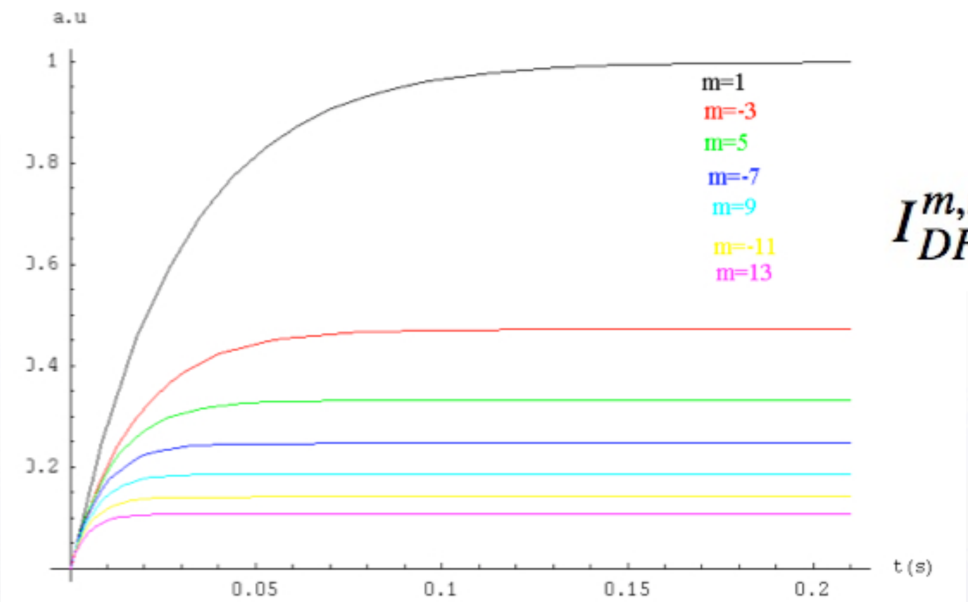
Intelligent shell issues: aliasing

- 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**.

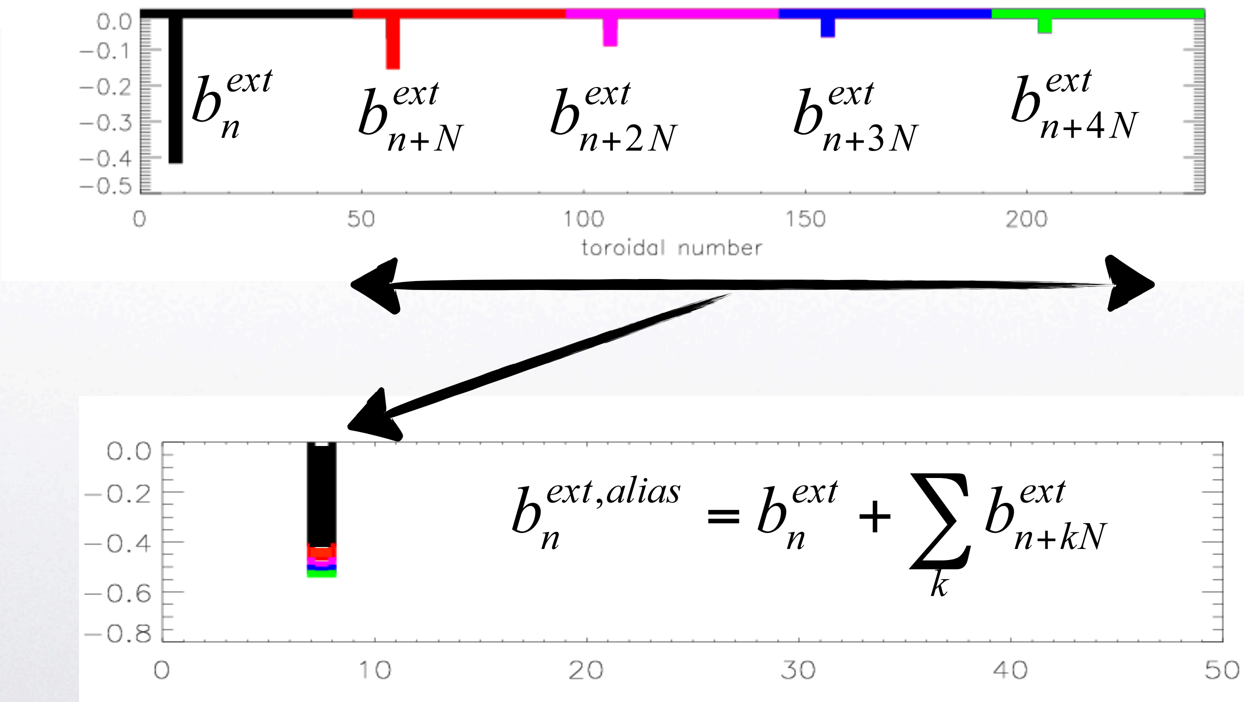


$$I_{DFT}^{m,n} \rightarrow b_{r,c}^{m+lM,n+kN} \quad l,k \in Z$$

- If we have MxN sensors, higher sidebands harmonics are aliased in the measurements of the tearing modes.

Sideband aliasing

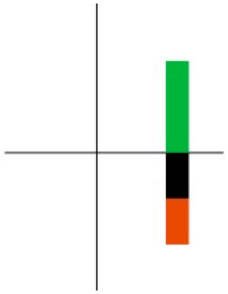
- **GOAL: we want to cancel a mode with toroidal mode number *n***
  - The spectrum of the field with toroidal mode number *n* generated by **N saddle coils** contains many harmonics (sidebands)...
  - ... which are aliased into the spectrum measured by the array of **N sensors**



Paccagnella et al Nucl. Fusion (2002) **42** 1102

Plasma harmonics are not cancelled

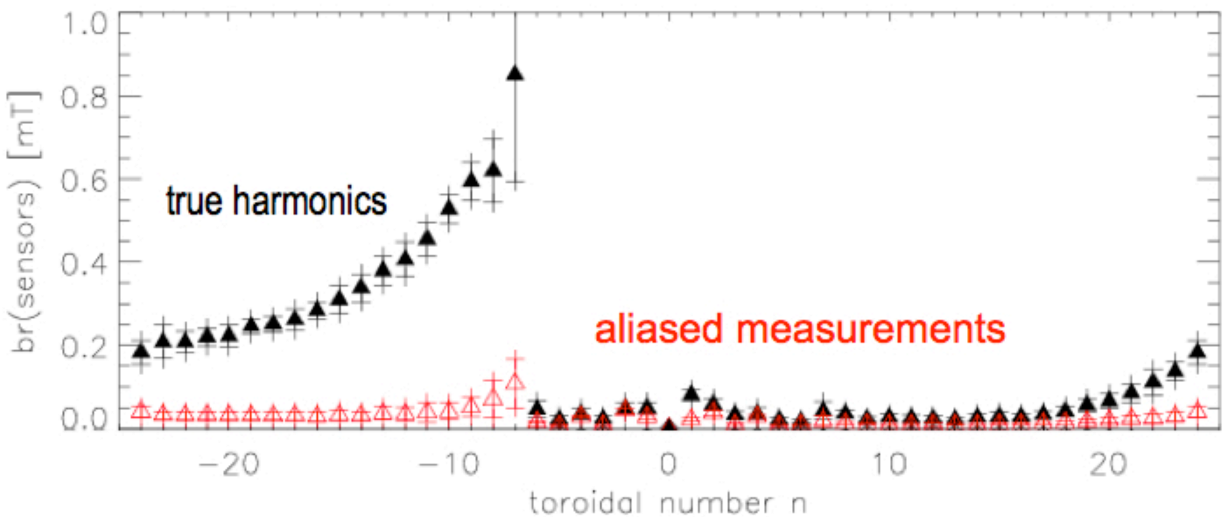
- Zeroing the aliased measurements does not imply that the harmonics produced by the plasma are cancelled



$$b_n^{plasma} - \left(b_n^{ext} + \sum_k b_{n+kN}^{ext} \right) = 0$$

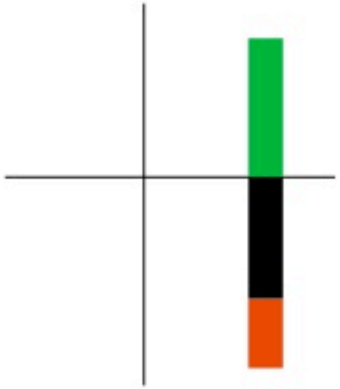
$$b_n^{plasma} - b_n^{ext} \neq 0$$

RFX-mod



Sidebands removal

- Sidebands are unavoidable, but aliasing can be removed real-time from measurements.
- The "clean" Fourier harmonics b_n^{ext} are available real-time by subtracting from the DFT harmonics the sidebands.



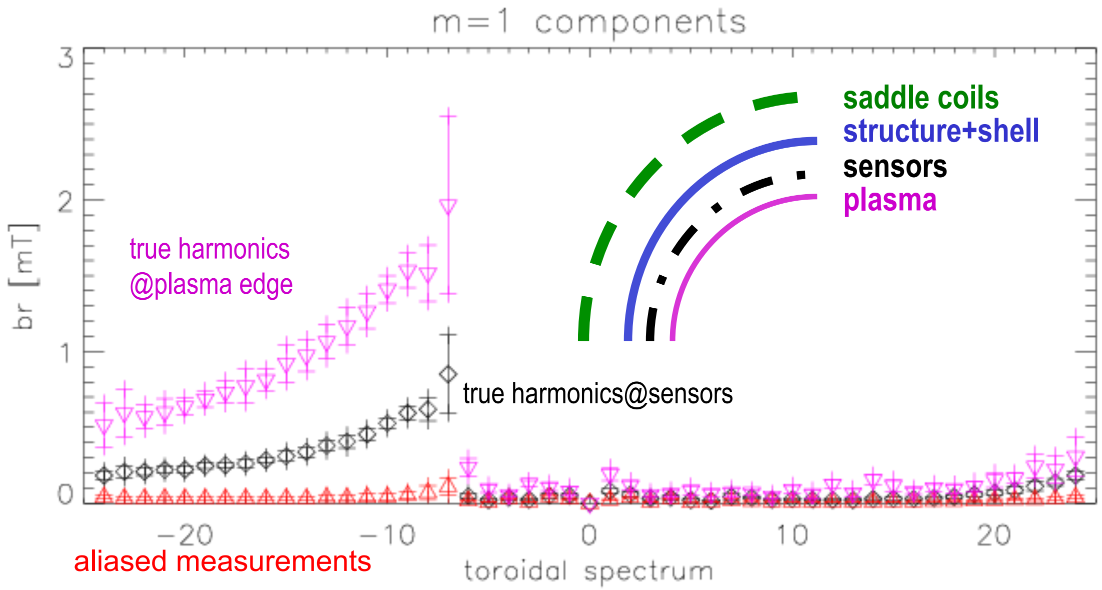
$$b_n^{plasma} - \left(b_n^{ext} + \sum_k b_{n+kN}^{ext} \right)$$

$$b_n^{plasma} - b_n^{ext} = 0$$

Zanca, Marrelli , NF **47** 1425 (2007)
Marrelli et al., PPCF **49** B359 (2007)

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



RFX-mod

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

Zanca, Marrelli , NF **47** 1425 (2007)
Marrelli et al., PPCF **49** B359 (2007)

From intelligent shell to clean mode control

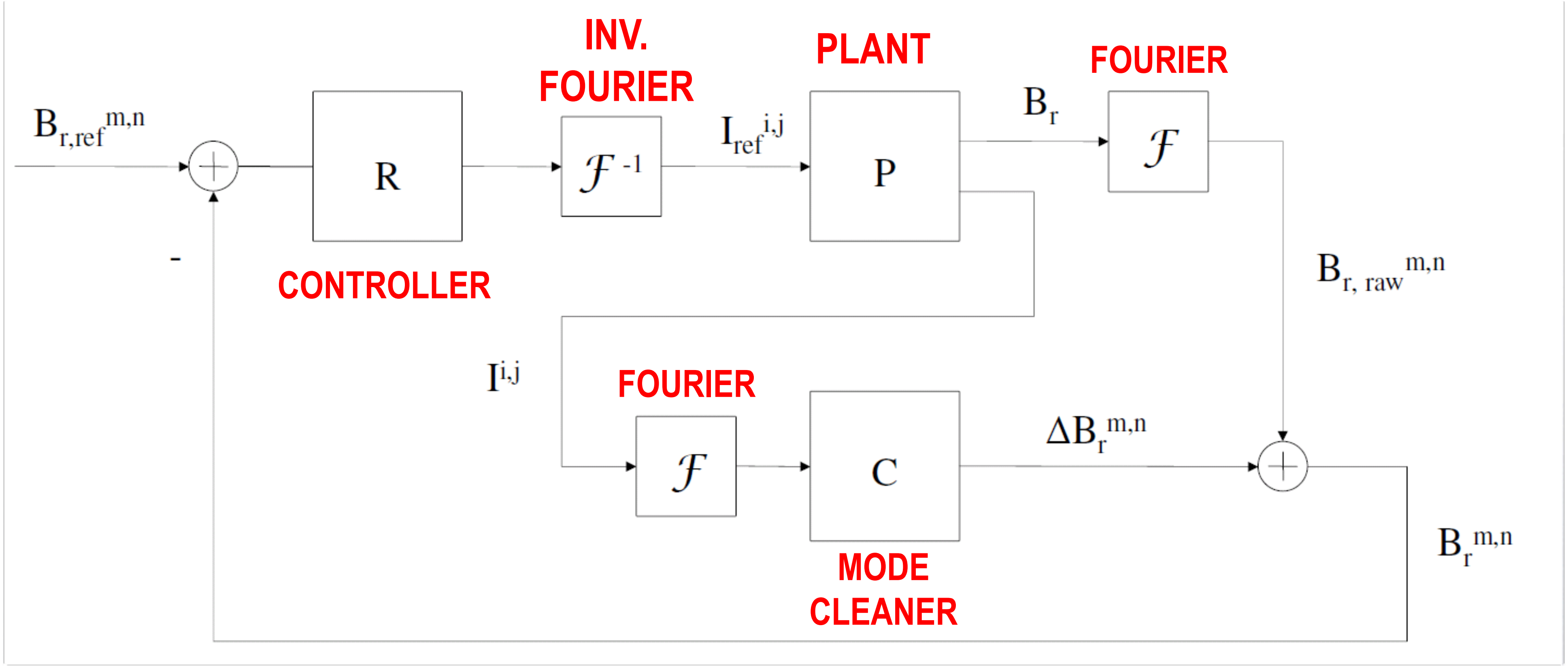
- Clean Mode Control (CMC) : to each mode is assigned its own PID regulator with individual *COMPLEX* gains

$$b_{m,n}^{coil}(t) = -K_P e_{m,n}(t) - K_I \int_0^t dt\, e_{m,n}(t) - K_D \frac{d}{dt} \Im\left(e_{m,n}(t), f_{cut}\right)$$

- **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)
  - .....

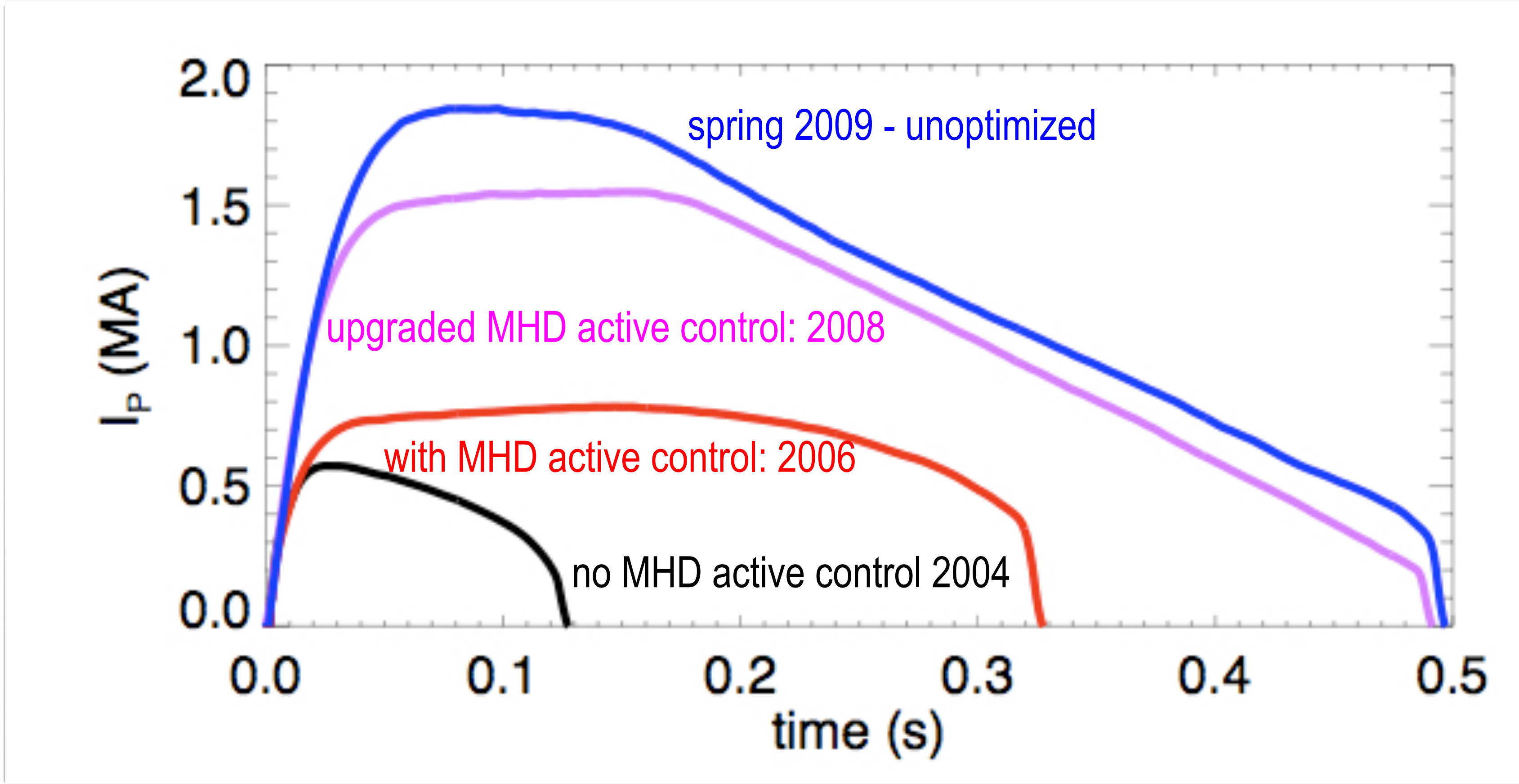
Zanca, Plasma and fusion res. (2010) **5** 017-1
Zanca, PPCF **51** 015006 (2009)

RFX-mod feedback control architecture



Active control means performance improvement

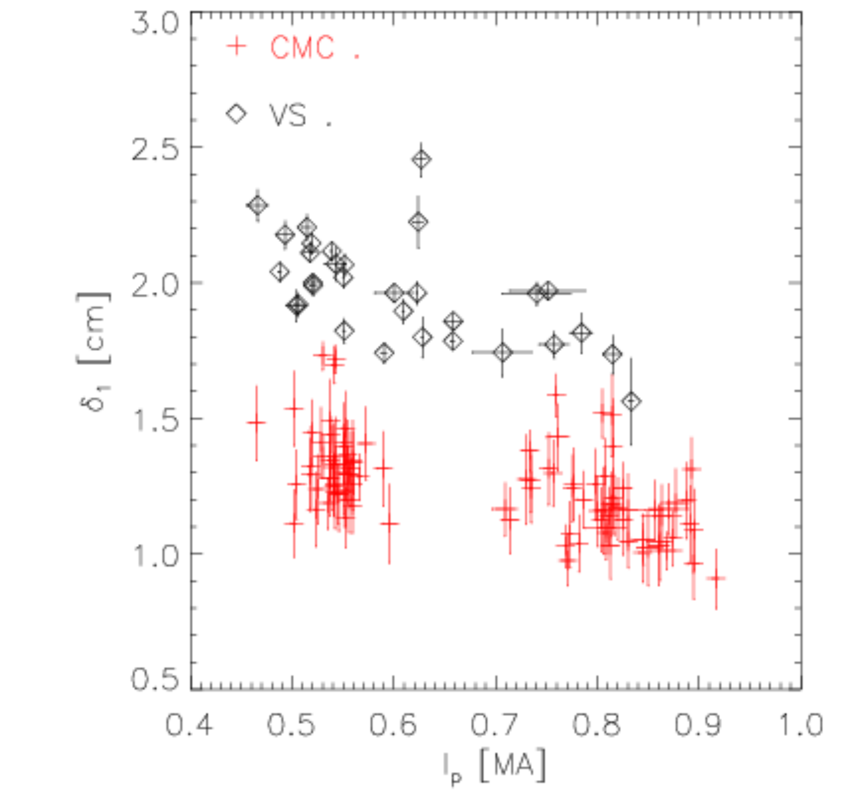
- RFX-mod reliably operates at plasma current close to 2 MA thanks to feedback control of magnetic boundary

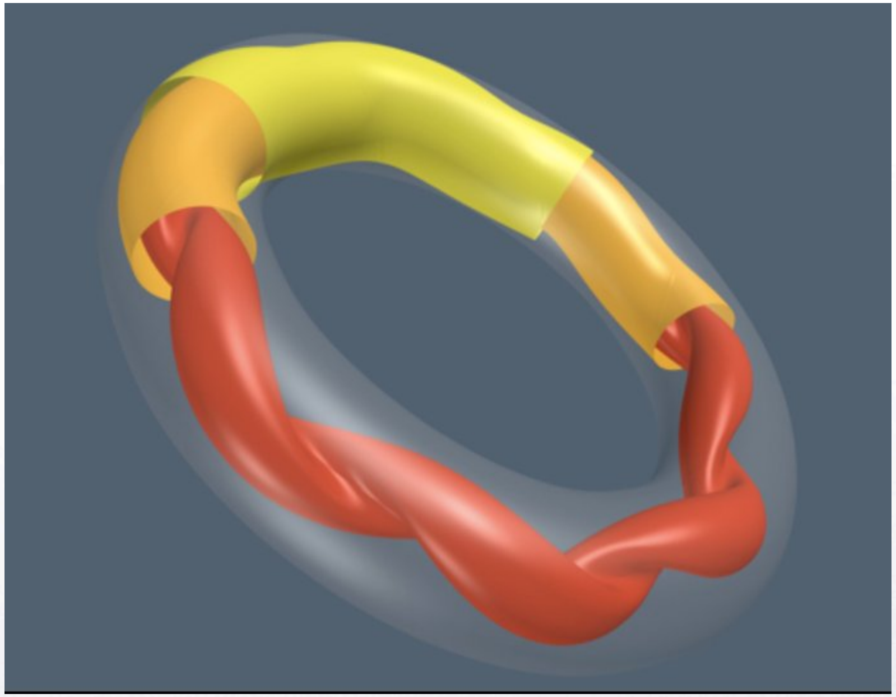


Significant plasma improvement with CMC

smoother plasma boundary

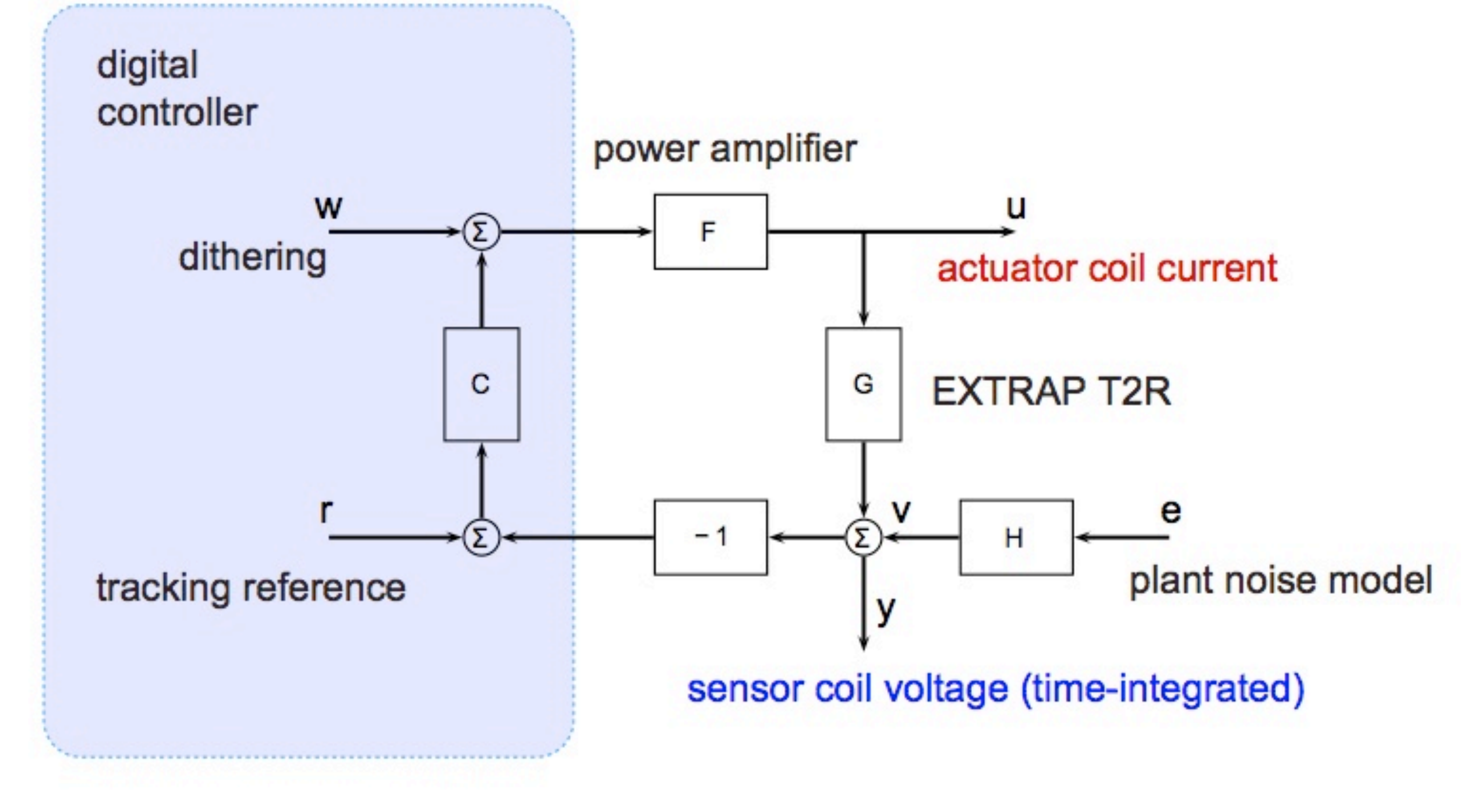
high performance helical state





Lorenzini et al., Nature Phys. **5** 570 (2009)

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

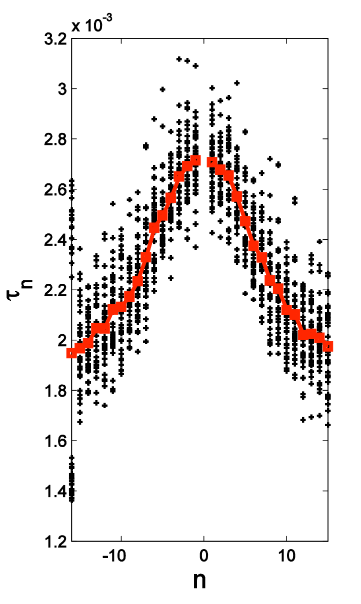


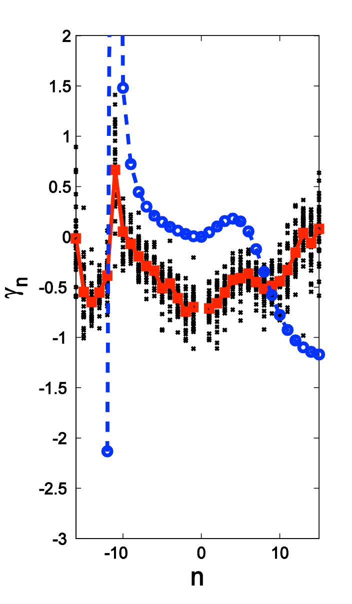
Olofsson et al., to appear in PPCF (2010), special issue on "MHD mode control in toroidal devices"

Closed-loop MHD spectroscopy in EXTRAP T2-R

- **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 psuedo-random dithering signal is applied to all coils.

Wall penetration time constant





RWM growth rate

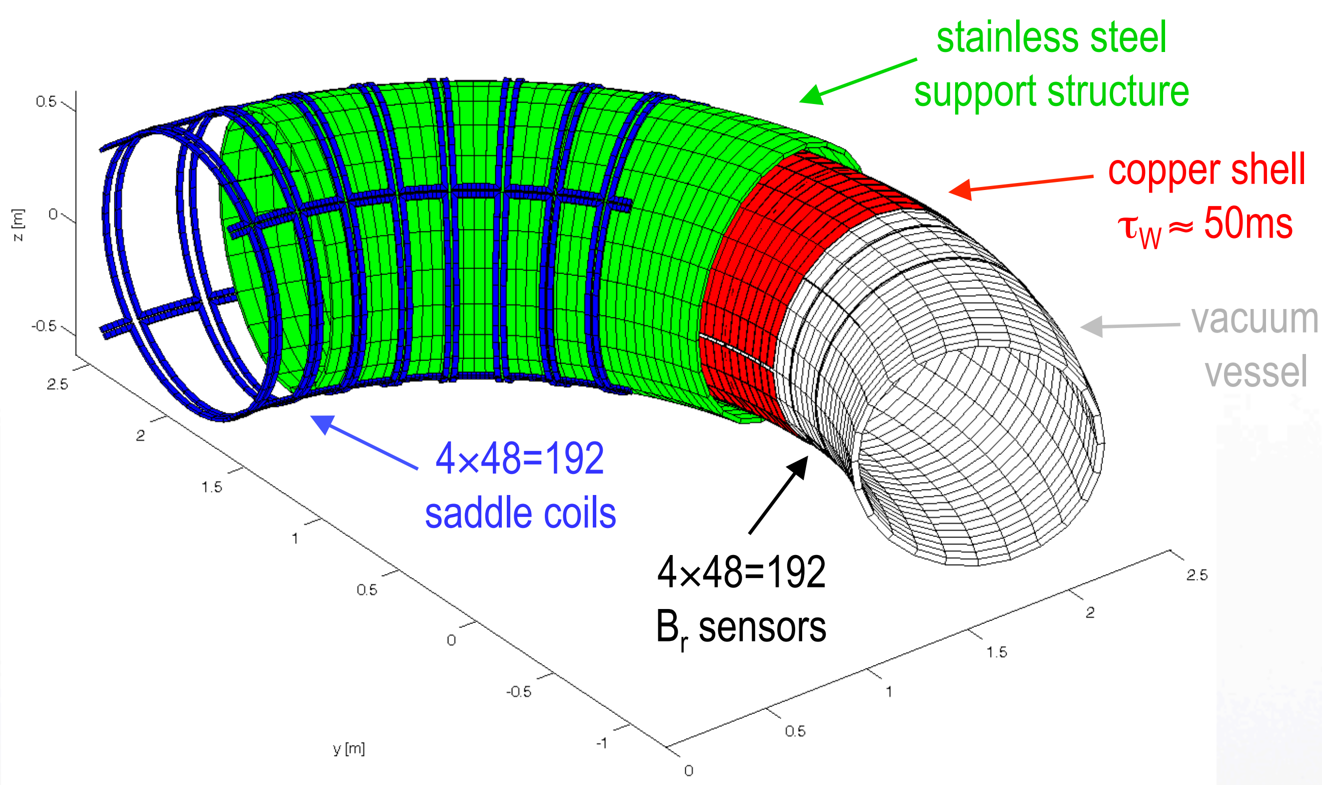
Olofsson et al., accepted to IEEE MSC-09 (2010)

VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

Lesson #3:

what you do may not be exactly what you think you are doing

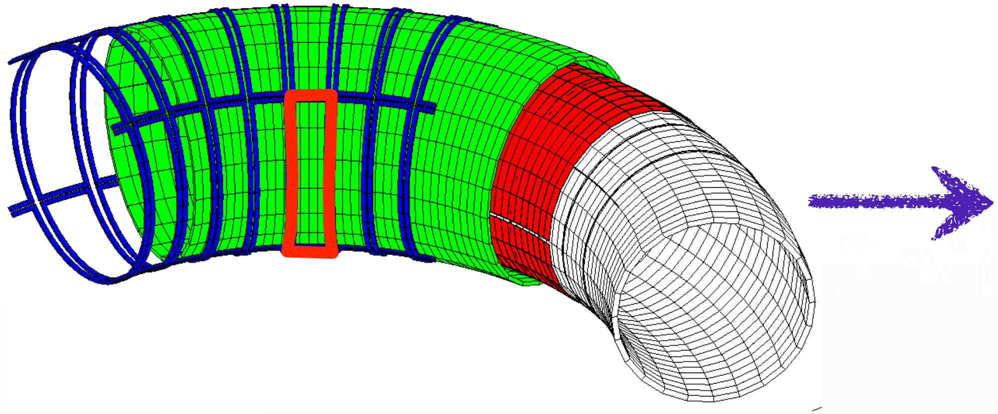
Three dimensional effects



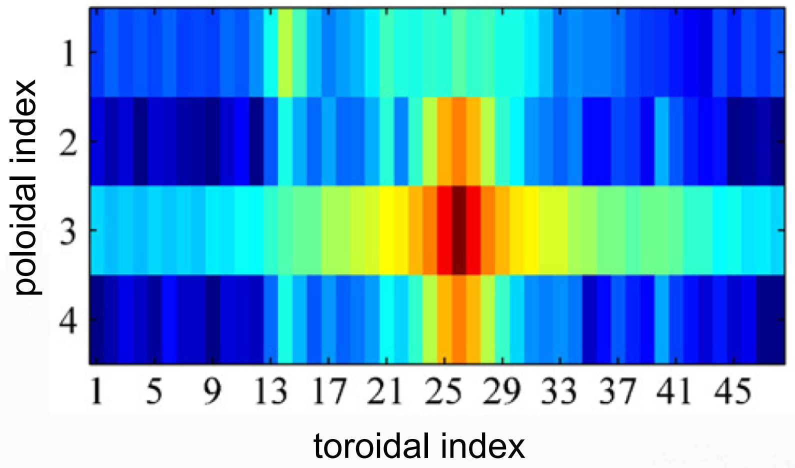
- Feedback coils and passive front-end structure are complex, non uniform, three dimensional structures.
- In RFX-mod wall has1 poloidal gap, 2 toroidal gaps, portholes, …

Probing the coupling

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



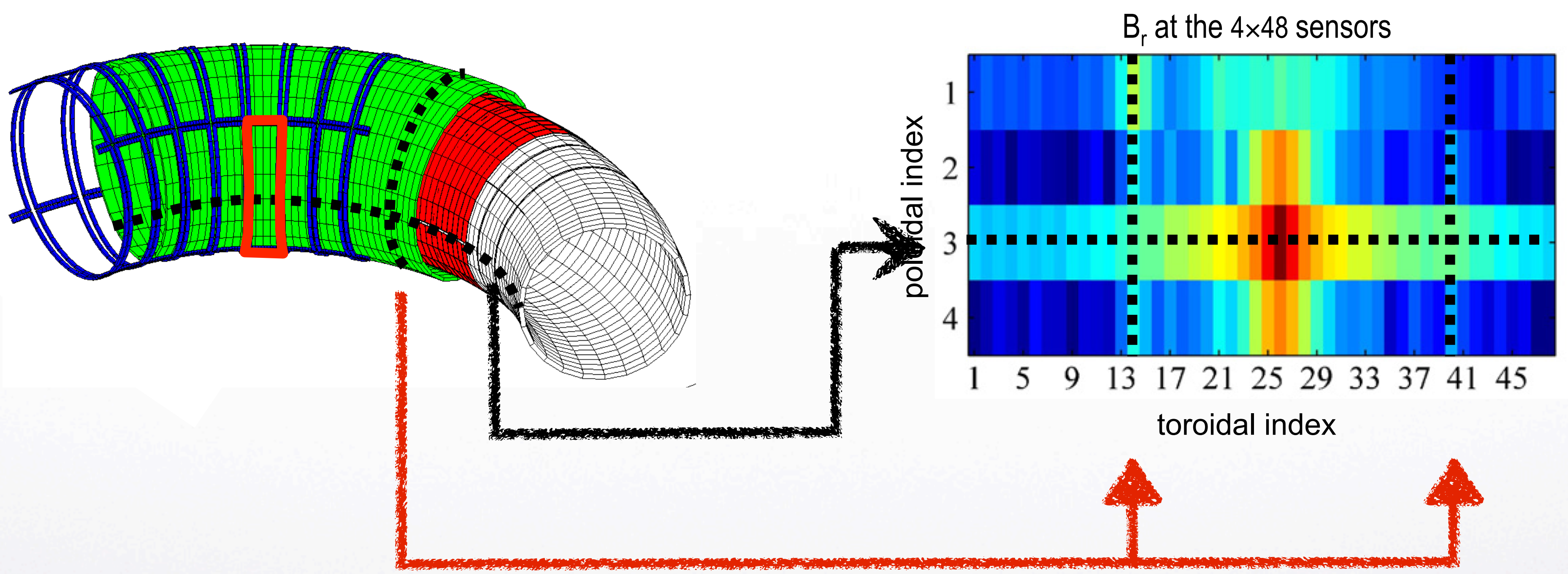
B_r measurements at the 4x48 sensors



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.

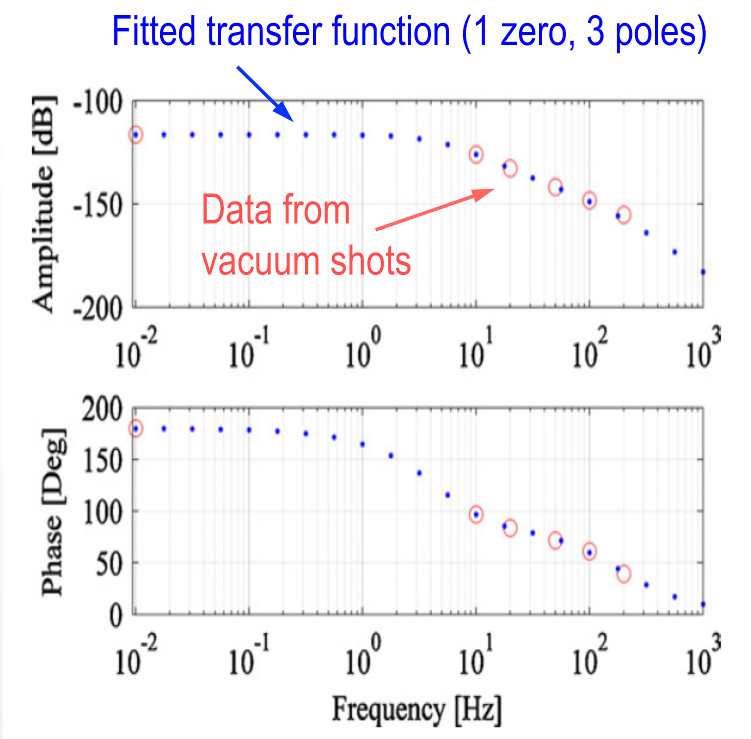
The Br at the sensors produced by arbitrary currents in the active coils can be thus computed :

$$I_c^{i,j} \rightarrow M(f) \rightarrow b_r^{i,j}$$

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:

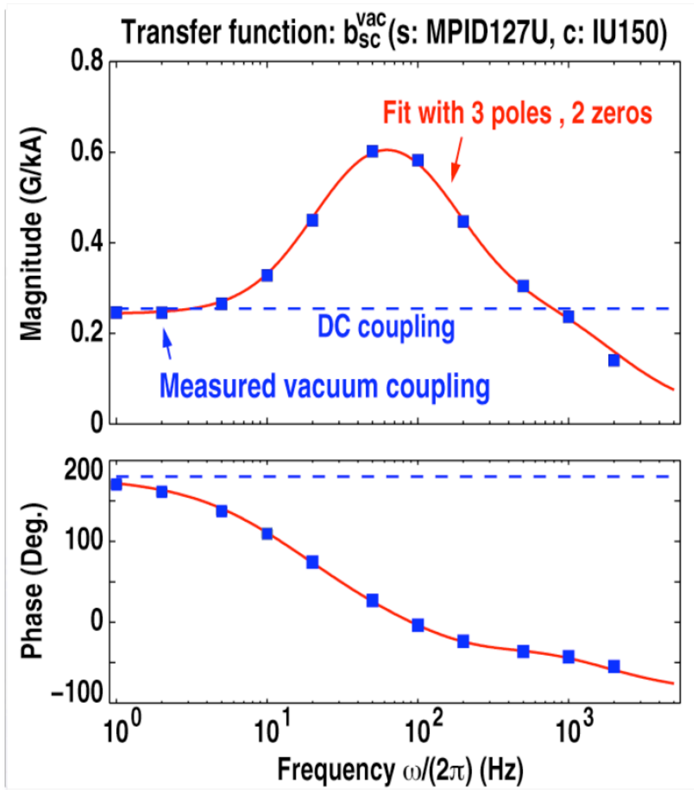
$$b_r^{i,j} \rightarrow M^{-1}(f) \rightarrow I_c^{i,j}$$



Soppelsa et al., Fusion Eng. Des. 83, 224 (2008)

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

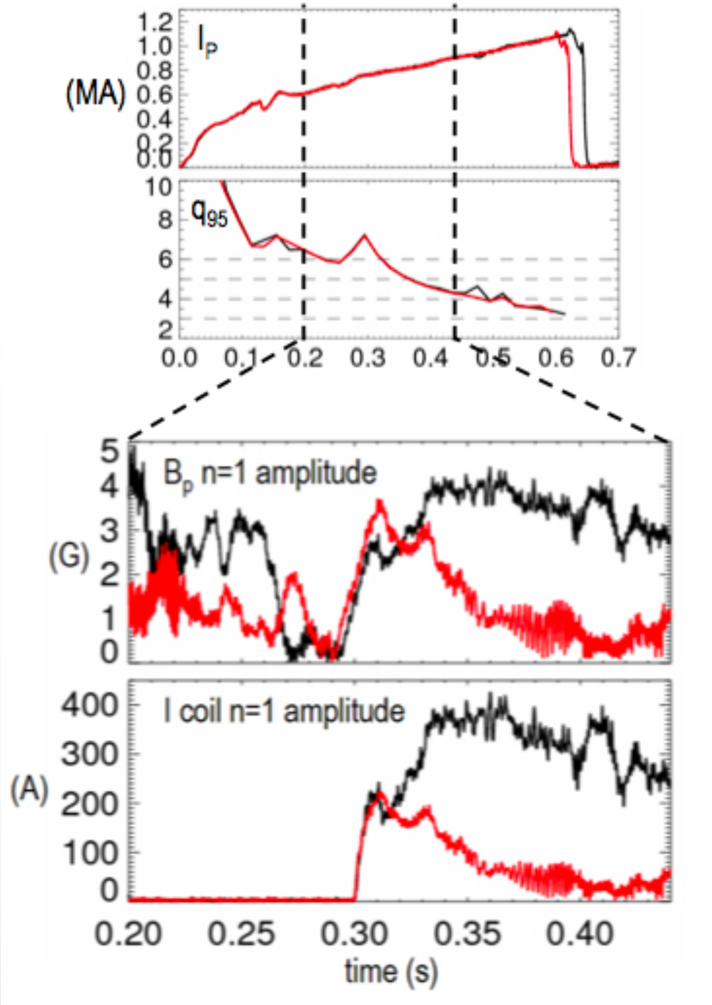
- Feedback sensors in DIII-D sense not only n=1 plasma field but also spurious AC field produced by various coils.
  - Spurious B field must be subtracted from the measurement to have clean feedback.
  - These effects depend on frequency, couplings described by complex transfer functions
- An algorithm to compensate the sensor signals including these frequency dependent effects has been implemented in real time and tested in Ohmic plasmas



AC compensation in DIII-D

AC compensation spares significant feedback coil current for dynamic error field correction

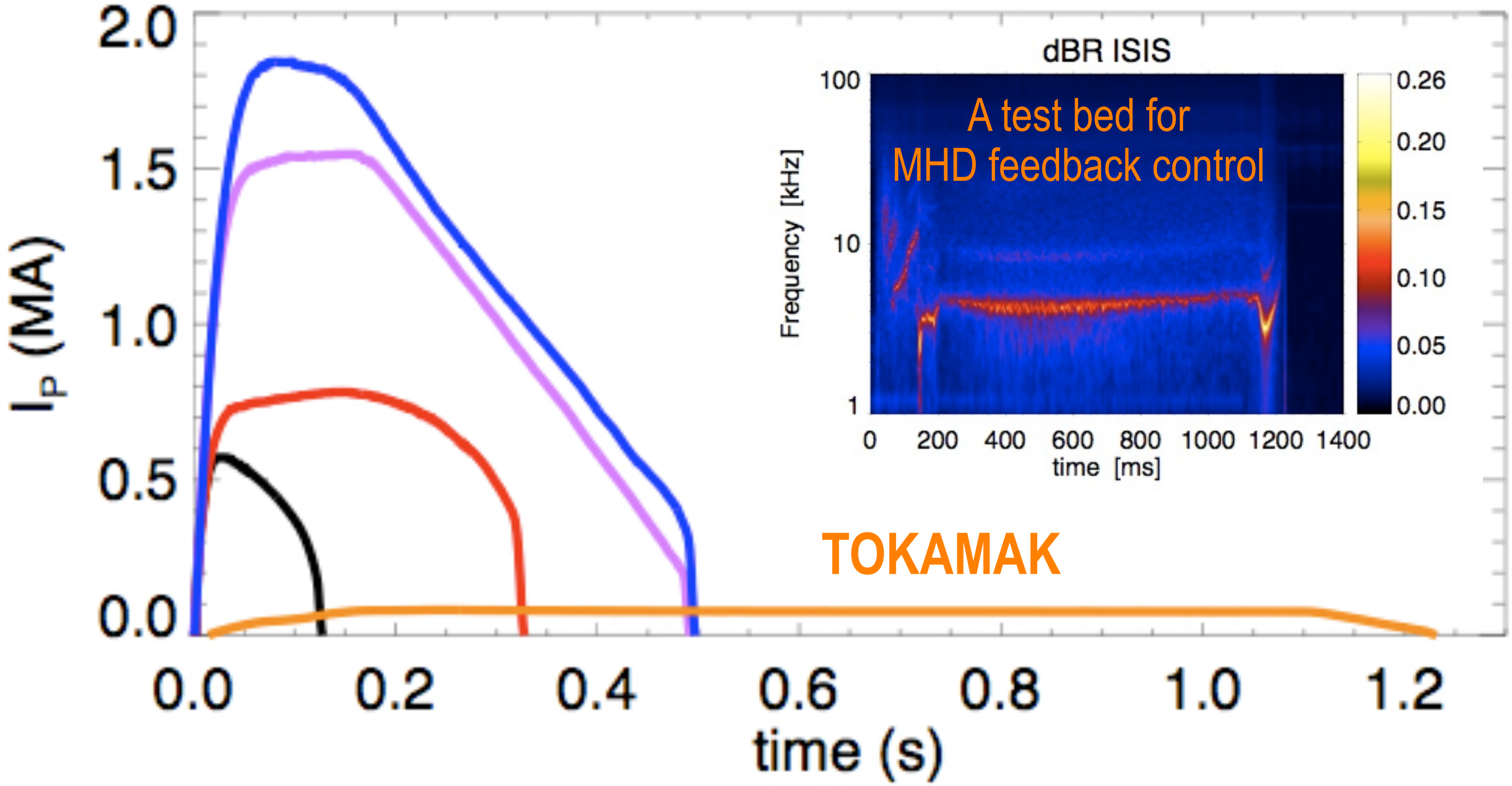
- #141242 with DC compensation
- #141243 with AC compensation



Lesson #4:
think broad

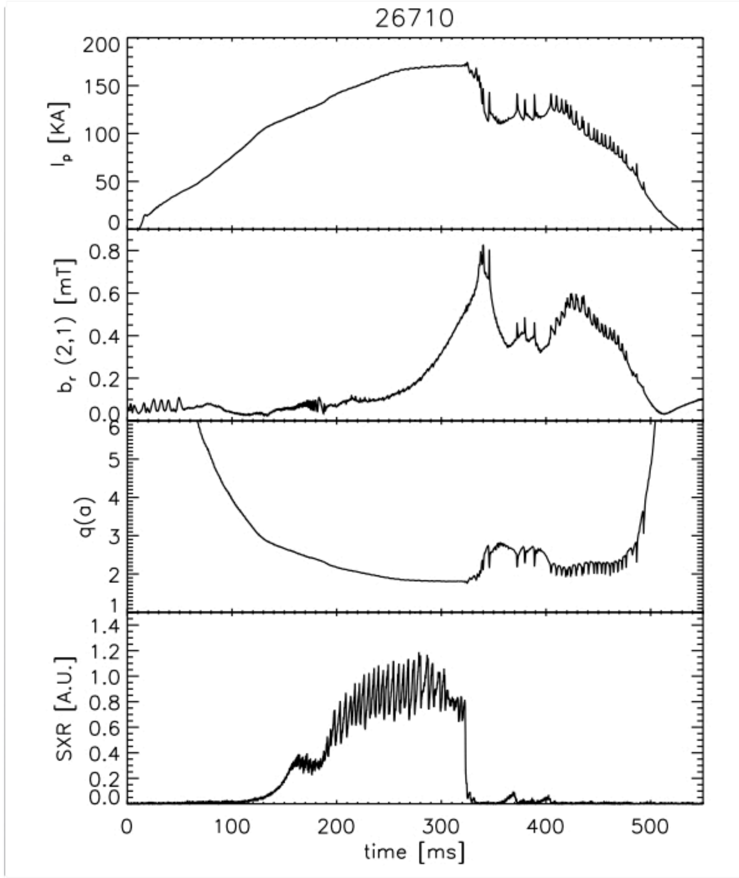
RFP: versatile devices

- RFX-mod can be run as a tokamak



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

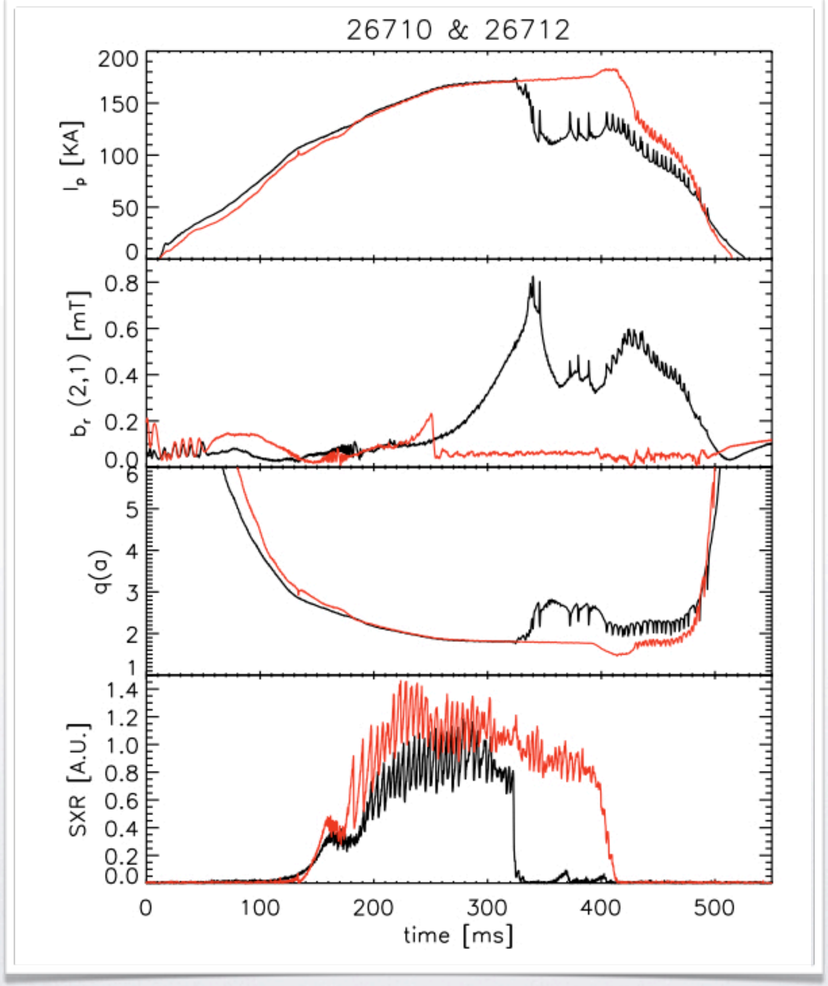
q_{edge}

SXR emission

Active control of a (2,1) mode in RFX tokamak with $q_{edge} \approx 2$

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

no feedback
with feedback



plasma current

(2,1) amplitude

q_{edge}

SXR emission

Piovesan et al., 14th IEA - RFP Workshop (Padova, 2010)

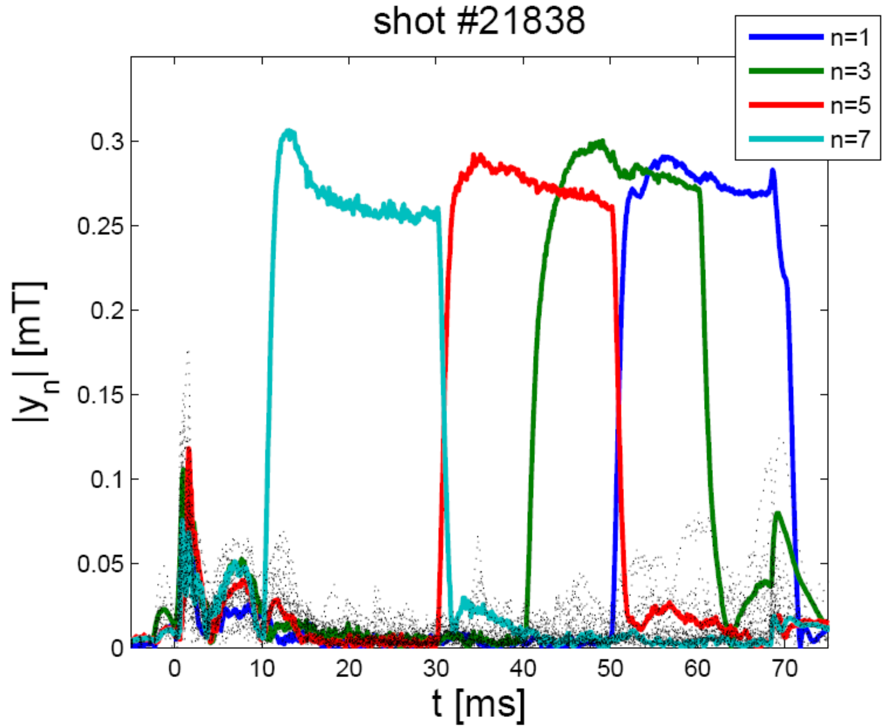
Lesson #5:

output tracking control for RWM and tearing modes

RWM output tracking in EXTRAP T2-R

amplitude of the mode tracked
by the controller

- 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

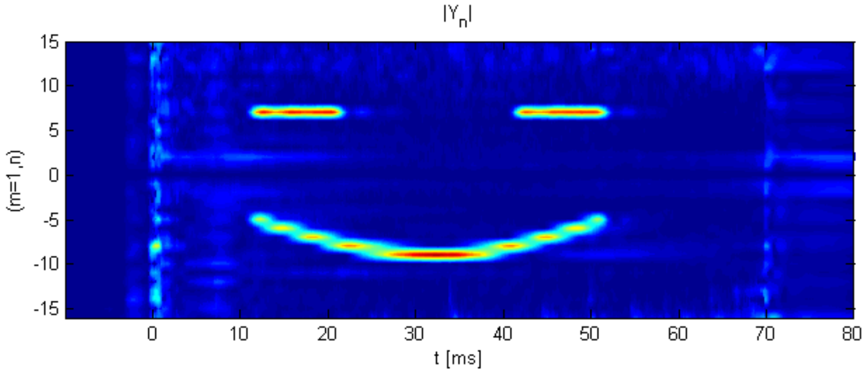


(a) Static-phase (overlapping) sequence of modes.

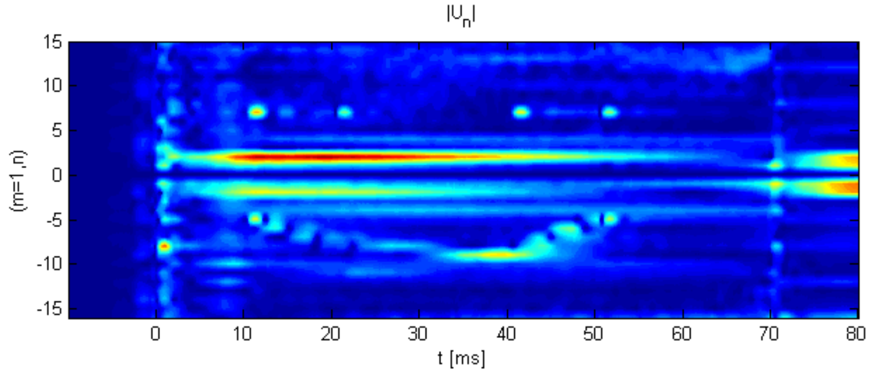
Olofsson et al., Fusion Engineering and Design **84** (2009) 1455

Tracking a reference spectrum in EXTRAP T2-R

|Yn | (spectrum from sensor signal)



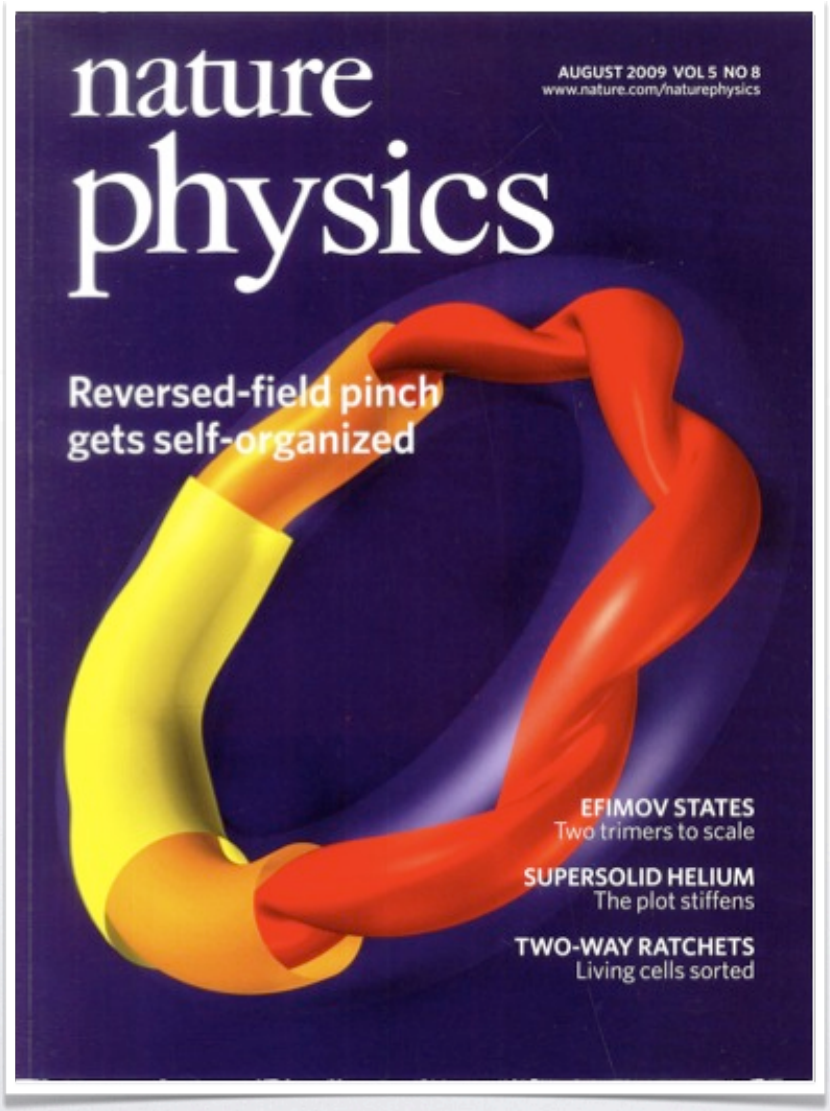
|Un | (spectrum from coil currents)



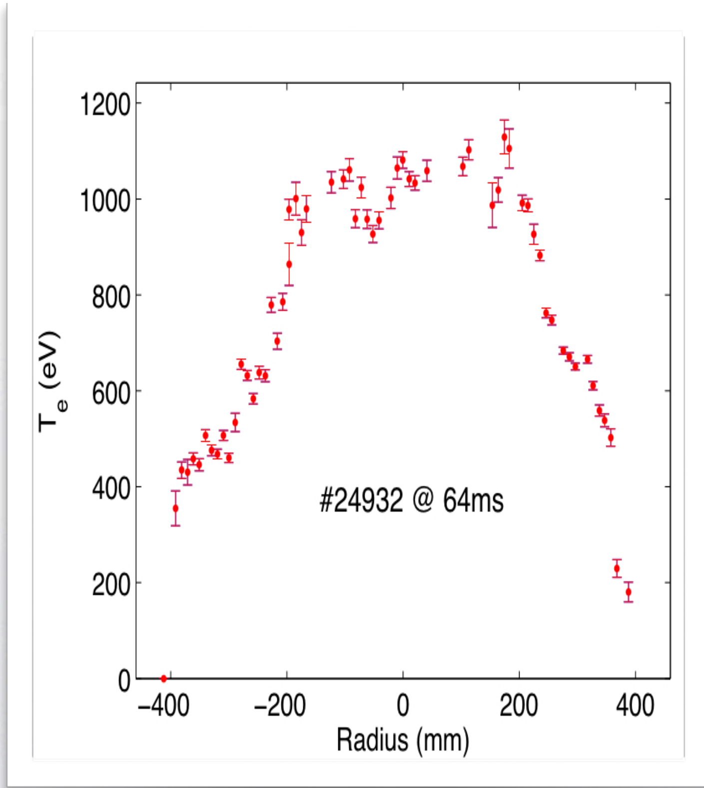
Note that some features of the reference spectrum (seen in sensor signal) can be recognized in the spectrum of the actuator coil currents, but it is clear that the controller provides a "broader" spectrum to the actuator in order to reproduce the sharp reference spectrum

Drake et al., 2010 IEA RFP Workshop

High performance helical equilibria in RFX

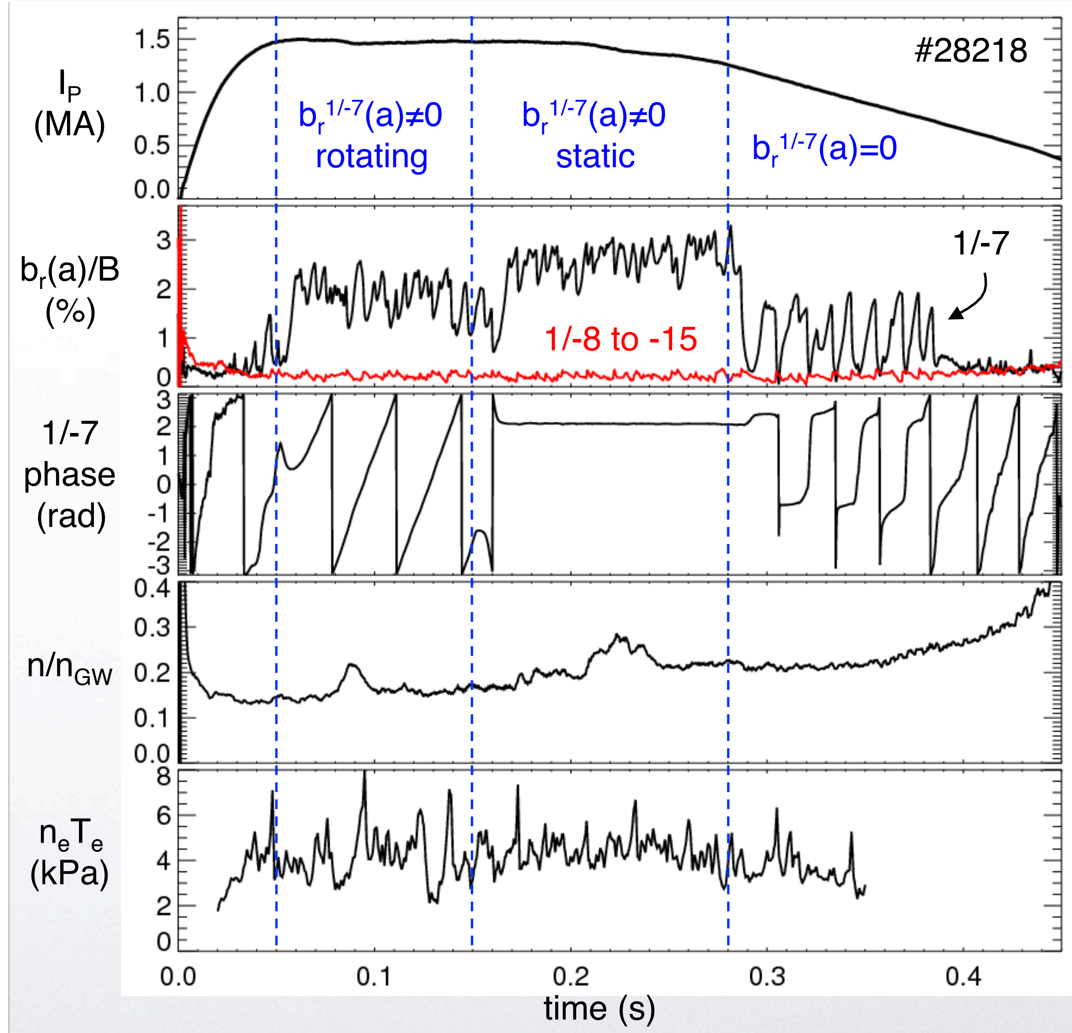


- At high current plasma spontaneously self-organizes in a helical state (m=1, n= −7)
- Helical equilibria come with electron transport barriers



Tracking a non-zero reference for the (1,-7) mode

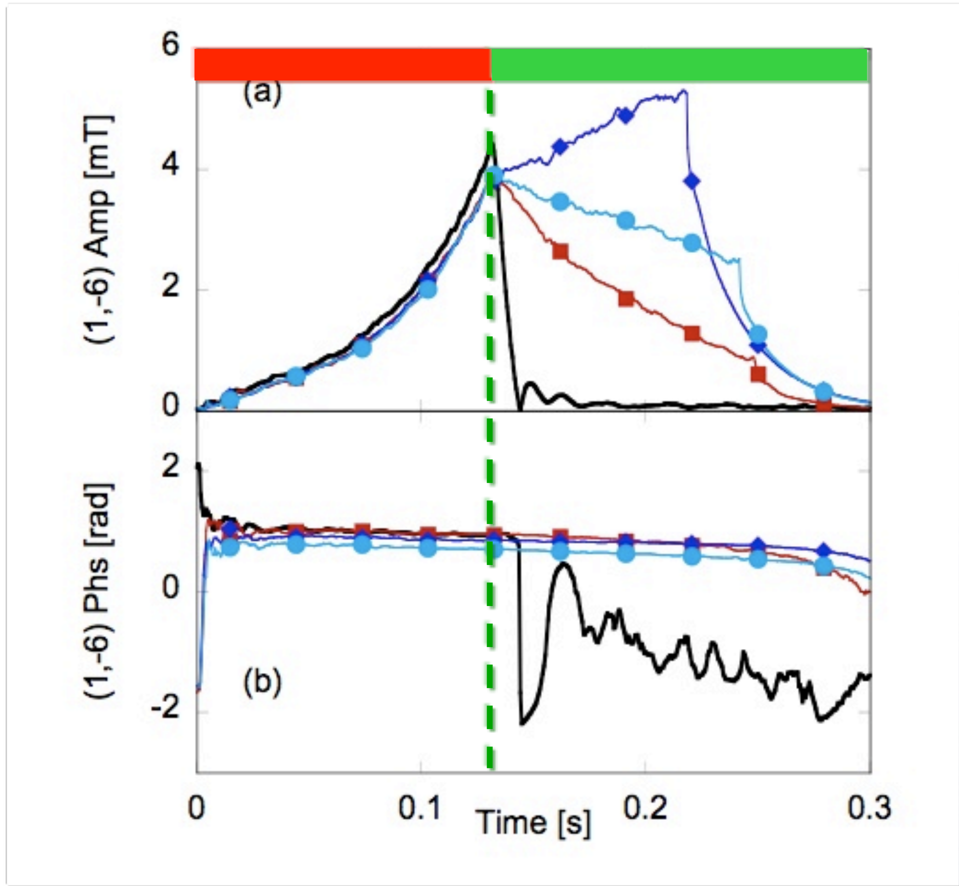
Imposing a non-zero static or rotating reference for the (1,-7) resistive kink mode favors long-lasting helical equilibria



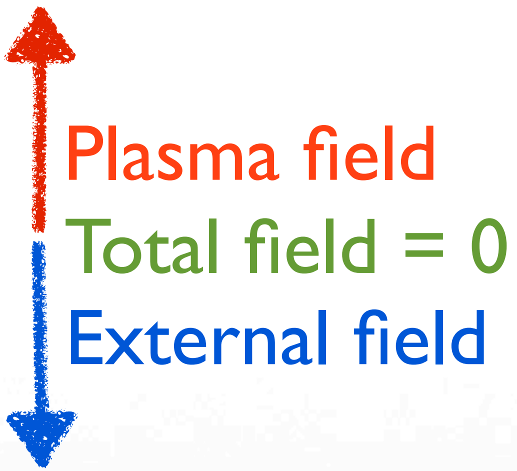
Lesson #6:
grasp & pull

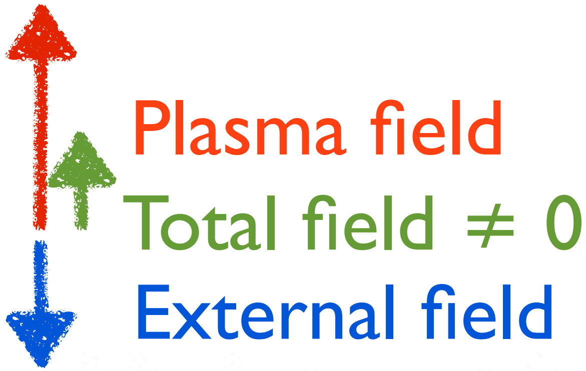
Forcing RWM rotation

- **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



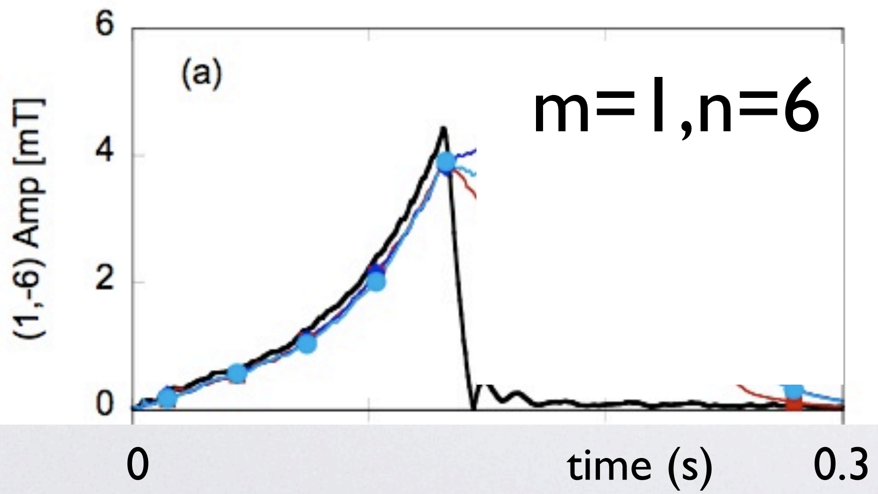
Options for controlling individual modes

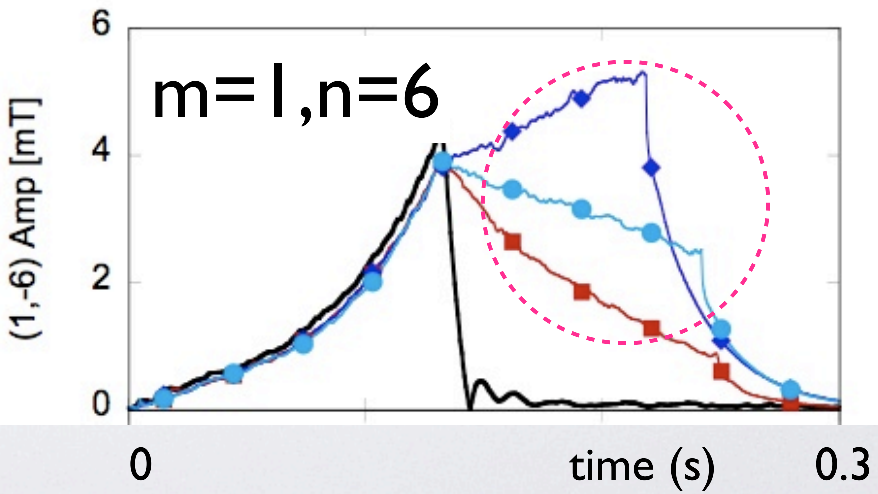




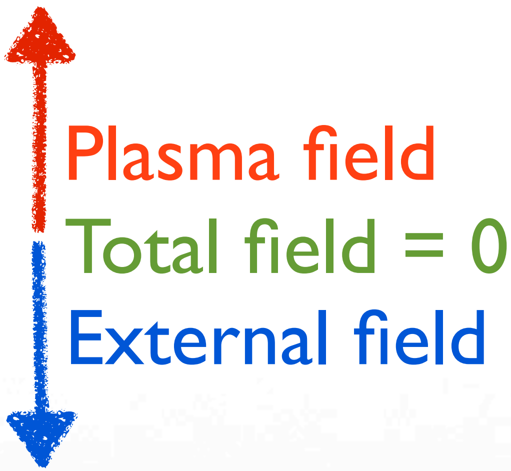
Perfect control

Incomplete control

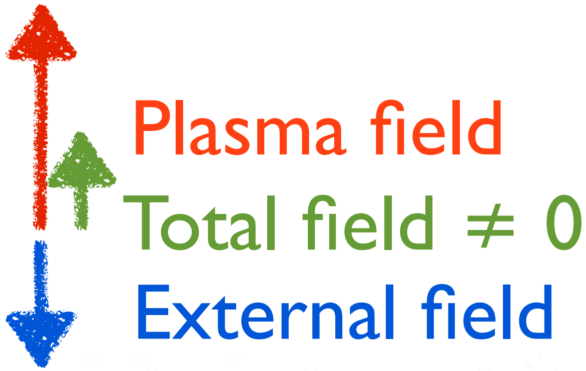




Complex gains ($k_R + ik_i$) to impose phase shift

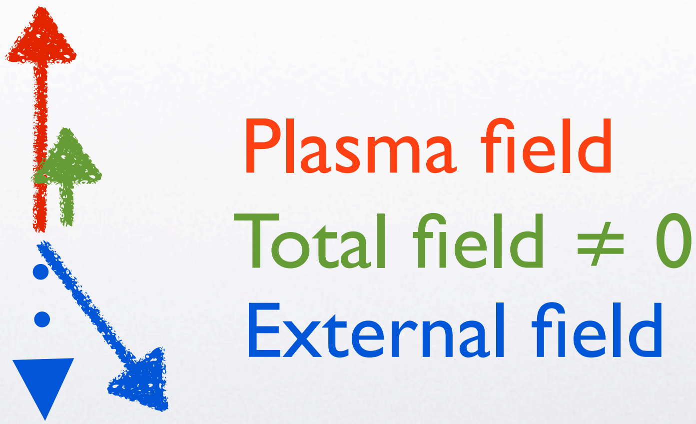


Perfect control



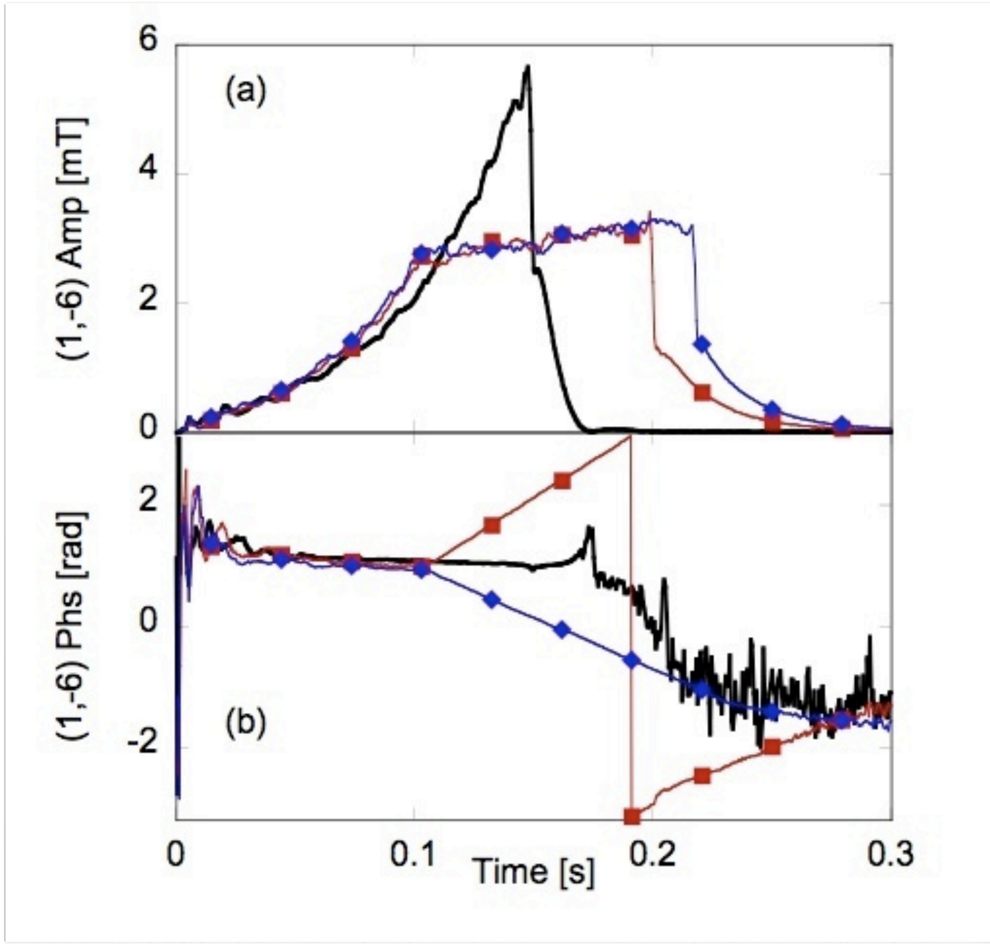
Incomplete control

Incomplete control with phase shift



Advanced RWM control and mode un-locking

- Active rotation of non-resonant wall-locked RWM is induced by applying complex gains (keeping the mode at the desired constant amplitude)



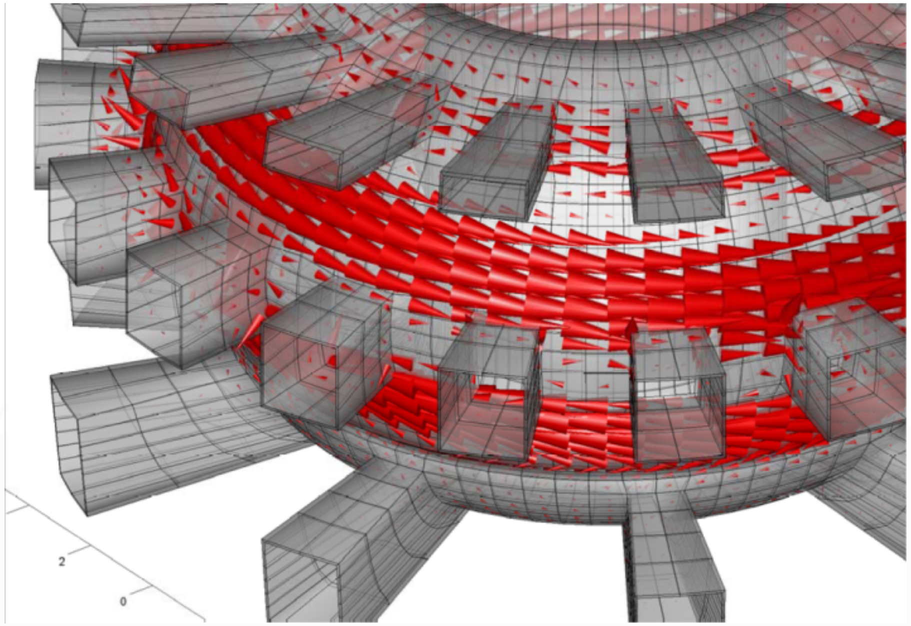
mode amplitude

mode phase

Lesson #7:

codes for ITER need benchmarking.
We are here for it.

ITER code benchmarking



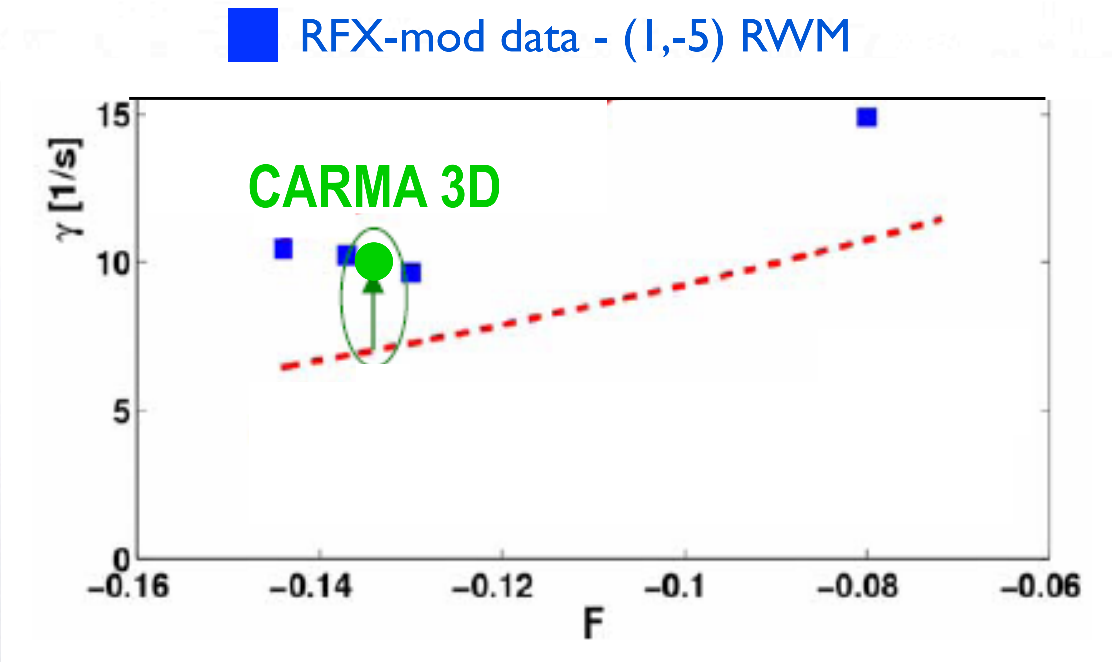
- Codes designed to predict ITER stability and feedback need:
  - to take into account three-dimensional features of the magnetic front-end (portholes, non-uniformity, asymmetries...etc)
  - to be validated against experimental data

ITER code validation in RFX-mod

- 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)

Villone et al., PRL **100**, 255005 (2008)

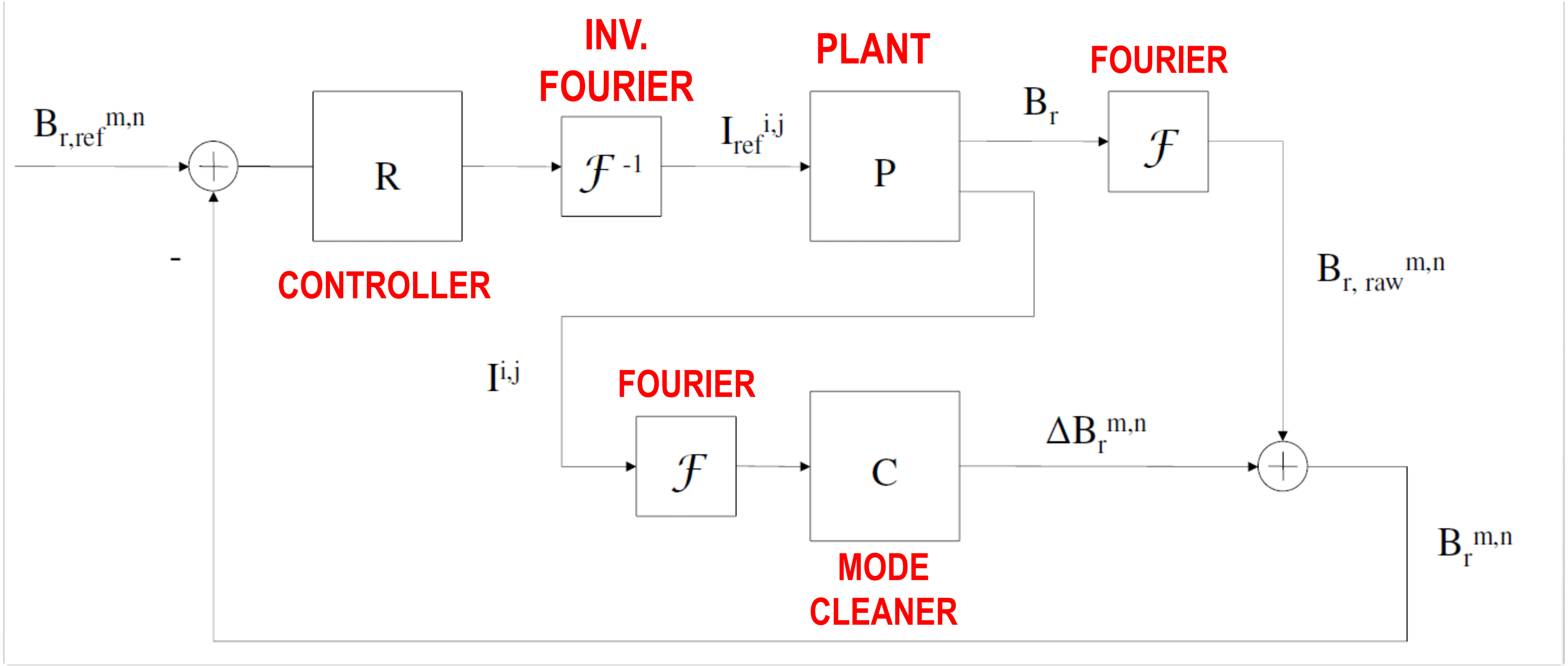
RFX-mod experimental growth rates allow for benchmarking CarMA and showing its superiority wrt two-dimensional codes



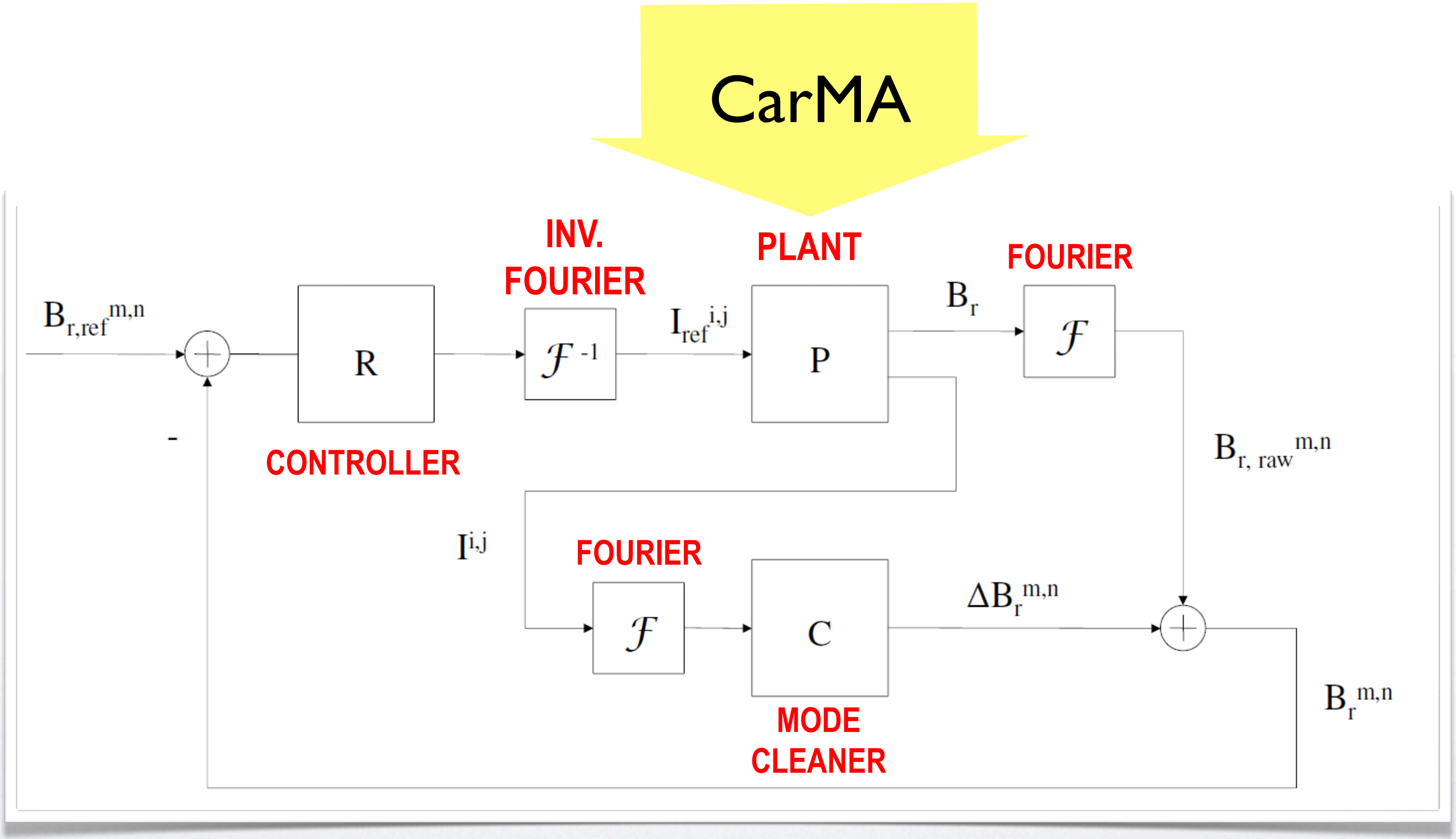
	ETAW	MARSF	CarMa	Exp.
n=4	5.27	5.07	7.30 7.48	≈ 6
n=5	8.63	8.55	12.8 13.1	≈ 12
n=6	14.5	14.4	22.6 23.4	≈ 22

Villone et al., PRL **100**, 255005 (2008)

RFX-mod control architecture



RFX-mod control architecture

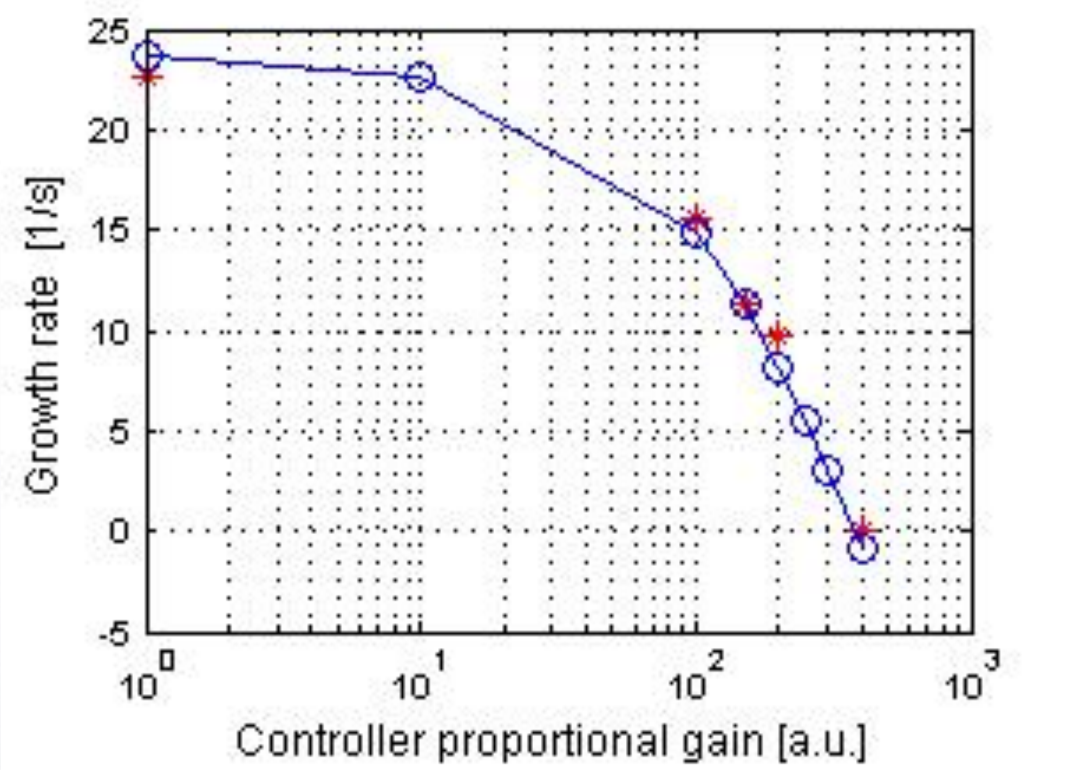


- **FULL closed loop simulator** of the whole plant/controller system successfully implemented based on the integration of CarMa with RFX boundary conditions and controller model

Flight simulator validated against experiment

Experimental (red) and model (blue) growth rates

vs. controller proportional gain.



A portable tool

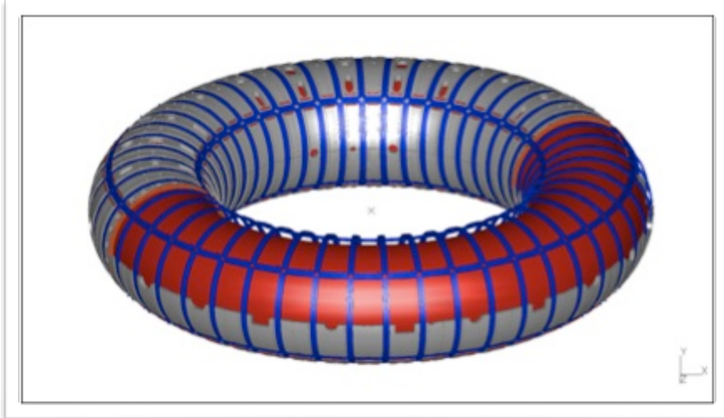
Marchiori et al., 36th EPS conference (Sofia, 2009)
Liu et al., PPCF in press (2010)

Lesson #8:

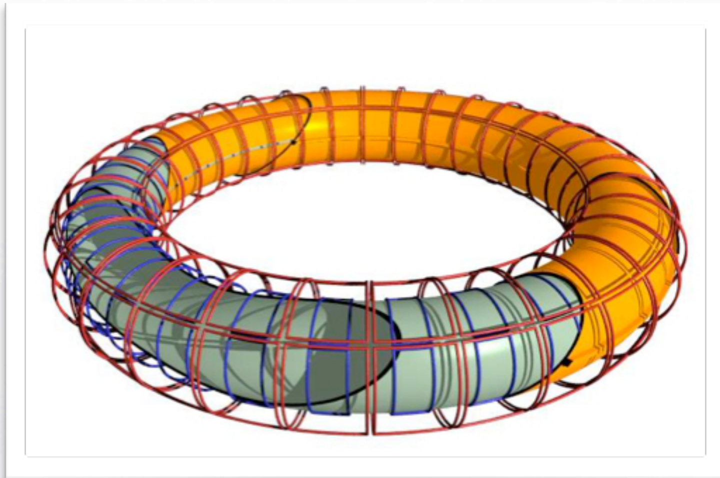
more is better than less...but sometimes you have to live with less....

From full to partial coverage

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



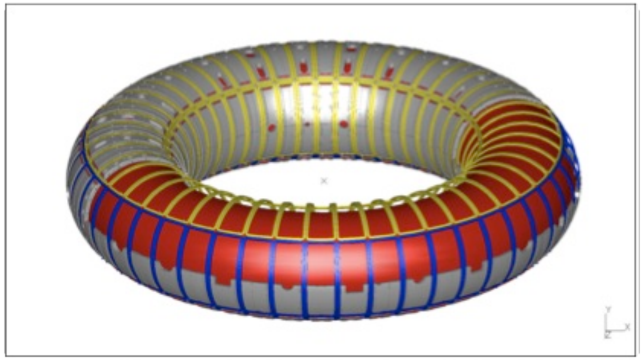
- This may not be the case in present tokamaks and in ITER



A reduced number of actuators is easier to implement but influences feedback efficiency

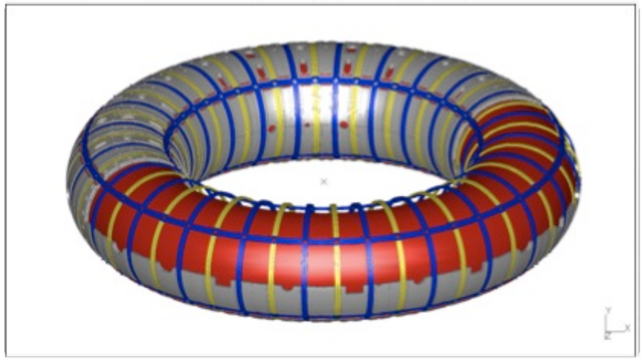
From full to partial coverage

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



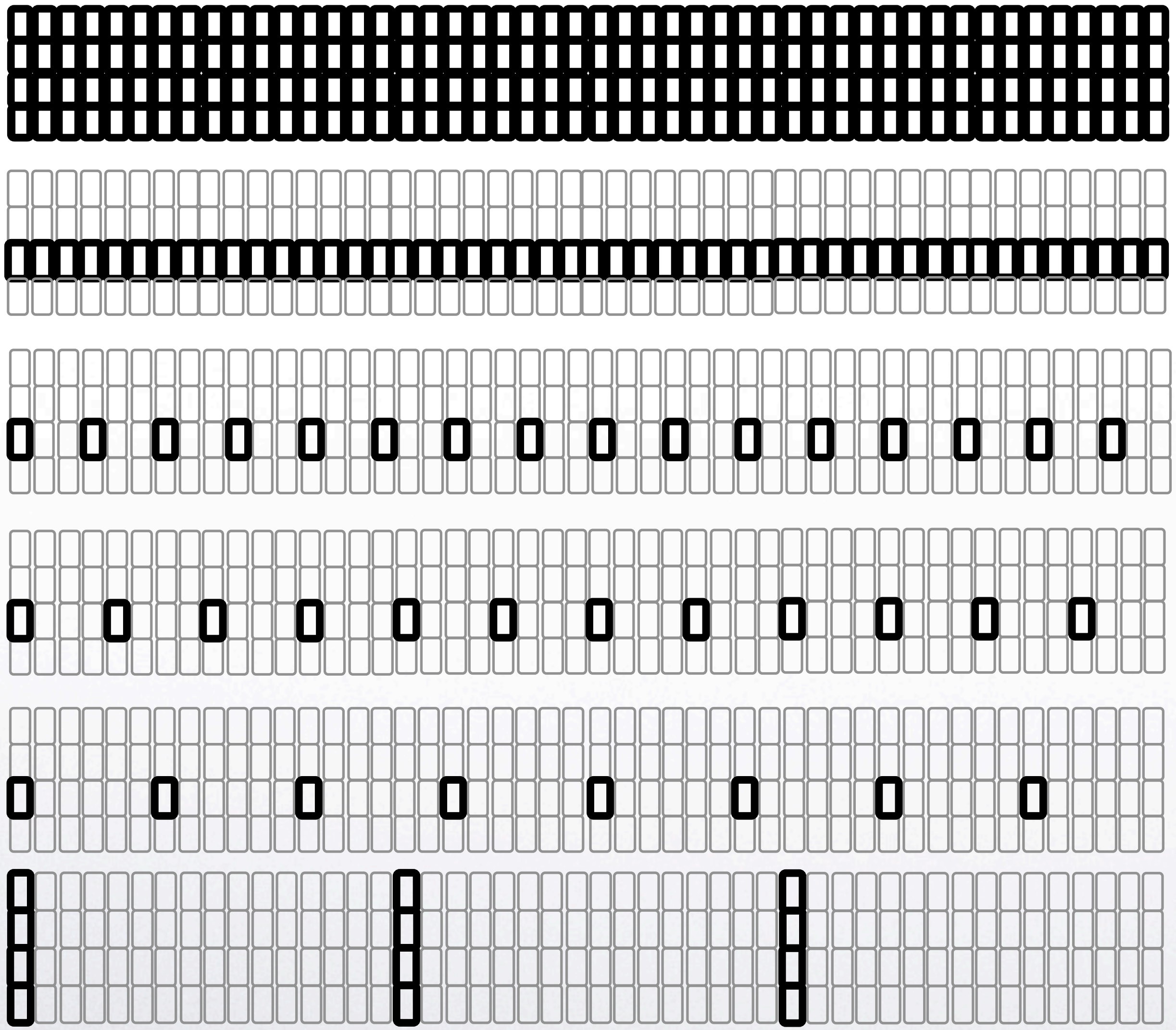
- Feedback downgrading experiment performed in RFX-mod by the JT-60SA team to gather information for the JT-60SA coil design
  - simplicity vs. efficiency threshold

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



48 (ϕ) x 4 (θ): **100%**

48 (ϕ) x 1 (θ): **25%**

16 (ϕ) x 1 (θ): **8.3%**

12 (ϕ) x 1 (θ): **6.25%**

8 (ϕ) x 1 (θ): **4.2%**

3 (ϕ) x 4 (θ): **6.25%**

JT-60SA plans: 6.8% coverage

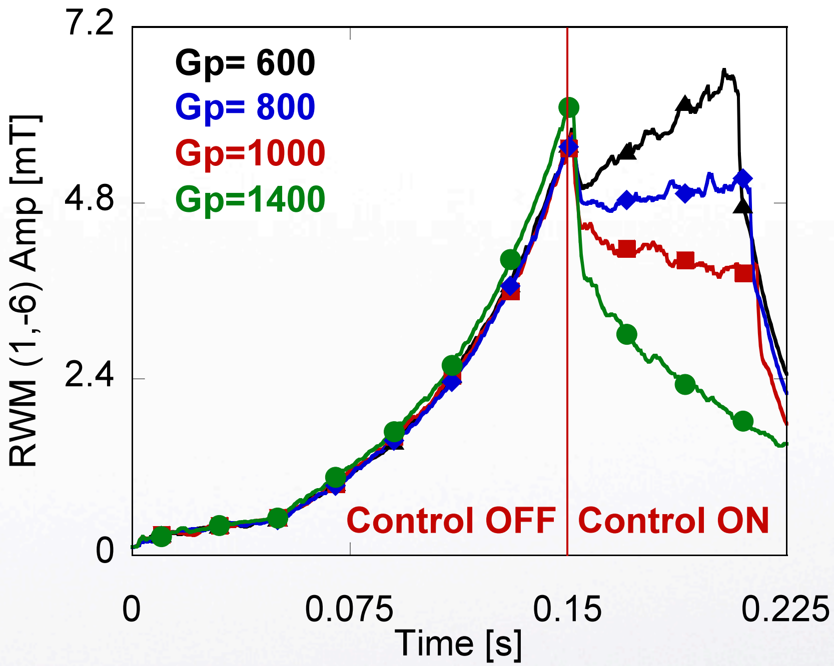
Bolzonella, Takechi et al., JT-60SA TCM 8 (2010)

JT-60SA Advanced Superconducting Tokamak BA-Satellite Tokamak Program

JAEA

From full to partial coverage

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



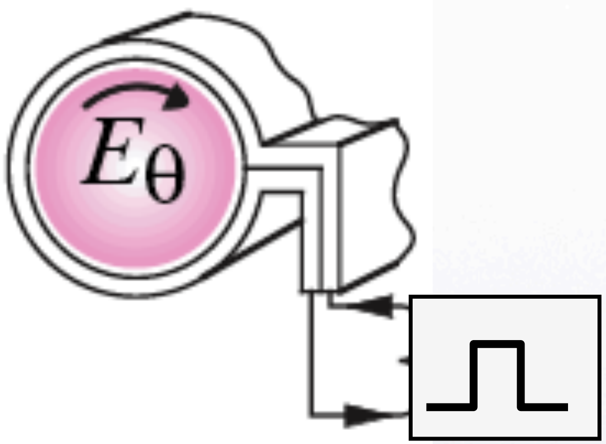
Bolzonella, Tekechi, 14th workshop on MHD stability control (Princeton, 2009)

Lesson #9:

tearing amplitude is affected by controlling the current density profile

Pulsed Poloidal Current Drive

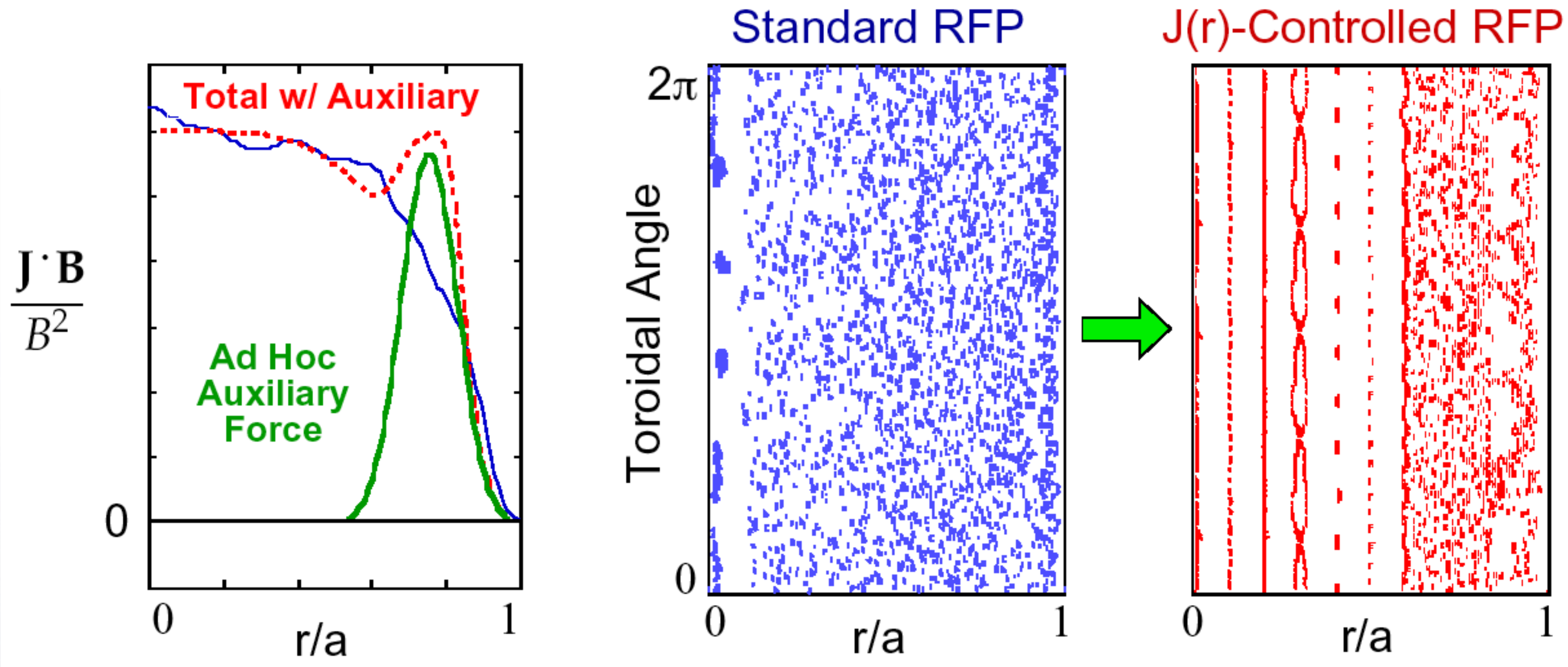
- Tearing Modes responsible for anomalous transport in standard RFP are driven by the current density J profile gradient.
- **Tayloring the J profile** with external means allows for controlling TM and reducing their amplitudes



- Current profile transiently modified by applying a pulsed poloidal electric field
- Mostly poloidal current drive

Pulsed Poloidal Current Drive in MST

- 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



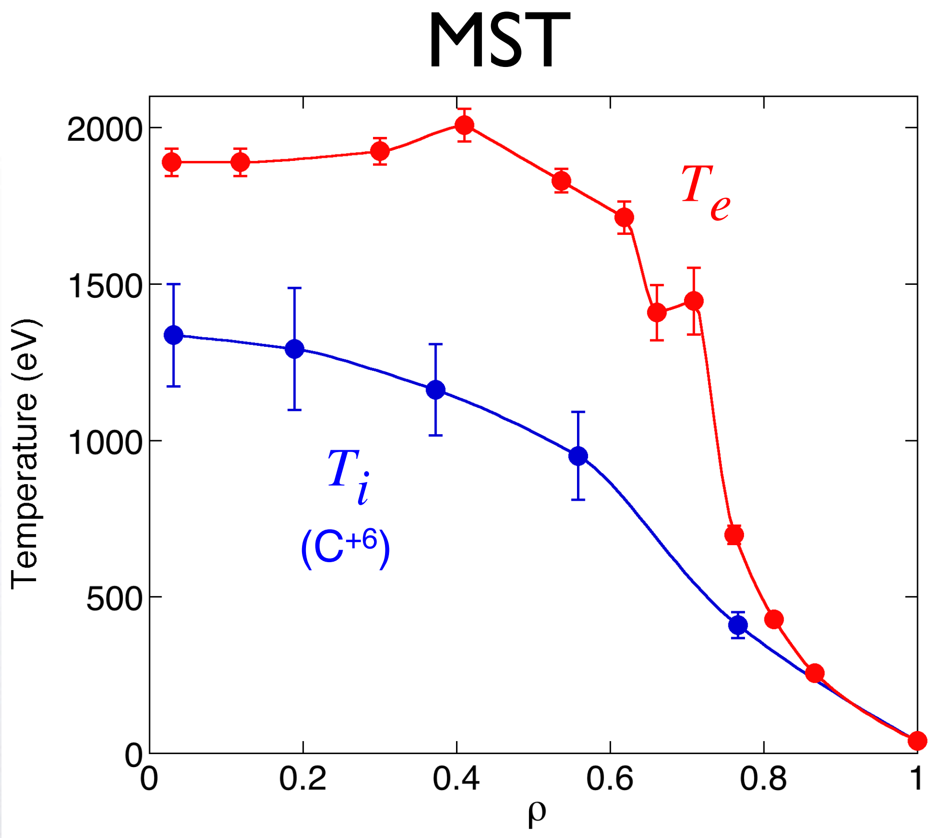
MST

Current drive "replaces" dynamo
Mostly poloidal current drive

Sarff et al., Phys. Rev. Lett. 72, 3670 (1994)
Chapman et al., NF 2009 Nucl. Fusion **49** 104020

PPCD strongly improves confinement

- Control of core resonant tearing modes reduces transport



$I_p = 0.5$ MA, $n/n_G = 0.13$

$\tau_E = 12$ ms, $\beta = 10\%$

Sarff et al., Phys. Rev. Lett. 72, 3670 (1994)
Chapman et al., NF 2009 Nucl. Fusion **49** 104020

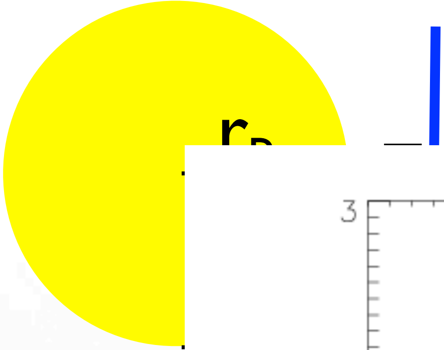
Conclusions

- 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.

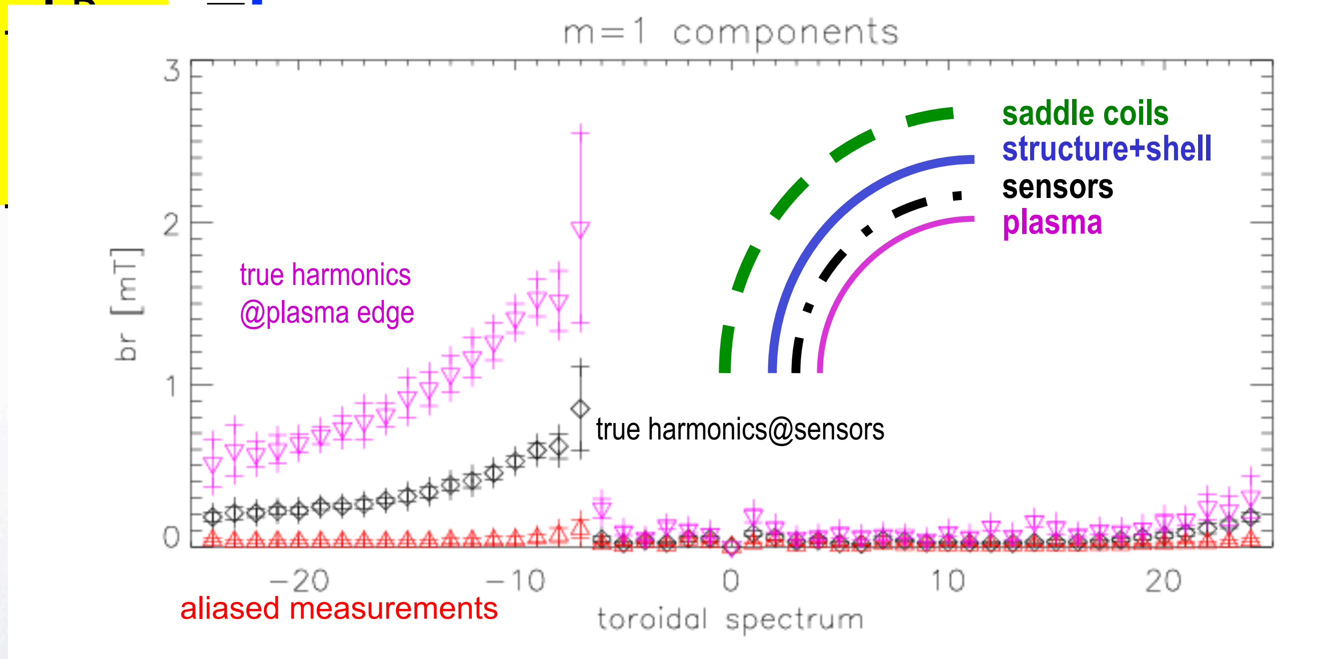
Conclusions:

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



...rier harmonics at the
...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

Text

	INPUTS	OUTPUTS
No sideband corrections	4X48 radial field signals	4x48 reference values
Clean measurements	4x48 radial field signals 4x48 currents flowing in the coils	4x48 reference values
Clean and Closer measurements	4x48 radial field signals 4x48 toroidal field signals 4x48 currents flowing in the coils	4x48 reference values