Reversed Field Pinch:
basics

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Notes for the lecture at the European Ph.D. Course (Garching, 27 September 2010)
Why studying RFP?

Meeting the RFP community

RFP equilibrium basics

RFP MHD dynamics

Beyond stability

Conclusions
Why studying RFPs?
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..
Many times it is necessary to analyze a complex problem from different view angles, since a single view may lead to wrong conclusions.
More views better than one… and often necessary

- Many times is necessary to analyze a complex problem from different view angles, since a single view may lead to wrong conclusions.

Pictures from wikipedia.com
Exploiting variety: a key element for success

Several MHD fusion issues are general and are more easily solved when attacked simultaneously from different points of view.
The RFP community
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
- Kyoto Institute of Technology, Kyoto, Japan
- $a=0.25 \text{ m}, R=0.51 \text{ m}$, plasma current up to 0.1 MA
• 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)
RFP equilibrium basics
The distinctive feature of the RFP that motivates its study for magnetic fusion is the \textit{weak applied toroidal} magnetic field.

The RFP configuration is \textit{similar} to a tokamak…
- like to the tokamak, the RFP is obtained by driving a toroidal electrical current in a plasma embedded in a toroidal magnetic field \textbf{\(\Rightarrow\) pinch effect.}

\textit{..but the applied toroidal field is 10 – 100 times weaker!}
Figure 1: Tokamak configuration. The toroidal and the poloidal field magnets as well as current in the plasma itself produce the main magnetic field. The central solenoid drives the current in the plasma through transformer action.
RFP: exploiting the weak field

Most of the RFP magnetic field is generated by current flowing in the plasma (driven also by a dynamo mechanism)
No need for large magnetic coils.
RFP: low safety factor

- Safety factor $q$ is **low**, and negative at the edge.
- $m=1$ and $m=0$ resonant surfaces in the plasma
Plasma heating systems

Figure 2: Various tokamak plasma heating techniques
m=1 n=1 instability
Kruskal Shafranov limit for tokamak

\[ \rho_0 \frac{\partial^2 \xi_0}{\partial t^2} = F(\xi) = \frac{2B_0^2}{\mu_0 q R_0^2} \left( \frac{b^2}{a^2} - \frac{1}{q} \right) \left( \frac{1}{q} - 1 \right) \xi_0. \]  \hspace{1cm} (25)

Clearly we have a growing mode when \( 1 > q > a^2/b^2 \) with growth rate,

\[ \gamma = \sqrt{\frac{2B_0^2}{\mu_0 \rho_0 q R_0^2} \left( \frac{b^2}{a^2} - \frac{1}{q} \right) \left( \frac{1}{q} - 1 \right)}. \] \hspace{1cm} (26)

When we set the conducting wall to go to infinity we get the Kruskal-Shafranov limit for stability:

\[ q > 1 \rightarrow \text{Stable.} \] \hspace{1cm} (27)
An ohmic low magnetic field, $q<1$ configuration as the RFP:

- Can in principle obtain fusion relying on ohmic heating only

- has several technological advantages as a potential reactor configuration and will therefore contribute to the development of a viable reactor concept

- has unique capabilities to contribute to fusion energy science and technology research
Fusion potential of the low magnetic field

- **high engineering beta**
  \[
  \beta = \frac{\text{volume-averaged pressure}}{\text{surface-averaged magnetic pressure (at the coils)}}
  \]
  
  - For configurations like the tokamak the maximum field at the magnet is of order twice the field in the plasma, whereas in the RFP the field at the magnet is less than in the plasma.
  
  - The engineering beta in an RFP reactor might be as much as twice the physics beta (up to 26% in present experiments).

- Use of **normal** (rather than superconducting) **coils**,
- **High mass power density**,
- **Efficient** assembly and disassembly,
- Possibly **free choice of aspect ratio**
A comprehensive understanding of toroidal magnetic confinement, and the possibility of predicting it, implies that plasma behavior would be predictable over a wide range of magnetic field strengths.

The RFP provides new information since it extends our understanding to low field strength, testing for example the results derived at high field with the tokamak.
MCF operational space

SELF ORGANIZATION

- RFP
- tokamak
- $|B|$
- stellarator
- RWM, RMP, field ripple, NTV ...

3D
RFP: bridging knowledge talking same language

Bridge to tokamak:
active control of magnetic boundary.
(192 feedback coils in RFX)

Bridge to stellarator & TOK:
Explore three-dimensional physics in broader regions.

We use tools common to Stellarator and Tokamak community.
We contribute to a common knowledge basis for all magnetic configurations.
4.2. BASIC EQUATIONS

To begin, consider the MHD equilibrium equations given by

\[ \mathbf{J} \times \mathbf{B} = \nabla p \]  \hspace{2cm} (4.6)

\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \]  \hspace{2cm} (4.7)

\[ \nabla \cdot \mathbf{B} = 0 \]  \hspace{2cm} (4.8)
Linear vs. toroidal configurations
Magnetic flux surfaces

\[ \mathbf{B} \cdot \nabla P = 0 \]
Current, magnetic and pressure surfaces

- The angle between $J$ and $B$ is in general arbitrary

Similarly, the equilibrium relation

$$J \cdot \nabla p = 0$$

(4.20)

implies that the current lines also lie on the surfaces of constant pressure; the current flows between and not across flux surfaces. Note that while

Figure 4.4. Toroidal flux surfaces showing the magnetic axis and the magnetic lines lying on a surface.
Rational, ergodic and stochastic

There are three important classes of magnetic field line trajectories that must be distinguished: rational, ergodic, and stochastic. A constant $p$ contour in which all the lines exactly close on themselves after a finite number of toroidal circuits is known as a rational surface. If instead the field lines do not close, but cover the entire constant $p$ surface, this corresponds to an ergodic surface. In those situations where the field line actually fills a volume, this is known as a region of stochasticity.

In general, toroidal magnetic geometries with ergodic or rational surfaces are the ones of interest and importance to MHD. Most configurations with desirable MHD confinement properties have both ergodic and rational surfaces. Usually the ratio of rational to ergodic surfaces is of measure zero. The tokamak, stellarator, reversed field pinch, and spheromak are configurations of this type. Counterexamples
Revisiting stochastic magnetic fields in present day fusion devices

- Coils like these are presently under consideration in ITER to produce, by purpose, stochastic magnetic field for ELM suppression (Resonant Magnetic Perturbation)

Figure 8. Proposed design of in-vessel coils for VS and ELM control. The ELM control windings can also be used for resistive wall stabilization.
pinch
A simple example: $\Theta$-pinch

- Configuration with pure toroidal field

\[ \mathbf{J} \times \mathbf{B} = \nabla p \]
\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \]
\[ \nabla \cdot \mathbf{B} = 0 \]
A simple example: $\Theta$-pinch

- The sum of magnetic and kinetic pressure is constant throughout the plasma.
- The plasma is confined by the pressure of the applied magnetic field.

![Equilibrium profiles for a $\Theta$ pinch.](image)
Experimental Θ-pinches

- Experimental Θ-pinches among the first experiments to be realized
- End-losses severe problem
- A Θ-pinch is neutrally stable, and can not be bent into a toroidal equilibrium
- Additional field must be added to provide equilibrium
Z-pinch
Z-pincho

- Purely poloidal field
- All quantities are only functions of $r$
In contrast to the Θ-pinch, for a Z-pinch it is the tension force and not the magnetic pressure gradient that provides radial confinement of the plasma.

\[
\frac{d}{dr} \left( p + \frac{B_\theta^2}{2\mu_0} \right) + \frac{B_\theta^2}{\mu_0 r} = 0 \quad (5.15)
\]

The Bennet pinch satisfies the Z-pinch equilibrium.

\[
B_\theta = \frac{\mu_0 I_0}{2\pi} \frac{r}{r^2 + r_0^2}
\]

\[
J_z = \frac{I_0}{\pi} \frac{r_0^2}{(r^2 + r_0^2)^2}
\]

\[
p = \frac{\mu_0 I_0^2}{8\pi^2} \frac{r_0^2}{(r^2 + r_0^2)^2}
\]
Tension force acts inwards, providing radial pressure balance.

These profiles are illustrated in Fig. 5.5. Also illustrated are curves of $p'$, $(B_\theta^2/2\mu_0)'$ and $B_\theta^2/\mu_0 r$. Note that in the outer region of the plasma, $r > r_0$, the plasma and magnetic pressure gradients are both pointing outward; magnetic pressure is not confining the plasma. Instead it is the tension force that acts inwards, thereby providing radial pressure balance. If one thinks of the magnetic field lines as rubber bands surrounding a column of plasma, the tension force is then obvious. In
Finally, with regard to toroidal equilibrium, recall that the Z pinch can easily be bent into a torus, although its stability properties remain poor. Nevertheless, the Z pinch represents the radial pressure balance properties of several interesting fusion concepts including the ohmically heated tokamak and the reversed field pinch.
The general screw pinch
General Screw Pinch

Though the momentum equation is non-linear, the Θ-pinch and Z-pinch forces add as a linear superposition, a consequence of the high degree of symmetry.
RFX coils

induction of plasma current

mean magnetic field radial profiles

toroidal magnetic field

poloidal magnetic field
Tokamak and RFP profiles

Figure 1-1. Example of the force-free magnetic field profiles for the RFP (RFM with μ = 3) and the tokamak.
safety factor profiles in tok and RFP

Fig. 5 - Tokamak and RFP $q$ radial profiles.
RFP $B$ profile
RFP MHD dynamics
Resonances in RFP:

- low $m$ (0-2)
- high $n$ ($2R/a$)

$B_t(0) > \langle B_t \rangle \approx B_p(a) >> B_t(a)$
Most of the RFP magnetic field is generated by current flowing in the plasma.
The RFP is an **ohmically driven system**: an **inductive toroidal electric field**, produced by transformer effect, continuously feeds energy into the plasma.

**Ohm’s law mismatch**: the electrical currents flowing in a RFP can not be **directly driven** by the inductive electric field $E_0$.

\[ \vec{E}_i \neq \eta \vec{J} \]

..but stationary ohmic RFP are **routinely produced for times longer than the resistive diffusion time**.
Ohm’s law

\[ \mathbf{E} + \mathbf{V} \wedge \mathbf{B} = \eta \ \mathbf{J} \]

at reversal

\[ E_\theta = \eta J_\theta + V_r B_z \]

Induction equation

\[ \frac{\partial \mathbf{B}}{\partial t} = -\nabla \wedge \mathbf{E} \]

\[ \frac{\partial}{\partial t} = 0 \quad \rightarrow \quad E_\theta(r) = 0 \]
Ohm’s law

\[ \mathbf{E} + \mathbf{V} \wedge \mathbf{B} = \eta \mathbf{J} \]

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Induction equation

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\[ \frac{\partial}{\partial t} = 0 \quad \rightarrow \quad E_\theta (r) = 0 \]

\[ J_\theta (r) = 0 \]

\[ J_\theta (r) \neq 0 \]
to resolve the previous inconsistency we need an “additional” mean electric field with respect to the one provided by mean \( \mathbf{B} \) and mean \( \mathbf{v} \) fields, i.e. within resistive MHD the contribution by coherent modulation of \( \mathbf{B} \) and \( \mathbf{v} \):

\[
\mathbf{E}_{\text{dynamo}} = < \mathbf{v} \wedge \mathbf{B} >
\]

\[
<E_\theta> = < \eta J_\theta > + < V_r > < B_z > - < \tilde{\mathbf{V}} \wedge \tilde{\mathbf{B}} > \theta
\]

In other words:

\( \mathbf{E}_{\text{dynamo}} \) allows us to balance Ohm’s law justifying that in stationary conditions:
• less mean \( J_z \) is driven in the core
• more mean \( J_\theta \) is driven in the edge then expected by externally applied \( \mathbf{E} \).
The RFP dynamo electric field

- **An additional electric field**, besides that externally applied, is necessary to sustain and amplify the toroidal magnetic flux.

- A Lorentz contribution $\nu \times B$ besides that produced by mean $\nu$ and $B$ is necessary, which implies the existence of a **self-organized velocity field**

\[
\vec{E} = \vec{E}_i + \vec{E}_{dynamo}
\]

\[
\vec{E}_{dynamo} = \left\langle \vec{v} \times \vec{b} \right\rangle
\]
The old paradigm: Multiple Helicity (MH) RFP

- the safety factor $q << 1$ and the central peaking of the current density combine to destabilize MHD resistive instabilities.

- For a long time a broad spectrum of MHD resistive instabilities ($m=0$ and $m=1$, variable $n$ ("multiple helicity" –MH – spectrum), was considered a high, but necessary, price to pay for the sustainment of the configuration through the "dynamo" mechanism.

$$\vec{E}_{dyn} = \langle \vec{v} \times \vec{b} \rangle$$
Resistive kink mode and dynamo: basic action

- Plasma is approximated as a current carrying wire placed on the axis of a cylindrical flux conserver where some axial magnetic field $B_z$ is present due to the azimuthal current $I_{\text{shell}}$ (flowing in the flux container).

- The wire is in an unstable equilibrium, and a small perturbation leads it to kink

- Escande et al., PPCF 42, B243, 2000
Resistive kink mode and dynamo: basic action

1. The azimuthal projection of the kinked current $I_\theta$ has the same direction as $I_{\text{shell}}$: growth of instability.

2. Solenoidal effect: $B$ inside the kinked wire increase

3. Flux conservation: $B'$ outside decreases

4. Continuous growth force $I_{\text{shell}}$ and $B'$ to reverse. Saturation

5. Final state: $B'$ in the outer region is reversed!
Wide $k$-spectrum $\rightarrow$ bulging in the physical space

A wide spectrum of $m=0$ and $m=1$ modes can produce severe plasma-wall interaction if the modes lock in phase and to the wall!
Overlapping islands produce magnetic chaos

Fig. 7.13.1  Diagrams showing change in magnetic field topology as the magnitude of the perturbing magnetic field is increased.

The trajectories of the magnetic field lines do not of course have this periodicity. These trajectories are determined by the equations.
The old story

For a long time it was considered that....

- ....a $q < 1$ configuration like the RFP would have been intrinsically unstable,
- with a broad spectrum of MHD resistive instabilities,
- causing magnetic chaos and driving anomalous transport.

This was viewed as an interesting scientific case but a show-stopper for the RFP reactor ambitions.
An emerging view for the RFP

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- with a broad spectrum of MHD resistive instabilities,
- causing magnetic chaos and driving anomalous transport.

This was viewed as an interesting scientific case but a show-stopper for the RFP reactor ambitions
Two strategies for chaos-free RFP: 1

- Control of the current profile to stabilize tearing modes
- Proof of principle experiment in MST to test RFP confinement and beta limits at the limit of negligible magnetic fluctuation (record values $\tau_E$ and $\beta$)
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.

Current drive “replaces” dynamo Mostly poloidal current drive

Chapman et al., NF 2009 Nucl. Fusion 49 104020
PPCD strongly improves confinement

- Control of core resonant tearing modes reduces transport

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

Chapman et al., NF 2009 Nucl. Fusion 49 104020
Two strategies for chaos-free RFP:

- **Self-organized helical state**: at high current the plasma *spontaneously chooses* a helical equilibrium where only one saturated mode is present, and *sustains the configuration*

- This is **potentially chaos-free** and allows to retain the good features of self-organization without the past degradation of confinement.

- For \( I_p > 1 \text{ MA} \) this is the **preferred state in RFX-mod**, with *strong electron transport barriers and improved confinement*
At high current plasma spontaneously self-organizes in a helical state \((m=1, n=-7)\).

Helical equilibria come with electron transport barriers.
Long periods with one large saturated $m=1$ mode
Synergistic dependence on Lundquist number $S$ (plasma current)

Strongly leading towards chaos-free plasmas

At higher current, when plasma gets hotter, the helical state is more pure

$$S = \frac{\tau_R}{\tau_A} \propto \frac{I_pT_e(0)^{3/2}}{Z_{\text{eff}}n_e^{1/2}}$$

Dominant mode ($m = 1, n = -7$)

Secondary modes (1,-8 to -15)
Single Helical Axis state (SHAx)
Single Helical Axis state (SHAx)


- Significant fraction of the plasma volume involved
- Predicted by theory

Escande et al., PRL. 85, 3169 (2000)
FAQ 2: stationarity

Question: is SHAx stationary?

Answer

- Occasionally we have back-transitions to the low confinement state

- They are caused by localized magnetic reconnection events.

- **Scaling is favourable:** at high current reconnection events are more rare.

**SHAx persistence increases**

- Optimization of feedback control will further reduce error fields

![Graph showing SHAx persistence vs. plasma current](image-url)
Strong internal electron transport barrier at the boundary of the helical core.
VMEC has been ported to RFP equilibrium, using the \textit{poloidal} flux coordinate instead than the \textit{toroidal} one.

The flux surfaces obtained both in axisymmetric and helical configurations fit experimental observations.
VMEC has been ported to RFP equilibrium, using the **poloidal** flux coordinate instead than the **toroidal** one.

The flux surfaces obtained both in axisymmetric and helical configurations fit experimental observations.

VMEC provides access to the suite of Stellarator codes:

*stability, transport, fast particles*...
Temperature and density are constant on helical magnetic flux surfaces

Square root of the reconstructed helical flux used as effective radial coordinate
VMEC has been ported to RFP equilibrium, using the *poloidal* flux coordinate instead than the *toroidal* one.

The flux surfaces obtained both in axisymmetric and helical configurations fit experimental observations.

VMEC provides access to the suite of Stellarator codes: *stability, transport, fast particles…*

Code modification thanks to S.P. Hirshman.
Limit for $L_{Te}$?

$L_{Te}$ never found below $\approx 0.1m$, indicating that some different gradient-driven mechanism adds to MHD instabilities and limits $\nabla Te$. 

**Lorenzini, this workshop poster on Wednesday**
Gyrokinetic calculations point towards microtearing modes.

The quasi-linear estimate of the electron thermal conductivity turns out to be in good agreement with the experimental values, \( \chi \approx 5 \div 20 \, \text{m}^2/\text{s} \).

\[ \gamma > 0 \quad @ \quad a/L_{Te} \approx 2 \quad L_{Te} \approx 0.22 \]

Predebon, submitted to PRL
Reduced particle diffusivity in presence of ITBs

**Experimentally**: inside the barrier $D$ is reduced by about one order of magnitude $D \approx 5 \text{ m}^2/\text{s}$

**From the ORBIT code**: diffusion coefficient reduced by about two orders of magnitude with respect to the situation dominated by magnetic chaos, $D \approx 0.5-5 \text{ m}^2/\text{s}$

![Graph showing diffusion coefficient $D$ vs. $\nu_{coll}/\tau_{tor}$]

axisymmetric magnetic configuration outside the helical structure: superbabananana particles in the helical core become passing approaching the axisymmetric region

*Gobbin, submitted to PRL*
Beyond stability
The fusion-oriented RFX mission

- no MHD active control: 2004
- with MHD active control: 2006
- upgraded MHD active control: 2008
- 2010 unoptimized
**Reliability and performance**

- Ultimate goal of our research is **energy production**.

- **To be attractive**, fusion reactor need to be:
  
  - **Reliable**
  
  - **Performing**

- In many systems, the **balance between reliability and performance** depends on the target.

- In fusion, the threshold is high.
Fusion performance and $\beta$

The key plasma physics quantity to maximize for high gain, steady state fusion energy is $\beta$.

\[
nT\tau \propto \frac{\beta_NH}{q_{95}^2} \cdot f(a,B,\ldots)
\]
\[
f_{ind} = (1 - f_{BS} - f_{CD}) \cdot I = 0
\]

- e.g., Advanced Tokamak scenarios have two key roles in burning plasma devices:
  - To access steady state operation with high fusion gain
  - To deliver the maximum neutron fluence, to facilitate a mission of nuclear testing.
MHD stability:

- set limits on $\beta$
- causes major transient events
It is an option, and sometimes works (e.g. second stability region), but alone:

- it might be not enough to achieve the desired performance in a burning plasma, if it restricts to passively stable regions;
- It may not protect against dangerous off-normal events.

Active control is essential in a burning plasma
Modern fighters are designed to be unstable. Unstable design is intended to increase agility and to decrease drag. A computer is needed and a regulator will supply the necessary stability.

…but sometimes inherent stability helps…
Safe navigation beyond passive limits calls for efficient control

- **Beyond the limits**: a fusion reactor operating in a robust steady state at pressure **beyond conventional stability limits** would bring big advantages in terms of economy and efficiency.

---

*eXtreme Shape Controller in JET*  
Ariola, Pironti IEEE Control System magazine 2005

*RWM feedback control in DIII-D*  
RFX-MOD has the best system of coils for active control of MHD stability ever built for a fusion device.

- **192 independently feedback controlled coils** covering the whole torus.
- Digital Controller with Cycle frequency of 2.5 kHz.
- On-going collaborations with:
  - DIII-D
  - JT60-SA
  - AUG
  - CREATE/ITER
- On topics like:
  - Advanced feedback algorithms
  - Multimode control
  - Mode non rigidity
  - Benchmarking of ITER codes
  - ...

Active Coils
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
- **Digital Controller**: 7 computing nodes, 2 Gflop/s, Cycle frequency 2.5 kHz
- **Output**: Reference values
  - 192 reference values for the currents in the control coils
- **RFX Plasma**
Rational surfaces in RFP

RFX-mod

RWMs

Tearing / resistive kink

RWMs

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

(m=1, n=2, 3..)
The name of the game: the right questions

- A flexible feedback system in a flexible device like RFX-mod may provide a number of key contributions on the topic of active control of MHD stability.....

- ....if you find the right questions to answer!
RWM active rotation experiment: setup

- **2 control time windows:**
  - **FIRST:** the mode is not controlled
  - **SECOND:** the mode is initially feedback controlled with a pure real proportional gain. Gain scan performed (to obtain constant RWM amplitude)

- The external field is always opposing the plasma error field with the same helicity and no net force is present to induce a controlled rotation.

*Byproduct: simulation of feedback control systems with not enough power to cope with the growth of the selected instability.*
Feedback rotation control principle

- Perfect control
  - Plasma field
  - Total field = 0
  - External field

- Incomplete control
  - Plasma field
  - Total field ≠ 0
  - External field
Complex gains \((k + ik)\) can be used.

**Perfect control**

- Total field = 0
- External field

**Incomplete control**

- Total field ≠ 0
- Plasma field
- External field

**Incomplete control with phase shift**

- Total field ≠ 0
- Plasma field
- External field
Active rotation of non-resonant wall-locked RWM is induced by applying complex gains (keeping the mode at the desired constant amplitude)

Bolzonella, Igochine et al, PRL 08
Thank you.