Physics and control of Resistive Wall Mode

Valentin Igochine

Max-Planck-Institut für Plasmaphysik, Euratom-Association, Garching, Germany

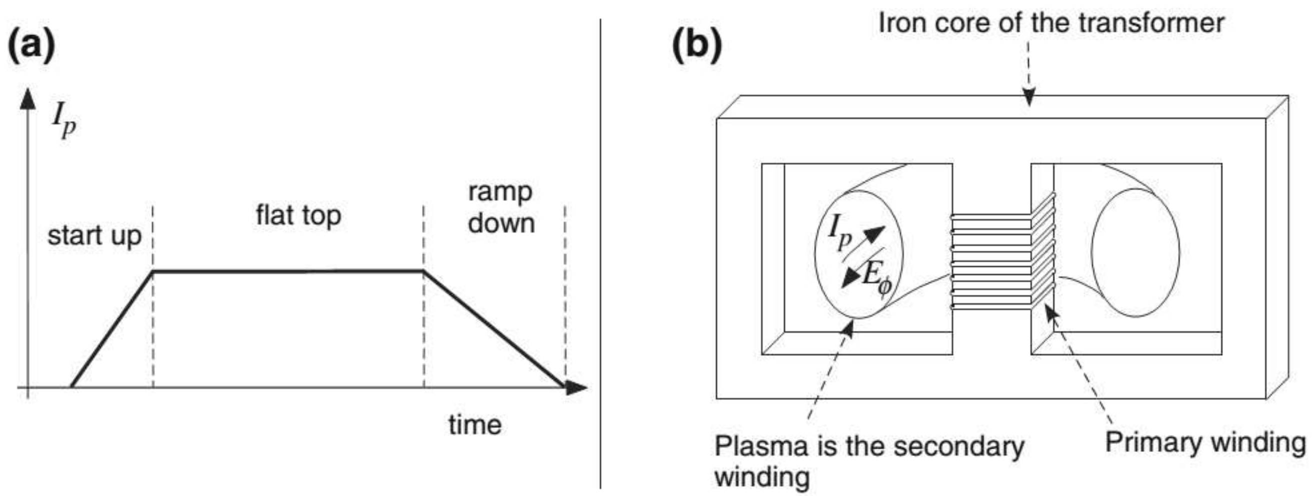
Outline

- Introduction
  - Motivation
  - Simple dispersion relation

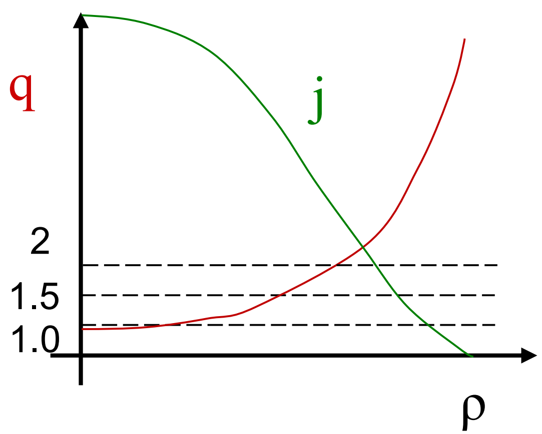
- Physics of the RWM
  - Electromagnetic part
  - Kinetic part

- Control of RWM
  - Control methods
  - Triggering of RWMs

Conventional tokamak scenario



[V. Igochine, "Active Control of Magneto-hydrodynamic Instabilities in Hot Plasmas", Springer]



Ohmic heating

↓

Current diffusion and peaked profile

↓

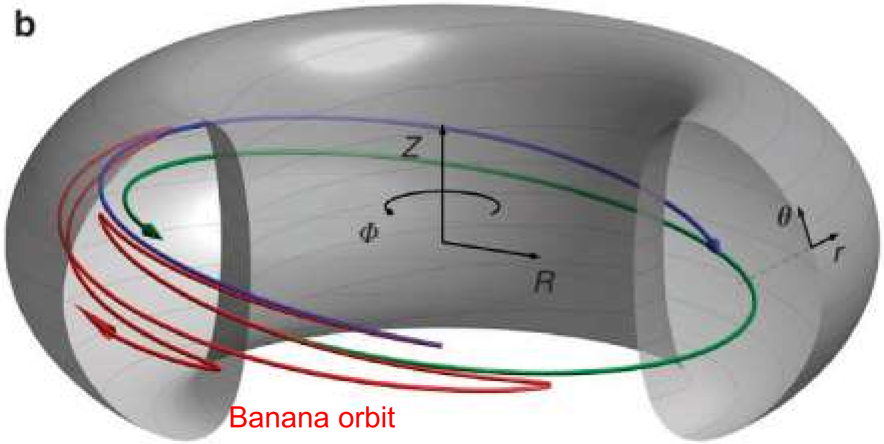
Non-inductive current drive

↓

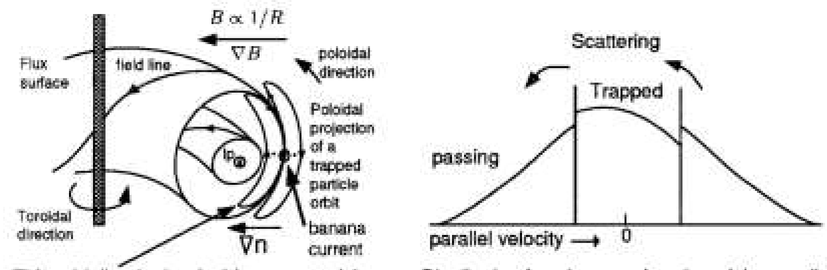
Only discharges with limiting length are possible

Bootstrap current $\boxed{j_b \sim \nabla p}$

b



A G Peeters   Plasma Phys. Control. Fusion **42** (2000) B231–B242.



This orbit lies further inside more particles follow this orbit than the orbit further out.

Distribution function as a function of the parallel velocity for constant perpendicular velocity.

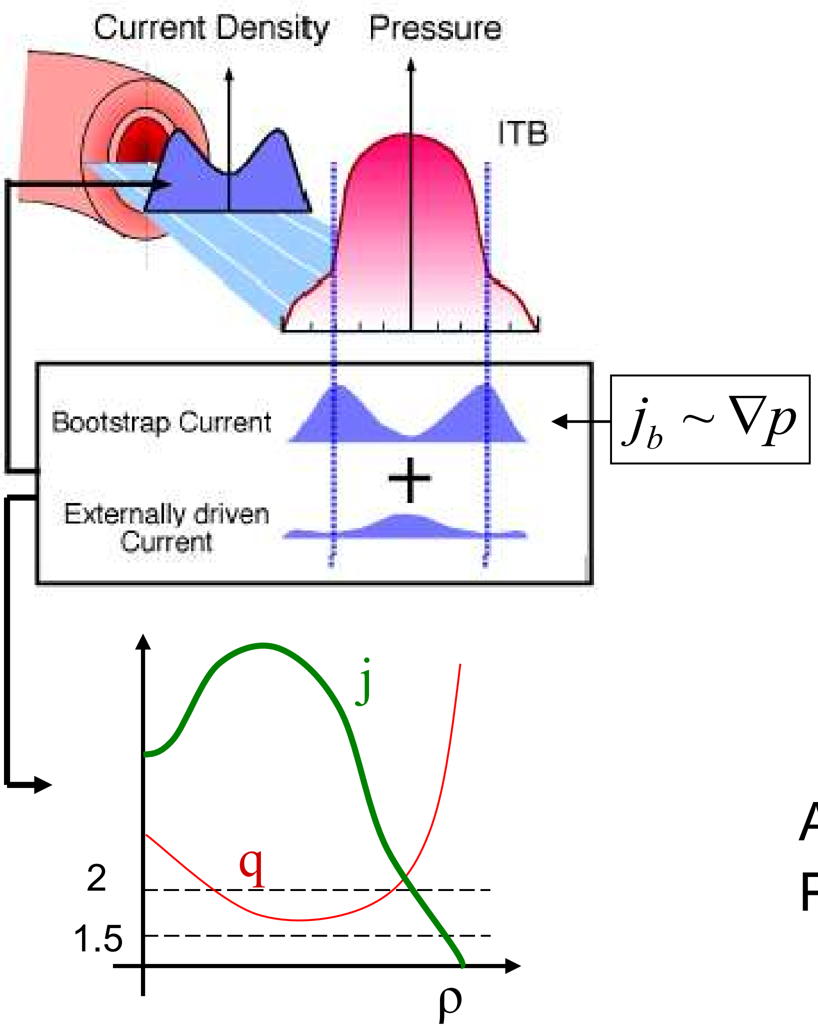
Figure 1. The banana current driven by the density gradient.

$$J_{\mathrm{BS}} = -\sqrt{b}\,\frac{RB_{\mathrm{t}}}{B_0}\left[2.44(T_{\mathrm{e}}+T_{\mathrm{i}})\frac{\mathrm{d}n}{\mathrm{d}\psi_{\mathrm{p}}} + 0.69n\frac{\mathrm{d}T_{\mathrm{e}}}{\mathrm{d}\psi_{\mathrm{p}}} - 0.42n\frac{\mathrm{d}T_{\mathrm{i}}}{\mathrm{d}\psi_{\mathrm{p}}}\right]$$

$$\boxed{j_b \sim \nabla p}$$

Bootstrap current is
- in the direction of the main current
- non-inductive
- proportional to the pressure gradient

Advanced tokamak scenario



Flat or hollow current profiles

↓

Suppression of the turbulence

↓

Internal Transport Barrier (ITB)

↓

Reduced energy transport

↓

Promises steady state operations

Aim: Steady state operations

Problem: Up to now this is only a transient scenario

Basic classification of MHD instabilities

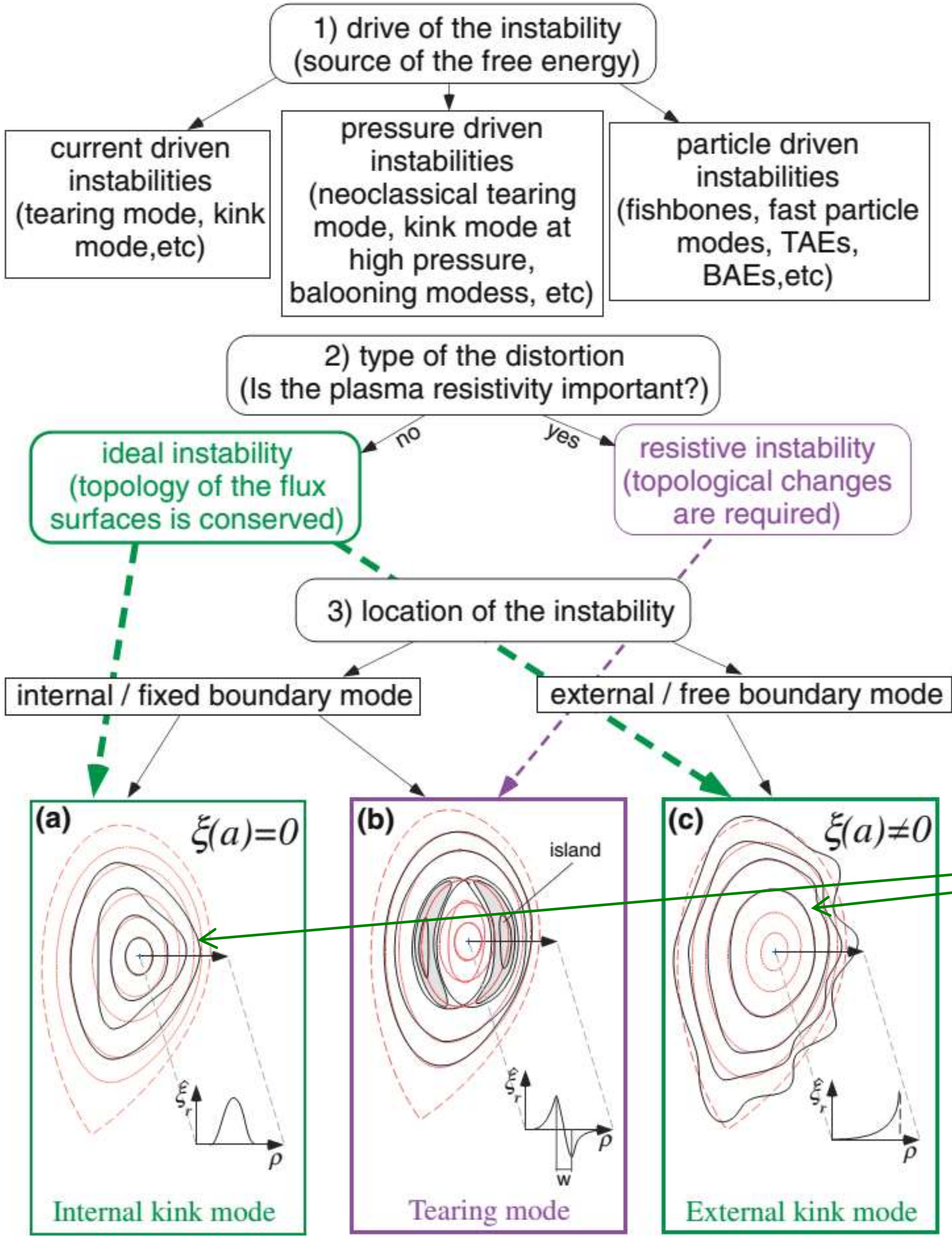


Fig. 2.8 The basic classification of MHD instabilities

V. Igochine, "Active Control of Magneto-hydrodynamic Instabilities in Hot Plasmas", Springer Series on Atomic, Optical, and Plasma Physics, Vol. **83**, 2015 (Chapter 2)

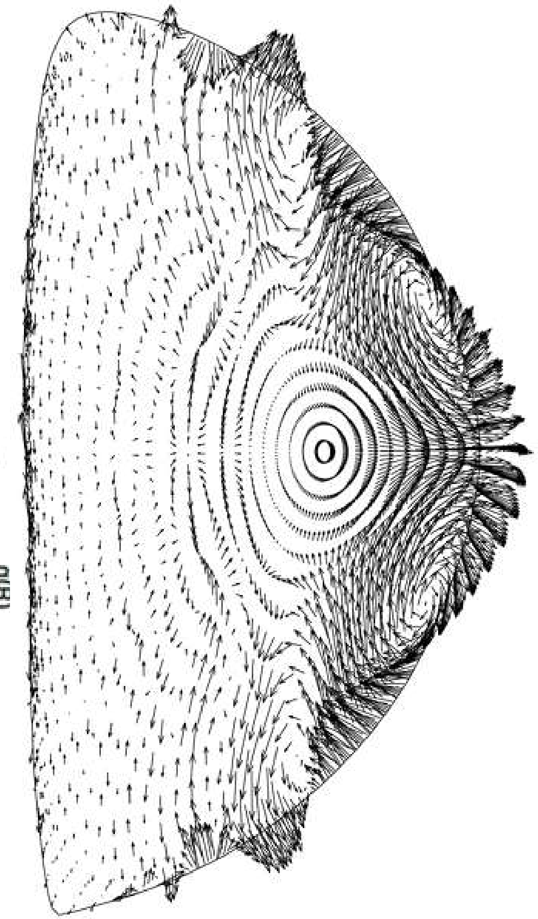
RWM is the sum of these two instabilities

Resistive Wall Mode (RWM)

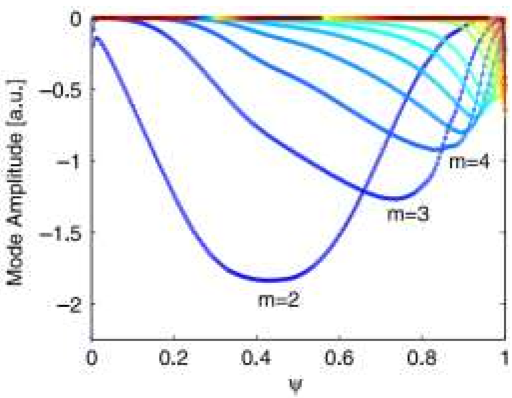
• Resistive wall mode is an external kink mode which interacts with the resistive wall.

• The mode will be stable in case of an perfectly conducting wall. Finite resistivity of the wall leads to mode growth.

[T. Luce, PoP, 2011]

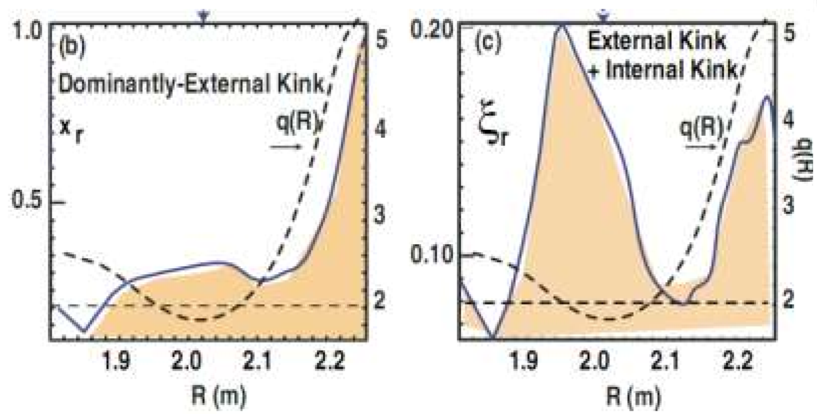


JET



[I.T.Chapman, PPCF, 2009]

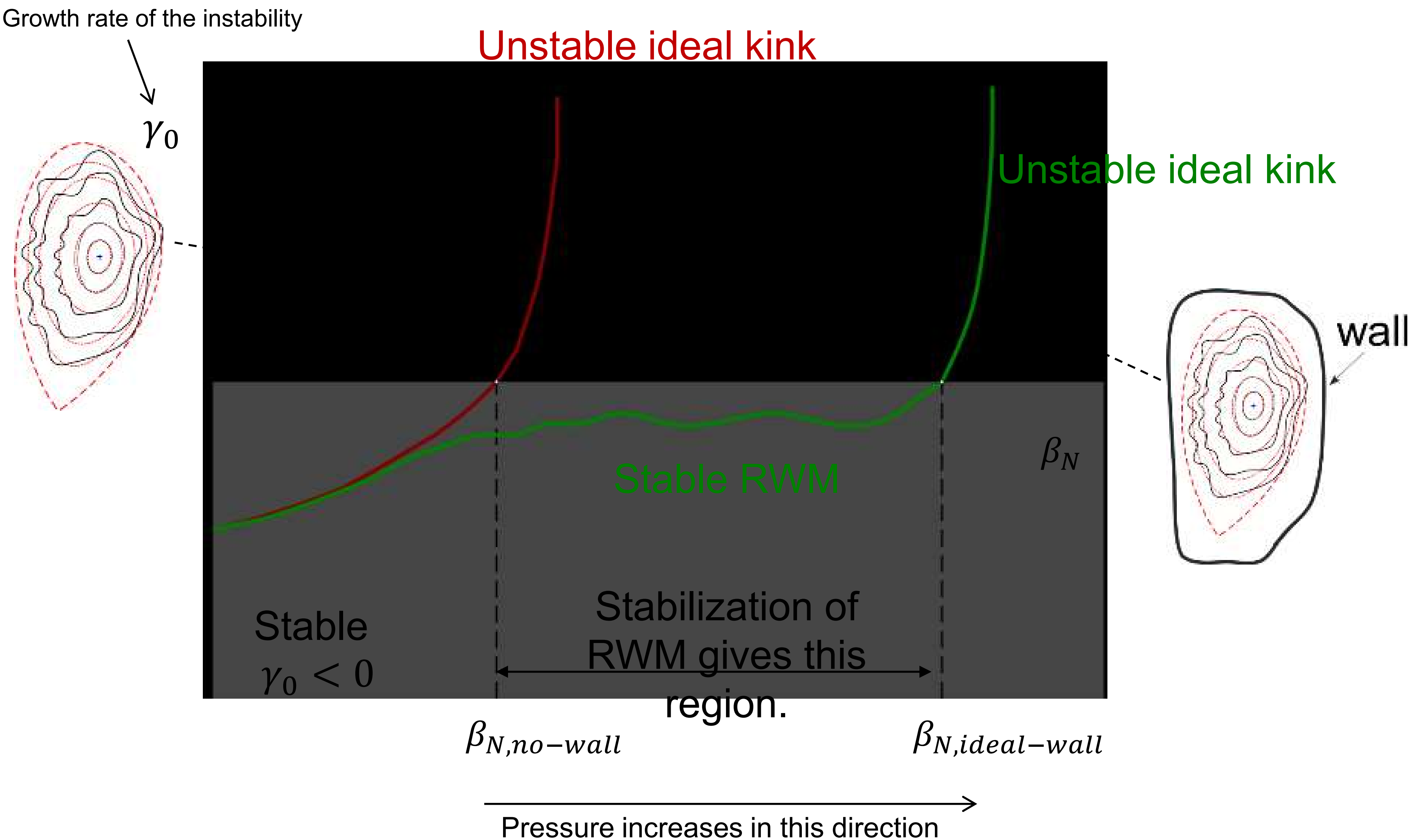
DIII-D



[M.Okabayashi, NF, 2009]

RWM has global structure. This is important for “RWM ↔ plasma” interaction.

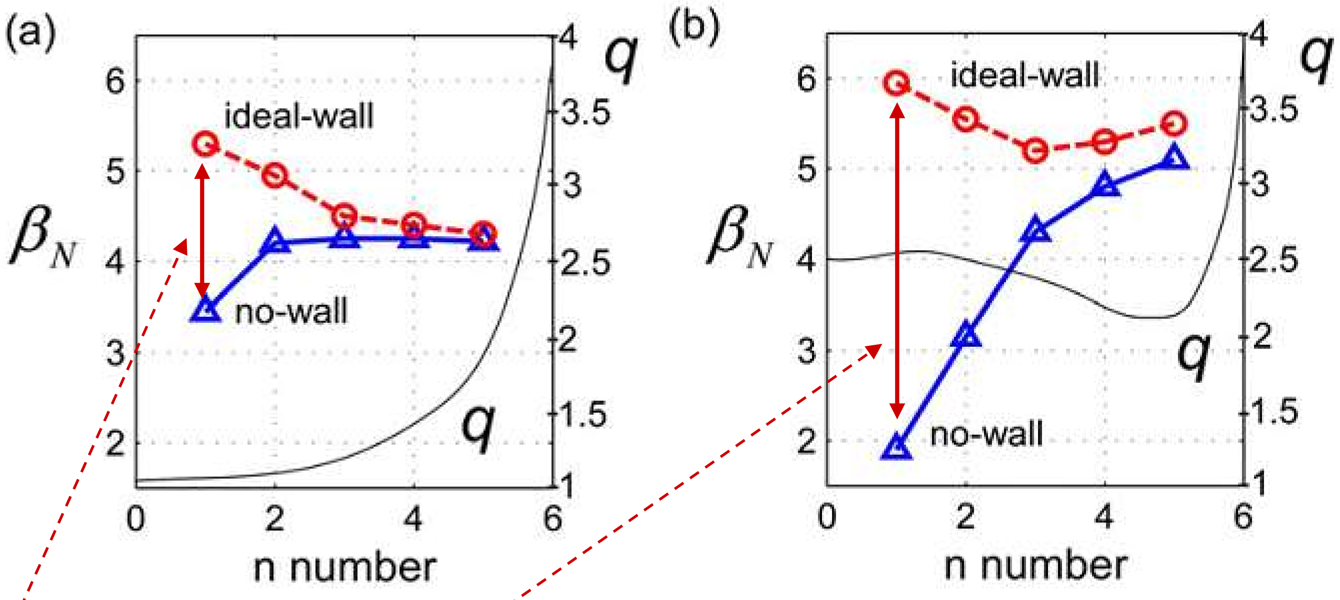
Definitions of the beta limits



Resistive Wall Mode (RWM)

<u>Conventional scenario</u>
(moderate improvements)

<u>Advanced scenario</u>
(crucial improvements)



V. Igochine Nucl. Fusion **52** (2012) 074010

RWM stabilization allows to gain this region.

Stabilization is really important only in the advanced scenario.

Physics of RWMs

RWM physics in tokamaks

RWM interaction with externally produced magnetic fields

- resistive wall
- error fields
- control coils

+

RWM interaction with plasma

- plasma rotation
- fast particles
- thermal particles

RWM physics in tokamaks

RWM interaction with externally produced magnetic fields

- resistive wall
- error fields
- control coils

+

RWM interaction with plasma

- plasma rotation
- fast particles

Mode can be represented as a surface currents

Physics: **electromagnetism**

Wave-particle interaction

Physics: **kinetic description of the plasma-wave interaction**

RWM physics in tokamaks

RWM interaction with externally produced magnetic fields

- resistive wall
- error fields
- control coils

Mode can be represented as a surface currents

Physics: **electromagnetism**

\+

RWM interaction with plasma

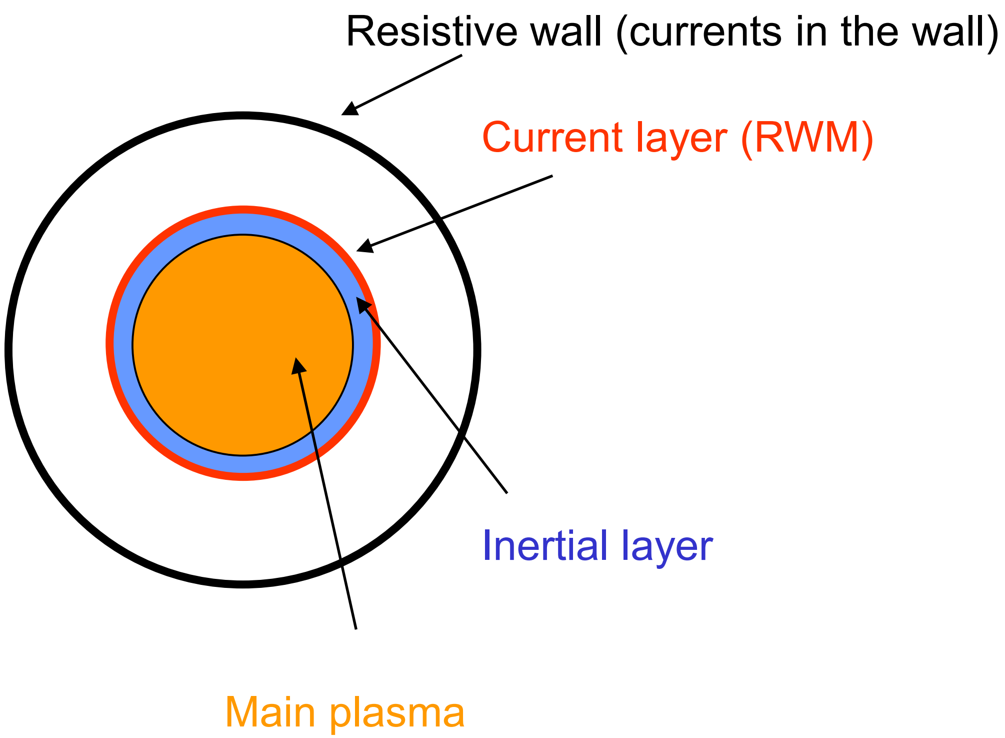
- plasma rotation
- fast particles
- thermal particles

Wave-particle interaction

Physics: **kinetic description of the plasma-wave interaction**

Interaction of RWM with external perturbations

Simple models



[R. Fitzpatrick, PoP, 2002;
V.D.Pustovitov, Plasma Physics Reports, 2003;
A.H.Boozer, PRL, 2001]

Real vessel

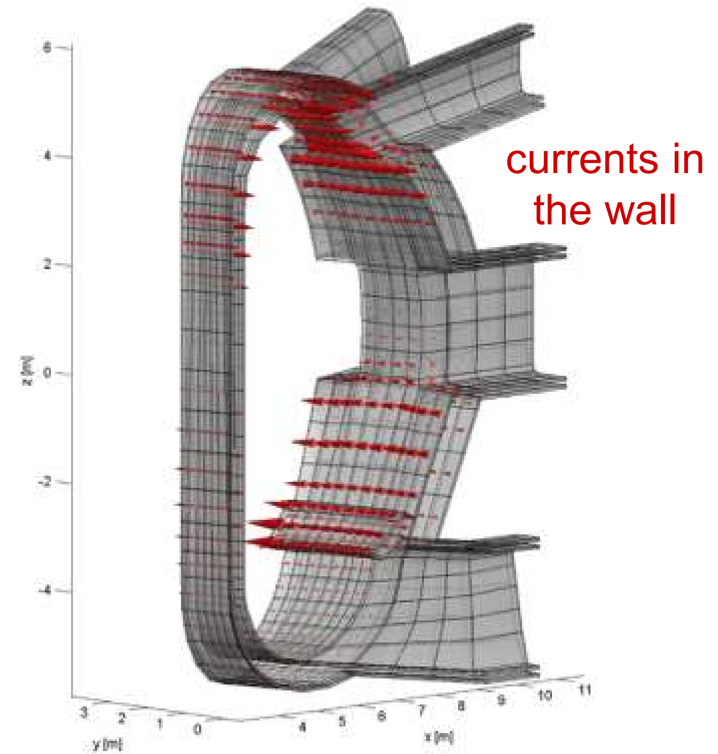


Figure 10. 3D current pattern in vacuum vessel corresponding to the $n = 0$ unstable mode (the BMs are present, although not shown).

[F.Vilone, NF, 2010;
E.Strumberger, PoP, 2008]

RWM physics in tokamak

Reversed Field Pinch:
- small plasma rotation
- no fast particles

physics in tokamaks

RWM interaction with externally produced magnetic fields

- resistive wall
- error fields
- control coils

Mode can be represented as a surface currents

Physics: **electromagnetism**

+

RWM interaction with plasma

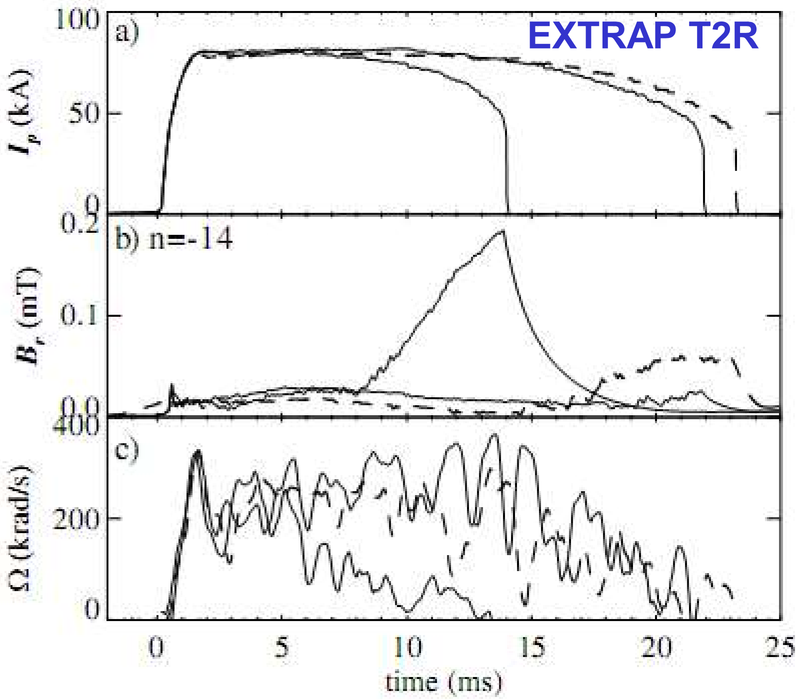
- plasma rotation
- fast particles

Wave-particle interaction

Physics: **kinetic description of the plasma-wave interaction**

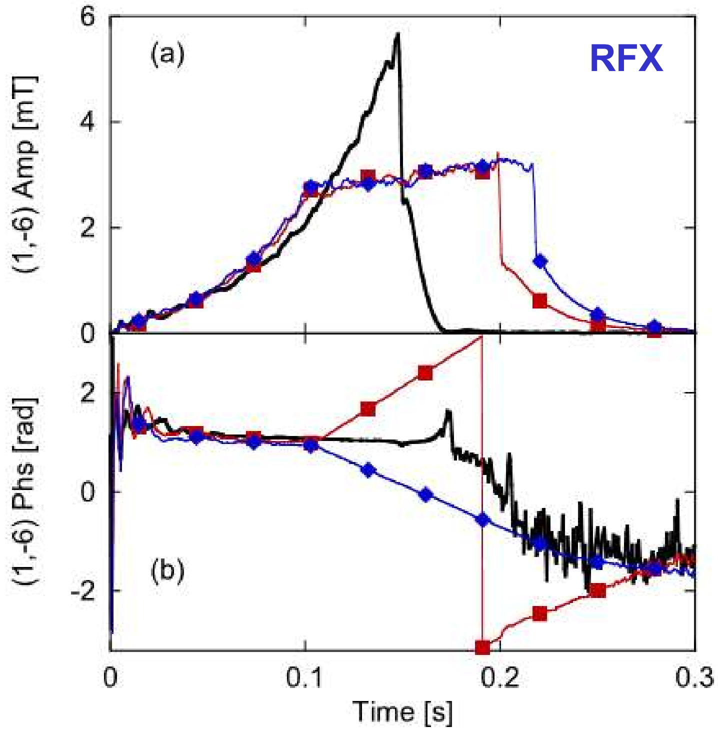
What one can achieve in RFPs with external coils ?

Feedback Stabilization of Multiple Resistive Wall Modes



[P. R. Brunsell et.al. , PRL, 2004]

Decoupling and active rotation of a particular RWM



[T. Bolzonella, V. Igochine, et.al., PRL, 2008; V. Igochine, T. Bolzonella, et.al., PPCF, 2009]

RWM physics in tokamaks

RWM interaction with externally produced magnetic fields

- resistive wall
- error fields
- control coils

+

RWM interaction with plasma

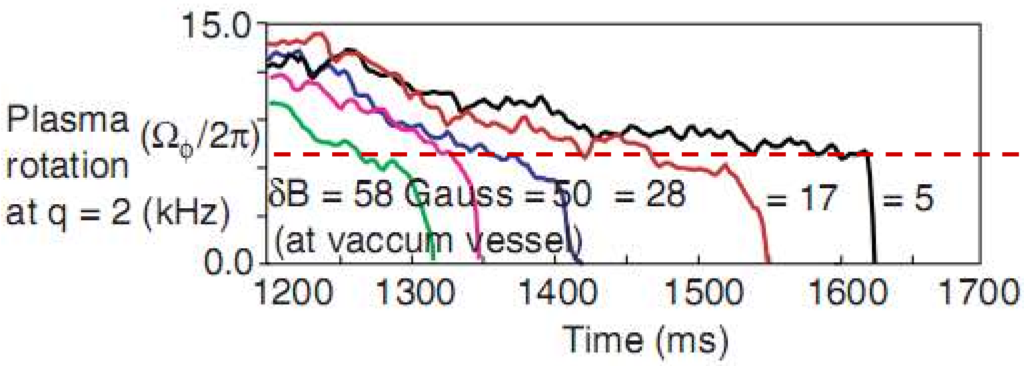
- plasma rotation
- fast particles
- thermal particles

Mode can be represented as a surface currents

Physics: **electromagnetism**

Wave-particle interaction

Physics: **kinetic description of the plasma-wave interaction**



[M. Okabayashi et. al. PPCF 2002]

RWM is unstable if rotation drops below critical value

Plasma rotation try to decouple RWM from the wall and plays stabilizing role

How strong the rotation stabilization?
What is the critical rotation which is necessary to stabilize RWM?
Is only the plasma rotation important?

The answers depend on the type of interaction between RWM and plasma rotation which is considered by the model and/or accuracy of the model for such interaction

Linearized MHD equations with influence of rotation

$$\rho(\gamma + in\Omega)\vec{v}_1 = -\vec{\nabla}\cdot\vec{p}_t + \vec{j}_1 \times \vec{B} + \vec{j} \times \vec{b}_1 - \vec{\nabla}\cdot\vec{\Pi}_1 - \rho\vec{U}(\vec{v}_1),$$

$$(\gamma + in\Omega)\vec{b}_1 = \vec{\nabla} \times (\vec{v}_1 \times \vec{B} - \eta\vec{j}_1) + (\vec{b}_1 \cdot \vec{\nabla}\Omega)R^2\vec{\nabla}\phi,$$

$$\vec{j}_1 = \vec{\nabla} \times \vec{b}_1,$$

$$(\gamma + in\Omega)p_1 = -(\vec{v}_1 \cdot \vec{\nabla})p - \Gamma p\vec{\nabla}\cdot\vec{v}_1,$$

$$(\gamma + in\Omega)\rho_1 = -(\vec{v}_1 \cdot \vec{\nabla})\rho - \rho\vec{\nabla}\cdot\vec{v}_1.$$

Ω is the (non-uniform) rotation frequency of the plasma at equilibrium

n is the toroidal mode number

In the above set of equations, $(\rho, \vec{v}, \vec{B}, \vec{j}, p_1, \vec{p}_t)$ are the (density, velocity, magnetic field, current, fluid pressure and total pressure). Equilibrium quantities are denoted without suffix,

Linearized MHD equations with influence of rotation

momentum equation

$$\rho(\gamma + in\Omega)\vec{v}_1 = -\vec{\nabla}\cdot\vec{p}_t + \vec{j}_1 \times \vec{B} + \vec{j} \times \vec{b}_1 - \vec{\nabla}\cdot\vec{\Pi}_1 - \rho\vec{U}(\vec{v}_1),$$

$$(\gamma + in\Omega)\vec{b}_1 = \vec{\nabla} \times (\vec{v}_1 \times \vec{B} - \eta\vec{j}_1) + (\vec{b}_1 \cdot \vec{\nabla}\Omega)R^2\vec{\nabla}\phi,$$

$$\vec{j}_1 = \vec{\nabla} \times \vec{b}_1,$$

$$(\gamma + in\Omega)p_1 = -(\vec{v}_1 \cdot \vec{\nabla})p - \Gamma p\vec{\nabla}\cdot\vec{v}_1,$$

$$(\gamma + in\Omega)\rho_1 = -(\vec{v}_1 \cdot \vec{\nabla})\rho - \rho\vec{\nabla}\cdot\vec{v}_1.$$

Ω is the (non-uniform) rotation frequency of the plasma at equilibrium

n is the toroidal mode number

In the above set of equations, $(\rho, \vec{v}, \vec{B}, \vec{j}, p_1, \vec{p}_t)$ are the (density, velocity, magnetic field, current, fluid pressure and total pressure). Equilibrium quantities are denoted without suffix,

Linearized MHD equations with influence of rotation

momentum equation

$$\rho(\gamma + in\Omega)\vec{v}_1 = -\vec{\nabla}\cdot\vec{p}_t + \vec{j}_1 \times \vec{B} + \vec{j} \times \vec{b}_1 - \vec{\nabla}\cdot\vec{\Pi}_1 - \rho\vec{U}(\vec{v}_1),$$

$$(\gamma + in\Omega)\vec{b}_1 = \vec{\nabla}\times(\vec{v}_1 \times \vec{B} - \eta\vec{j}_1) + (\vec{b}_1\cdot\vec{\nabla}\Omega)R^2\vec{\nabla}\phi,$$

$$\vec{j}_1 = \vec{\nabla}\times\vec{b}_1,$$

$$(\gamma + in\Omega)p_1 = -(\vec{v}_1\cdot\vec{\nabla})p - \Gamma p\vec{\nabla}\cdot\vec{v}_1,$$

$$(\gamma + in\Omega)\rho_1 = -(\vec{v}_1\cdot\vec{\nabla})\rho - \rho\vec{\nabla}\cdot\vec{v}_1.$$

Dissipation, viscous stress tensor

Ω is the (non-uniform) rotation frequency of the plasma at equilibrium

n is the toroidal mode number

One has to make approximations for kinetic description of the dissipation

In the above set of equations, $(\rho, \vec{v}, \vec{B}, \vec{j}, p_1, \vec{p}_t)$ are the (density, velocity, magnetic field, current, fluid pressure and total pressure). Equilibrium quantities are denoted without suffix,

Fluid approximation of the Landau damping:

'sound wave damping'

[Hammet G W and Perkins F W 1990 Phys. Rev. Lett]

$$\vec{\nabla} \cdot \vec{\Pi} = \kappa_{||}\sqrt{\pi}\,|k_{||} v_{\mathrm{th}_i}|\,\rho \vec{v}_1 \cdot \hat{b}\hat{b}.$$

Simplest variant of the viscous stress tensor

Fluid approximation of the Landau damping:

'sound wave damping'

[Hammet G W and Perkins F W 1990 Phys. Rev. Lett]

$$\vec{\nabla} \cdot \vec{\Pi} = \kappa_{||} \sqrt{\pi} |k_{||} v_{\mathrm{th}_i}| \rho \vec{v}_1 \cdot \hat{b}\hat{b}.$$

free parameter between 0.1 and 1.5

Simplest variant of the viscous stress tensor

Fluid approximation of the Landau damping:

'sound wave damping'

[Hammet G W and Perkins F W 1990 Phys. Rev. Lett]

$$\vec{\nabla} \cdot \vec{\Pi} = \kappa_{||} \sqrt{\pi} |k_{||} v_{\mathrm{th}_i}| \rho \vec{v}_1 \cdot \hat{b}\hat{b}.$$

free parameter between 0.1 and 1.5

'kinetic damping'model uses kinetic energy principle with $\omega_* = 0, \omega_D = 0$

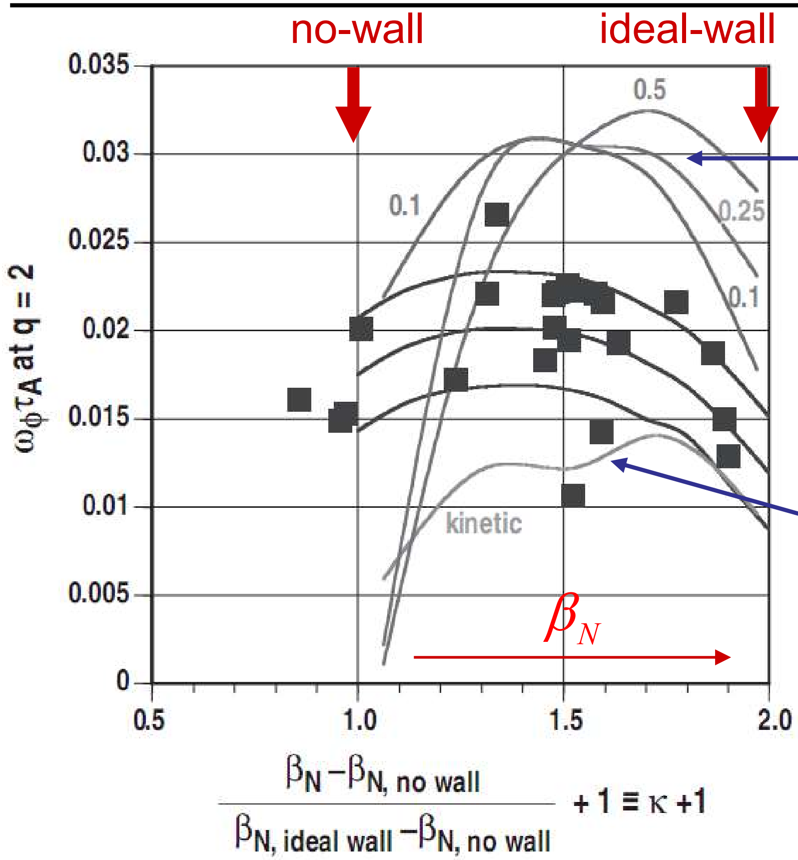
[Bondeson A and Chu M S 1996 Phys. Plasmas]

No free parameters

magnetic drift frequency $\omega_{\mathrm{D}} \sim k_{\perp} \rho_{\mathrm{i}} v_{\mathrm{th}} / R$, with $k_{\perp} \sim m/r$

diamagnetic frequency $\omega *$

Comparison of the critical rotation with experiments



sound wave damping
overestimate

„kinetic damping“ model
underestimate

Figure 14. MARS calculation of the critical plasma rotation at $q = 2$ for the marginal $n = 1$ RWM using the actual DIII-D equilibrium and wall. Data and fits are versus $\beta_N/2.4\ell_i \equiv \kappa + 1$ as in figure 11. MARS calculations are with sound wave damping model using $\kappa_\parallel = 0.1, 0.25$ or 0.5 or with kinetic damping model.

[LaHaye, NF, 2004]

Comparison of the critical rotation with experiments

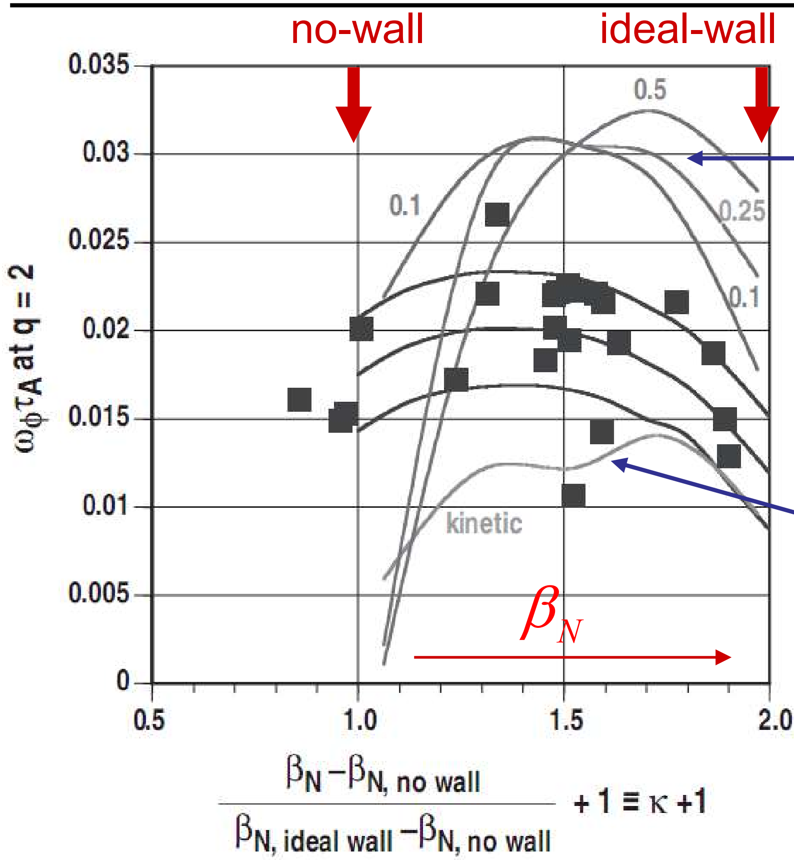


Figure 14. MARS calculation of the critical plasma rotation at $q = 2$ for the marginal $n = 1$ RWM using the actual DIII-D equilibrium and wall. Data and fits are versus $\beta_N/2.4\ell_i \equiv \kappa + 1$ as in figure 11. MARS calculations are with sound wave damping model using $\kappa_\parallel = 0.1, 0.25$ or 0.5 or with kinetic damping model.

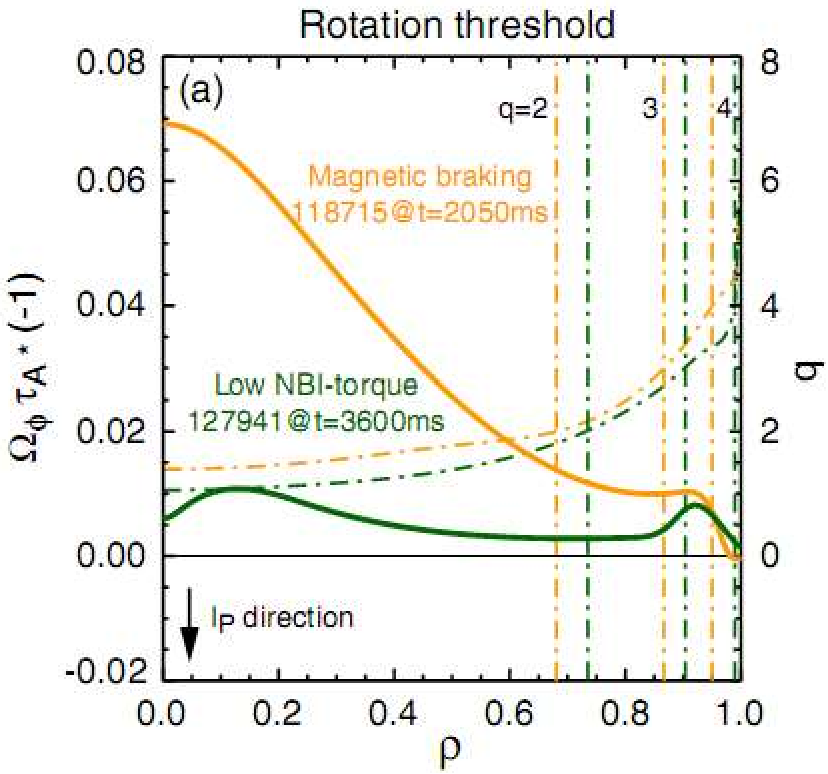
sound wave damping
overestimate

„kinetic damping“ model
underestimate

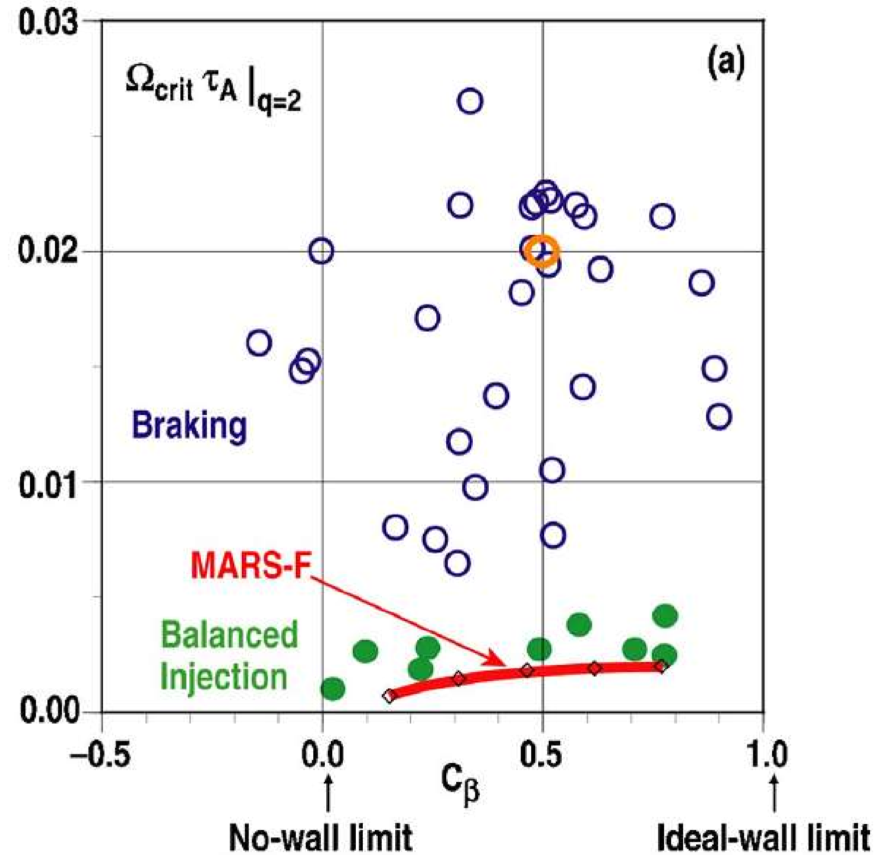
…but rotation is sufficiently strong in these experiments due to NBI

[LaHaye, NF, 2004]

Experiments with balanced NBI input in DIII-D

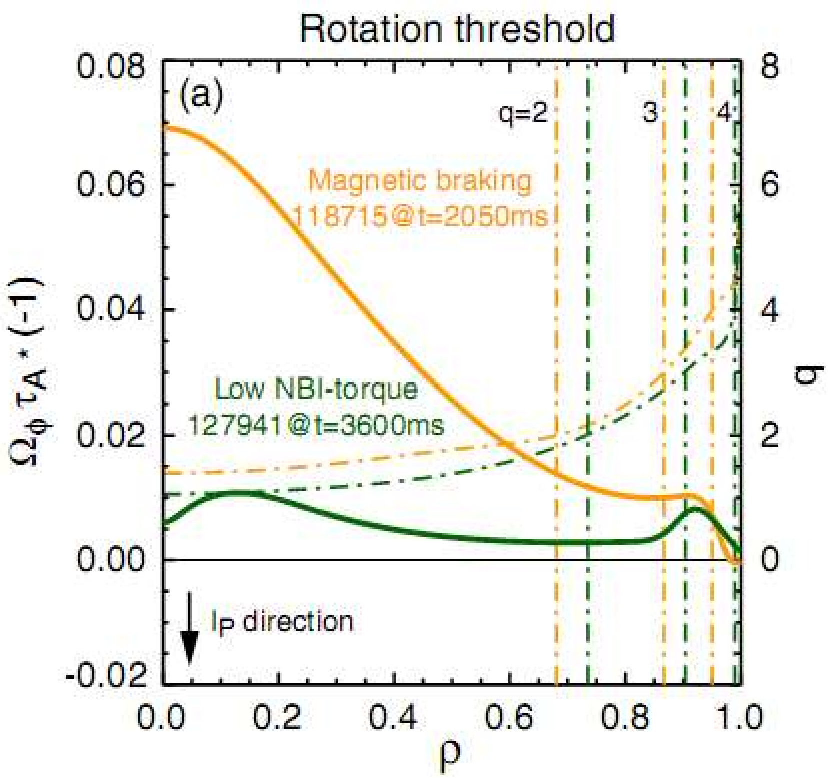


[Reimerdes, PPCF, 2007]

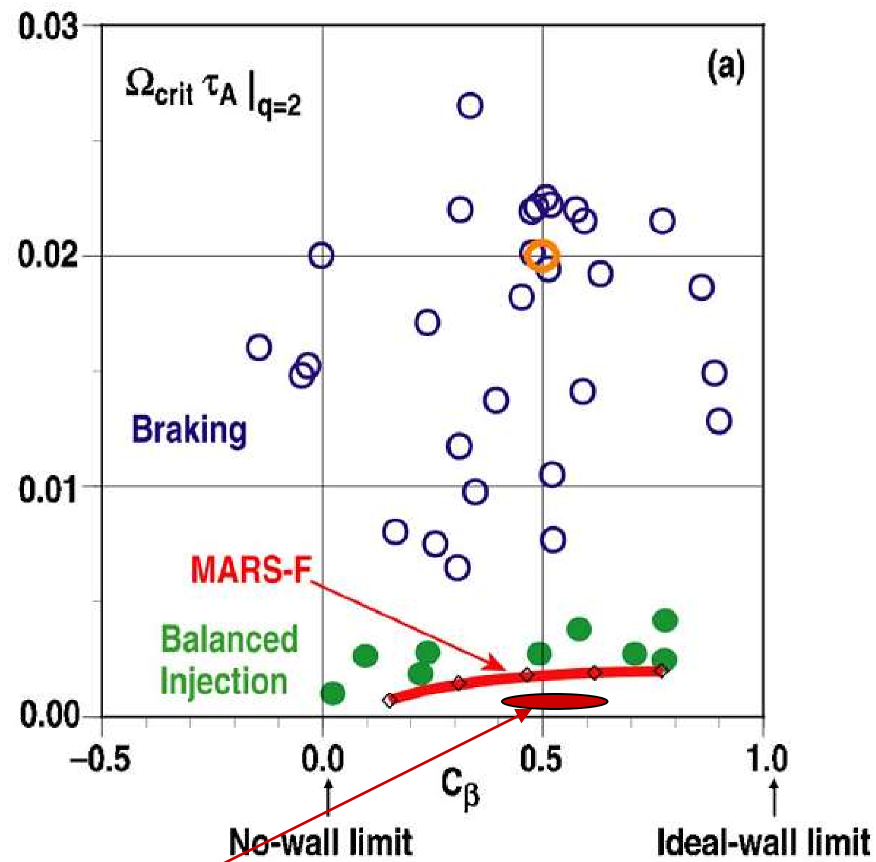


[Strait, PoP, 2007]

Experiments with balanced NBI input in DIII-D

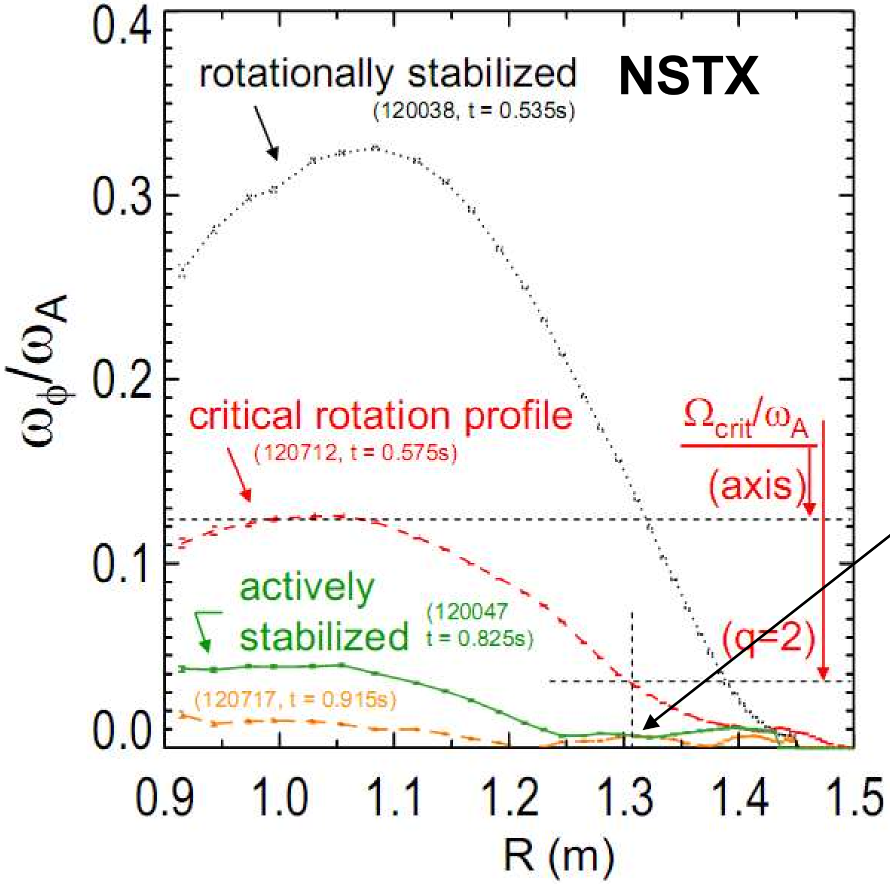


[Reimerdes, PPCF, 2007]



[Strait, PoP, 2007]

No stabilization is possible here



[S.A. Sabbagh, IAEA, 2010, PD/P6-2]

Stabilization is achieved for almost zero rotation (not possible in ”kinetic model”)

Thus, an important part is missing in the model!

Possible variants of modeling

Self-consistent modeling (MARS,…)

Linear MHD + approximation for damping term

- (+) rotation influence on the mode eigenfunction
- (-) damping model is an approximation

Perturbative approach (Hagis,…)

Fixed linear MHD eigenfunctions as an input for a kinetic code

- (-) rotation does not influence on the mode eigenfunctions
- (+) damping is correctly described in kinetic code

Self-consistent modeling (MARS,…)

Linear MHD + approximation for damping term

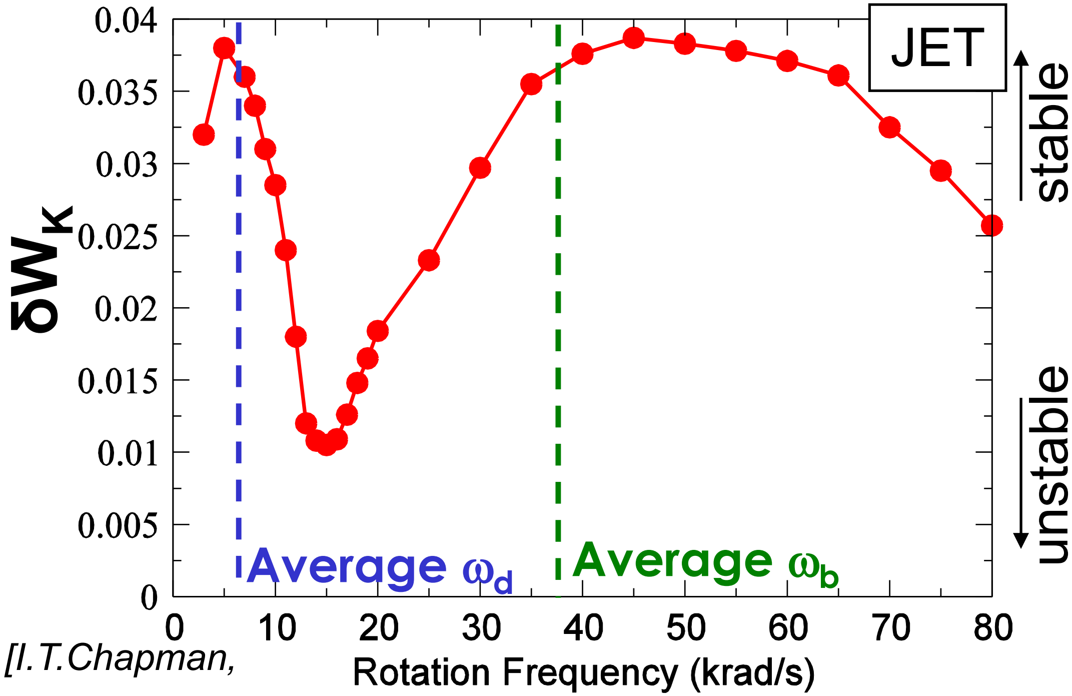
- (**+**) rotation influence on the mode eigenfunction
- (**-**) damping model is an approximation

Perturbative approach (Hagis,…)

Fixed linear MHD eigenfunctions as an input for a kinetic code

- (**-**) rotation does not influence on the mode eigenfunctions
- (**+**) damping is correctly described in kinetic code

Perturbative approach. Influence of the resonances



[I.T.Chapman, PPCF, 2009]

$$\gamma\tau_w^* \simeq -\frac{\delta W_\infty + \delta W_k}{\delta W_b + \delta W_k}$$

Change in mode energy has a term which contains several different resonances

(denominator of equation tends to zero, get a large contribution to δWκ)

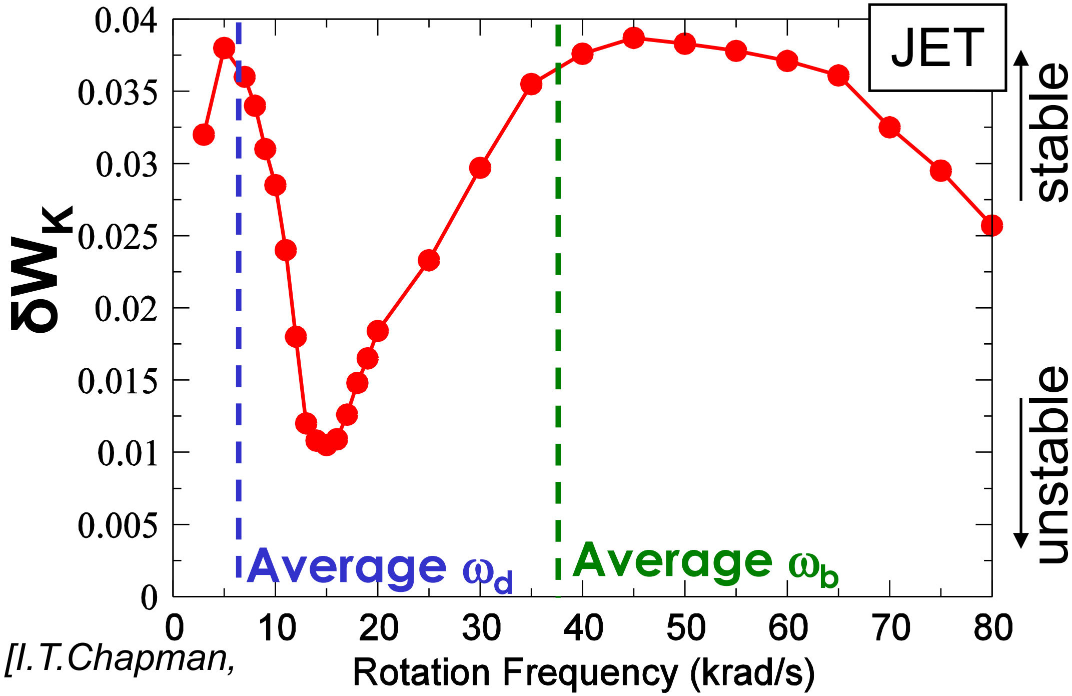
$$\boxed{\omega_d << \omega_b < \omega_t}$$

Transit Frequency $\omega_t \sim (v_{th} / R)$

Bounce Frequency $\omega_b \sim \sqrt{r/R}\,(v_{th} / R)$

Precession Drift Frequency $\omega_d \sim \rho_L / r\,(v_{th} / R)$

Perturbative approach. Influence of the resonances



[I.T.Chapman, PPCF, 2009]

$$\gamma\tau_w^* \simeq -\frac{\delta W_\infty + \delta W_k}{\delta W_b + \delta W_k}$$

Change in mode energy has a term which contains several different resonances

(denominator of equation tends to zero, get a large contribution to δWκ)

$$\boxed{\omega_d << \omega_b < \omega_t}$$

Transit Frequency $\omega_t \sim (v_{th} / R)$

Bounce Frequency $\omega_b \sim \sqrt{r/R}\,(v_{th} / R)$

Precession Drift Frequency $\omega_d \sim \rho_L / r\,(v_{th} / R)$

Different resonances are important! & Low frequencies are important!

New model for rotation influence on the MHD modes (MARS-K)

[Liu, PoP, 2008, Liu, IAEA, 2010]

$$
\begin{aligned}
(\gamma + in\Omega)\xi &= \mathbf{v} + (\xi \cdot \nabla\Omega) R\hat{\phi}, \\
\rho(\gamma + in\Omega)\mathbf{v} &= -\nabla \cdot \mathbf{p} + \mathbf{j} \times \mathbf{B} + \mathbf{J} \times \mathbf{Q} - \rho\left[2\Omega\hat{\mathbf{Z}} \times \mathbf{v} + (\mathbf{v} \cdot \nabla\Omega) R\hat{\phi}\right] \\
(\gamma + in\Omega)\mathbf{Q} &= \nabla \times (\mathbf{v} \times \mathbf{B}) + (\mathbf{Q} \cdot \nabla\Omega) R\hat{\phi}, \\
(\gamma + in\Omega)p &= -\mathbf{v} \cdot \nabla P, \\
\mathbf{j} &= \nabla \times \mathbf{Q},
\end{aligned}
$$

Kinetic effects are inside the pressure

$$
\mathbf{p} = p\mathbf{I} + p_{\|}\hat{\mathbf{b}}\hat{\mathbf{b}} + p_{\perp}(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}),
$$

$$
p_{\|}e^{-i\omega t + in\phi} = \sum_{e,i} \int d\Gamma M v_{\|}^{2} f_{L}^{1}, \qquad p_{\perp}e^{-i\omega t + in\phi} = \sum_{e,i} \int d\Gamma \frac{1}{2} M v_{\perp}^{2} f_{L}^{1},
$$

- full toroidal geometry in which the kinetic integrals are evaluated
- $\omega_* \neq 0, \omega_D \neq 0$

[Liu, PoP, 2008, Liu, IAEA, 2010]

$$
\begin{aligned}
(\gamma + in\Omega)\xi &= \mathbf{v} + (\xi \cdot \nabla\Omega)R\hat{\phi}, \\
\rho(\gamma + in\Omega)\mathbf{v} &= -\nabla \cdot \mathbf{p} + \mathbf{j} \times \mathbf{B} + \mathbf{J} \times \mathbf{Q} - \rho\left[2\Omega\hat{\mathbf{Z}} \times \mathbf{v} + (\mathbf{v} \cdot \nabla\Omega)R\hat{\phi}\right] \\
(\gamma + in\Omega)\mathbf{Q} &= \nabla \times (\mathbf{v} \times \mathbf{B}) + (\mathbf{Q} \cdot \nabla\Omega)R\hat{\phi}, \\
(\gamma + in\Omega)p &= -\mathbf{v} \cdot \nabla P, \\
\mathbf{j} &= \nabla \times \mathbf{Q},
\end{aligned}
$$

Kinetic effects are inside the pressure

$$
\mathbf{p} = p\mathbf{I} + p_{\|}\hat{\mathbf{b}}\hat{\mathbf{b}} + p_{\perp}(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}),
$$

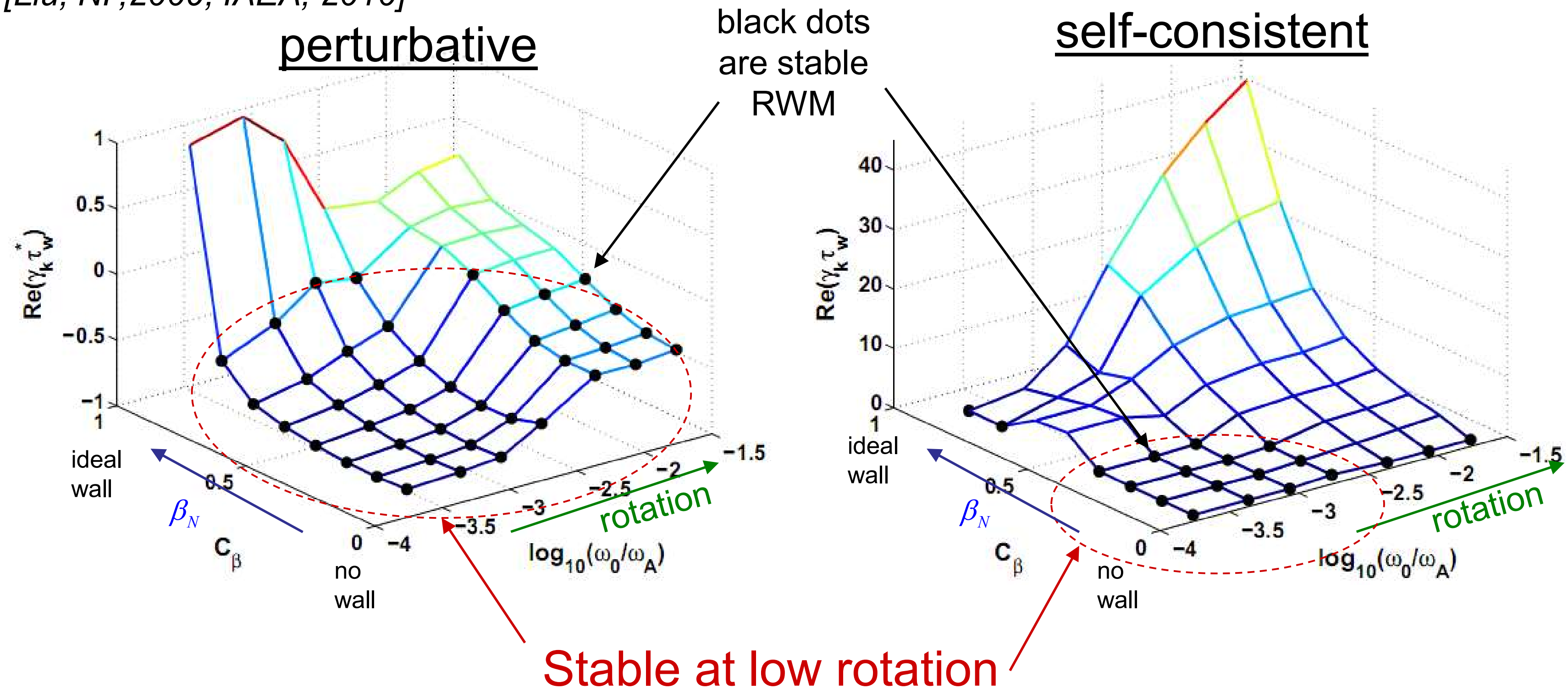
$$
p_{\|}e^{-i\omega t + in\phi} = \sum_{e,i}\int d\Gamma M v_{\|}^2 f_L^1, \qquad p_{\perp}e^{-i\omega t + in\phi} = \sum_{e,i}\int d\Gamma \frac{1}{2} M v_{\perp}^2 f_L^1,
$$

- full toroidal geometry in which the kinetic integrals are evaluated
- $\omega_* \neq 0, \omega_D \neq 0$

…but still some strong assumptions are made: neglects the perturbed electrostatic potential, zero banana width for trapped particles, no FLR corrections to the particle orbits. There is no guaranty that all important effects are inside.

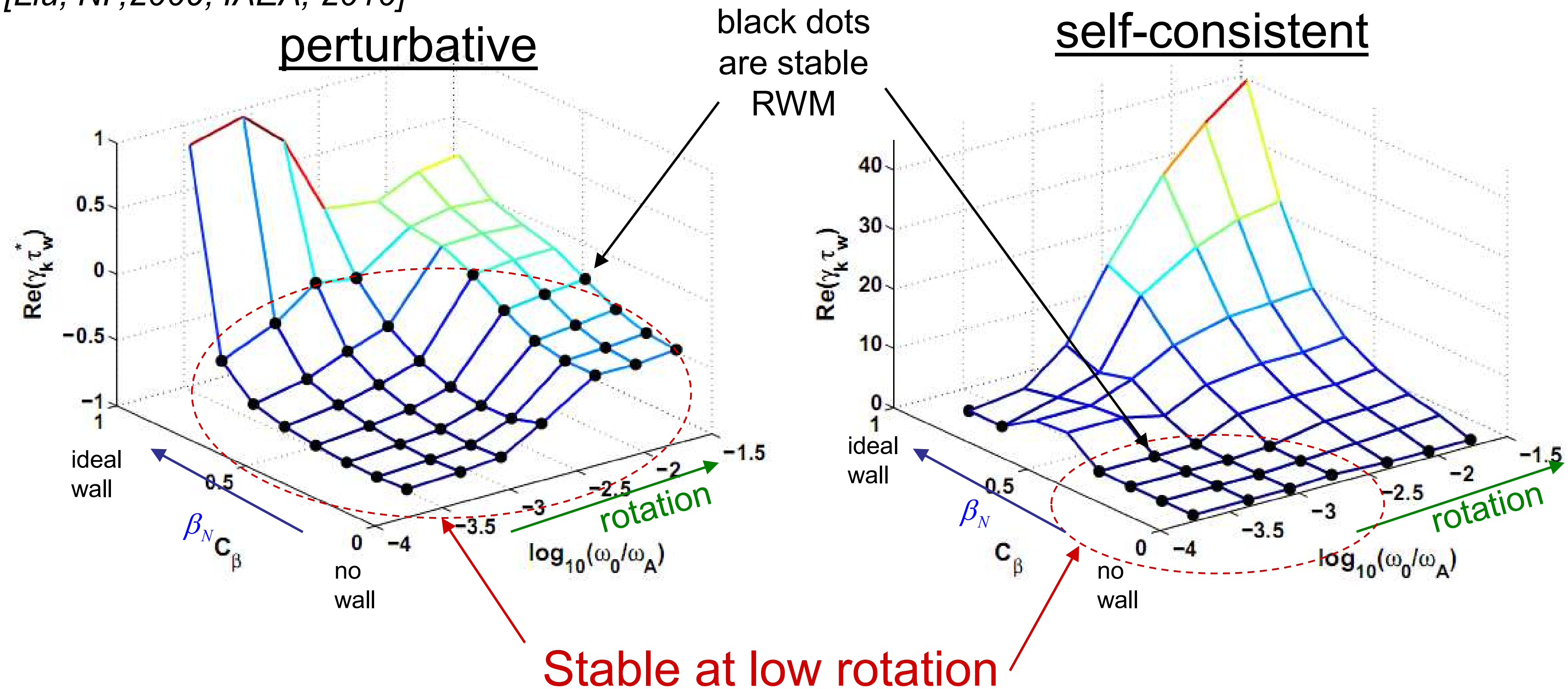
Application of both models for ITER

[Liu, NF,2009, IAEA, 2010]



RWM is stable at low plasma rotation up to $C_\beta \leq 0.4$ without feedback due to mode resonance with the precession drifts of trapped particles.

[Liu, NF,2009, IAEA, 2010]

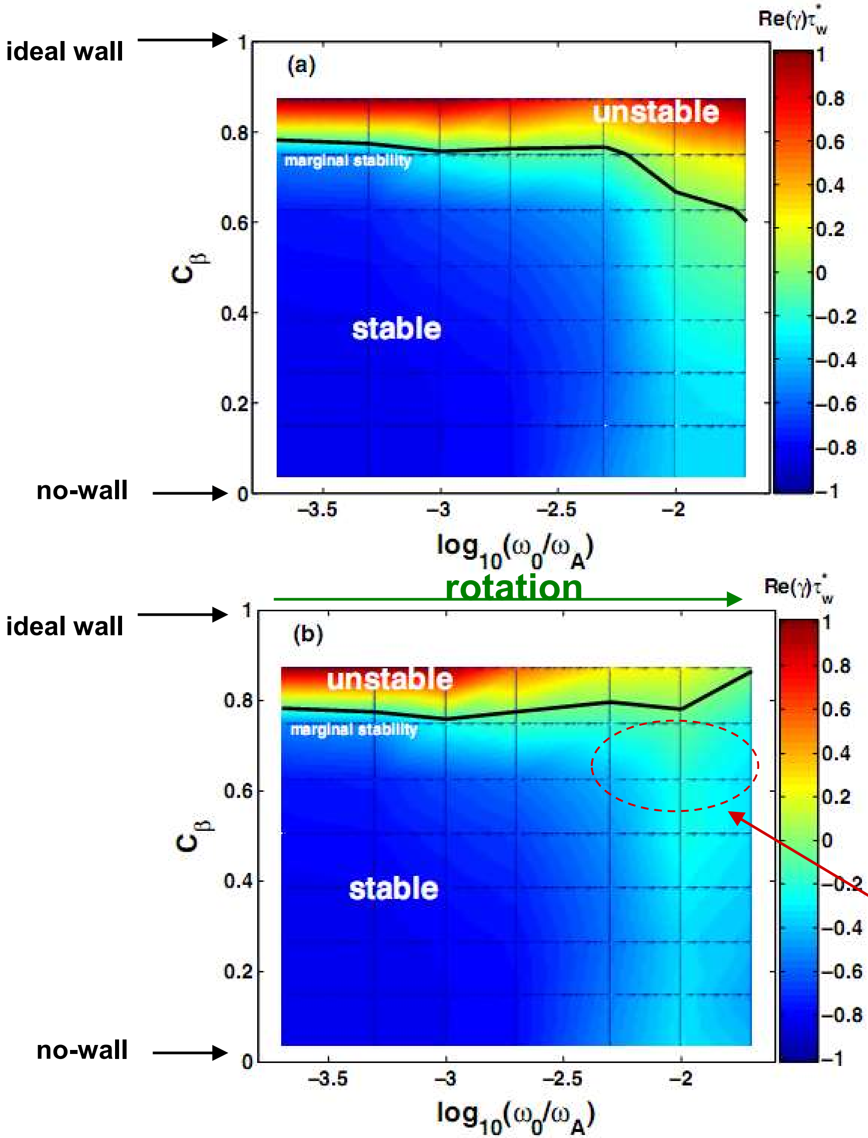


RWM is stable at low plasma rotation up to $C_\beta \leq 0.4$ without feedback due to mode resonance with the precession drifts of trapped particles.

… but some important factors are missing (for example alpha particles are not taken into account).

Influence of α-particles on RWM in ITER (perturbative)

[Liu, NF, 2010]



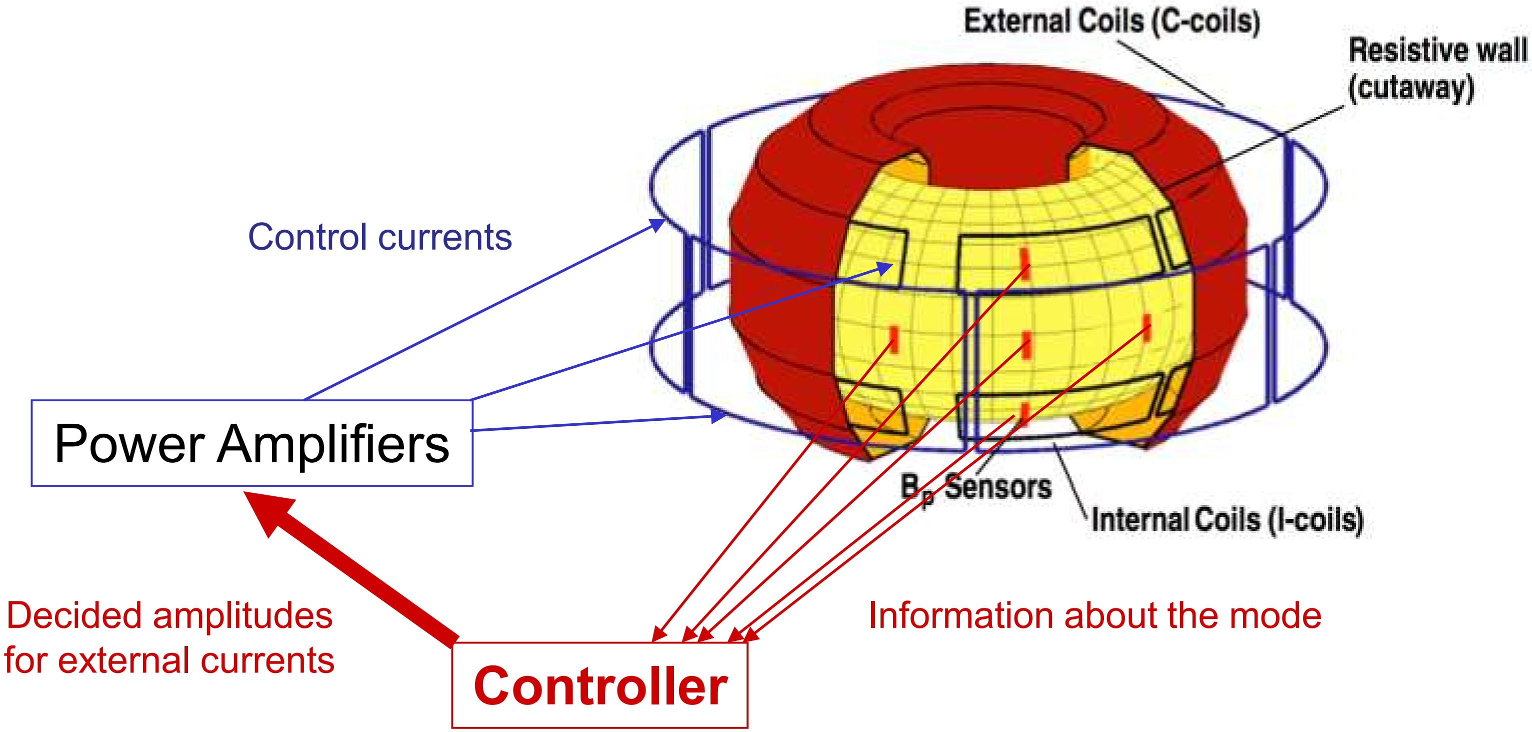
Thermal particles only

Thermal particles and α-particles

Stabilization at higher rotation from α-particles

Control of RWMs

Control by external magnetic coils



Control algorithm

DIII-D: two coil sets 6 C-coils, 12 I-coils usually connected in quartets.

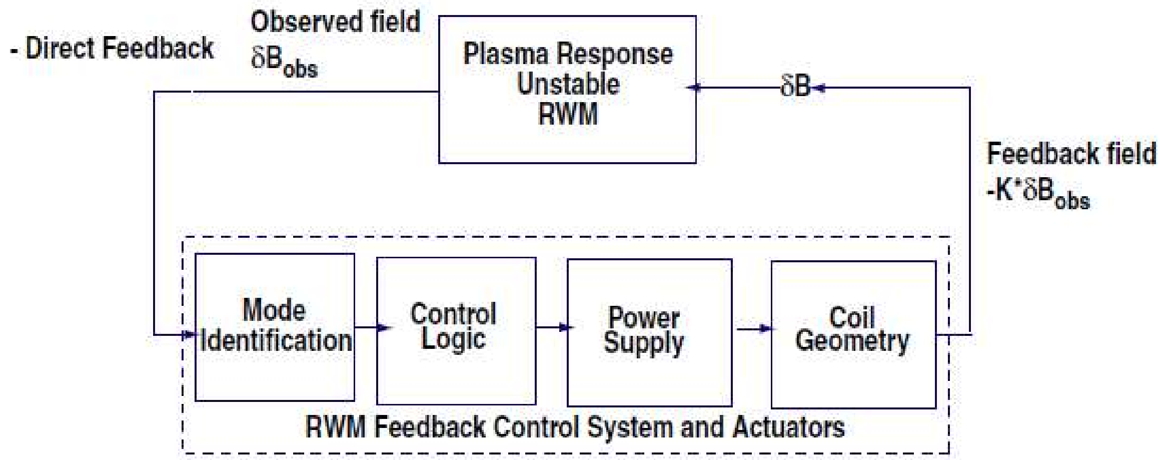
Feedback logic (inside the controller)

Table 3. Feedback logic and flux and method used for stabilization.

Logic	Type of flux and method of utilization
Smart shell	Uses total radial flux just outside or inside the wall: feedback tries to produce 'pseudo-ideal wall' at the observation location [32].
Fake rotating shell	Uses radial flux: the feedback currents are toroidally shifted relative to the observed mode pattern imitating the phase shift induced by toroidal rotation [58].
Explicit mode	Uses the radial flux compensated by the flux due to direct coupling between the coil and the sensors [144].
Mode control	Uses poloidal flux that is due to the unstable RWM and optimally decoupled from the applied B_r field from the feedback coils [86].

M S Chu[1] and M Okabayashi[2]
Plasma Phys. Control. Fusion **52** (2010) 123001

Basic control logic

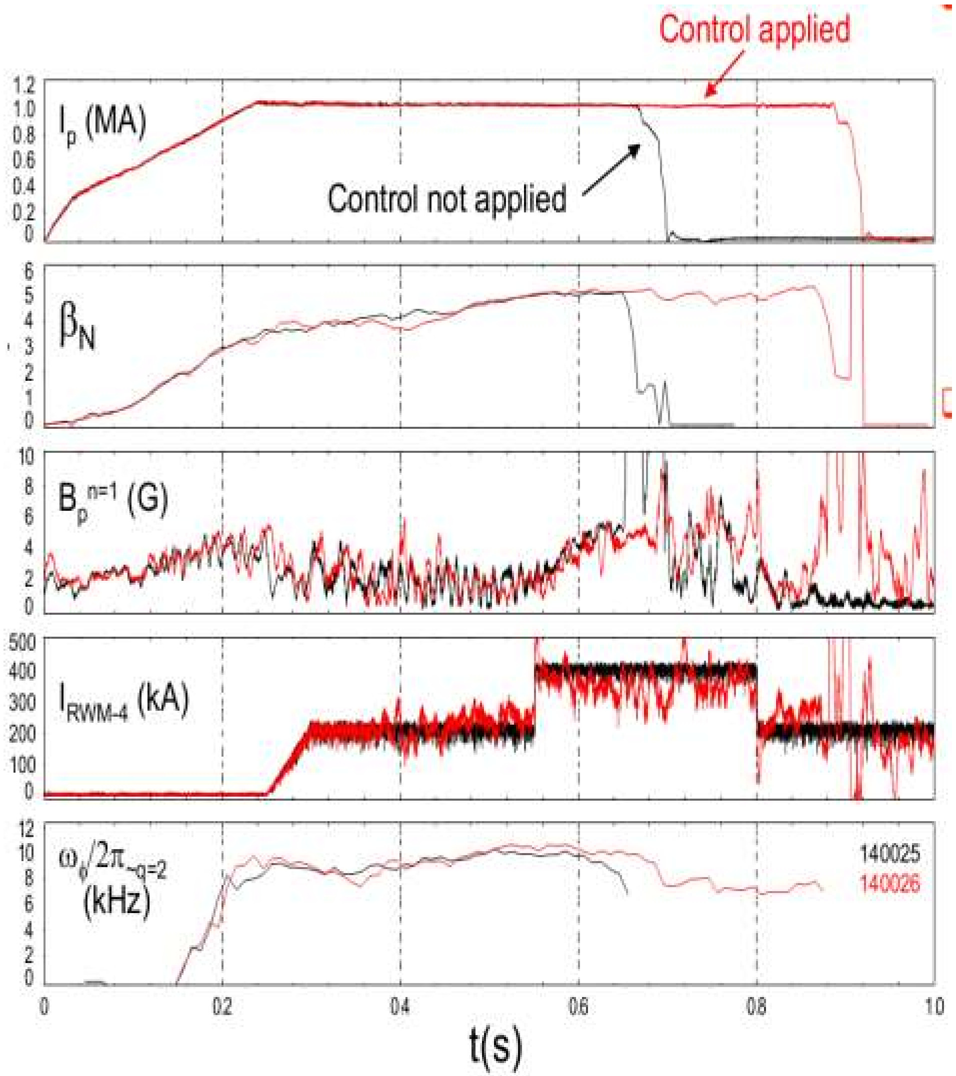


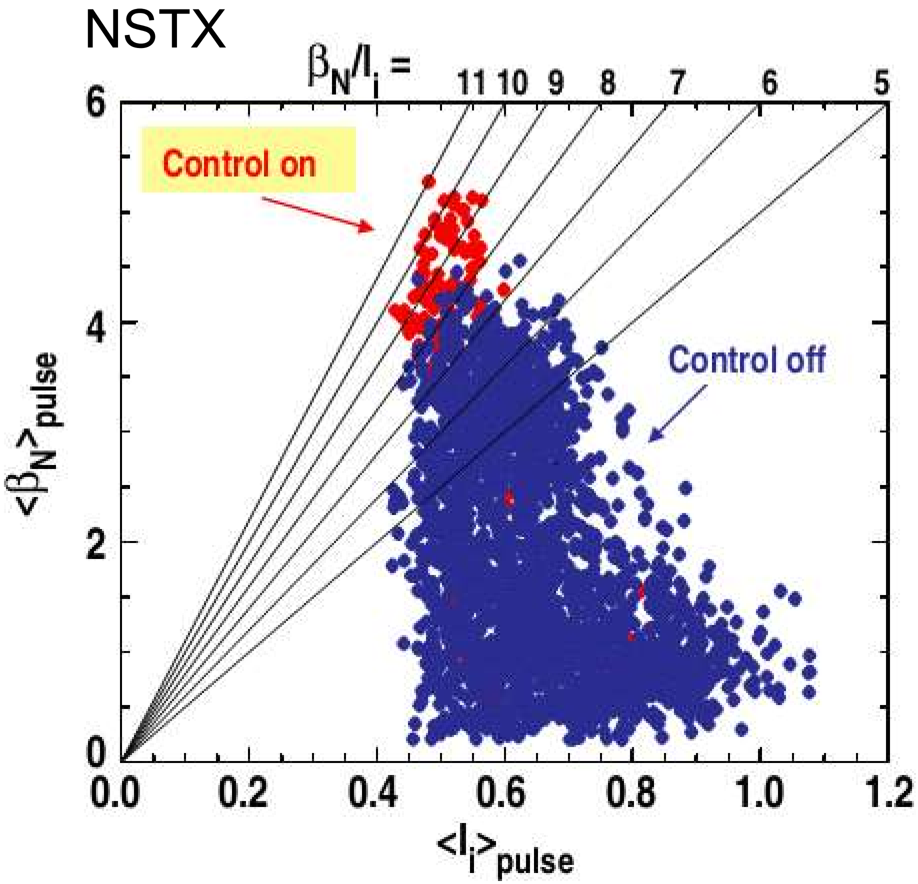
❑ Looking more closely at feedback control system components

- Sensors and mode identification
- Control logic: intelligent shell-like or including plasma response? …
- Power supply
- Coil geometry, number and position

There are multiple possibilities in each of the points and one has to find optimum solution.

How important low n control close to the pressure limit?

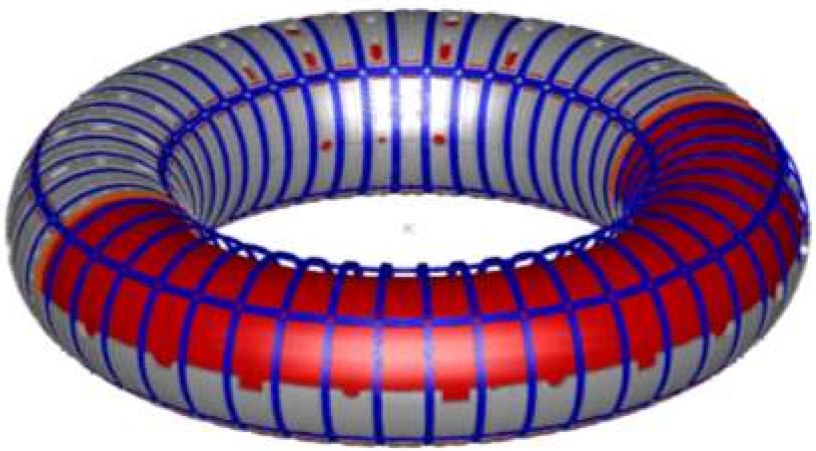




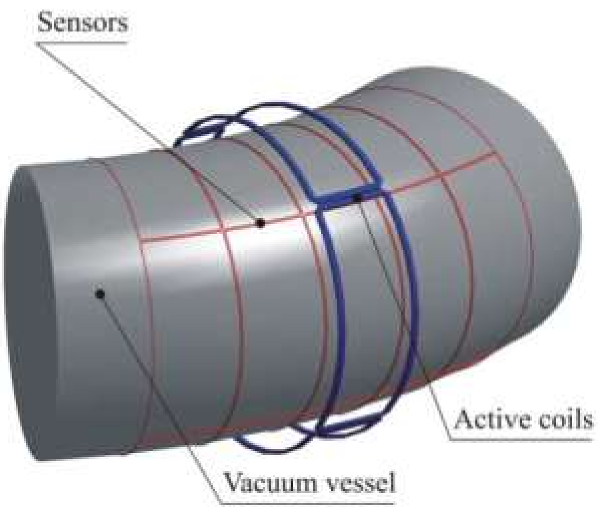
2010 *Nucl. Fusion* **50** 025020

Why the RFPs are important for RWM study?

RFX-mod control system is made by 192 active saddle coils, each independently fed. 100% coverage of the plasma surface.



RFX-mod control system is routinely working on discharges with 30-40 MW Ohmic input power, where effective control is essential.



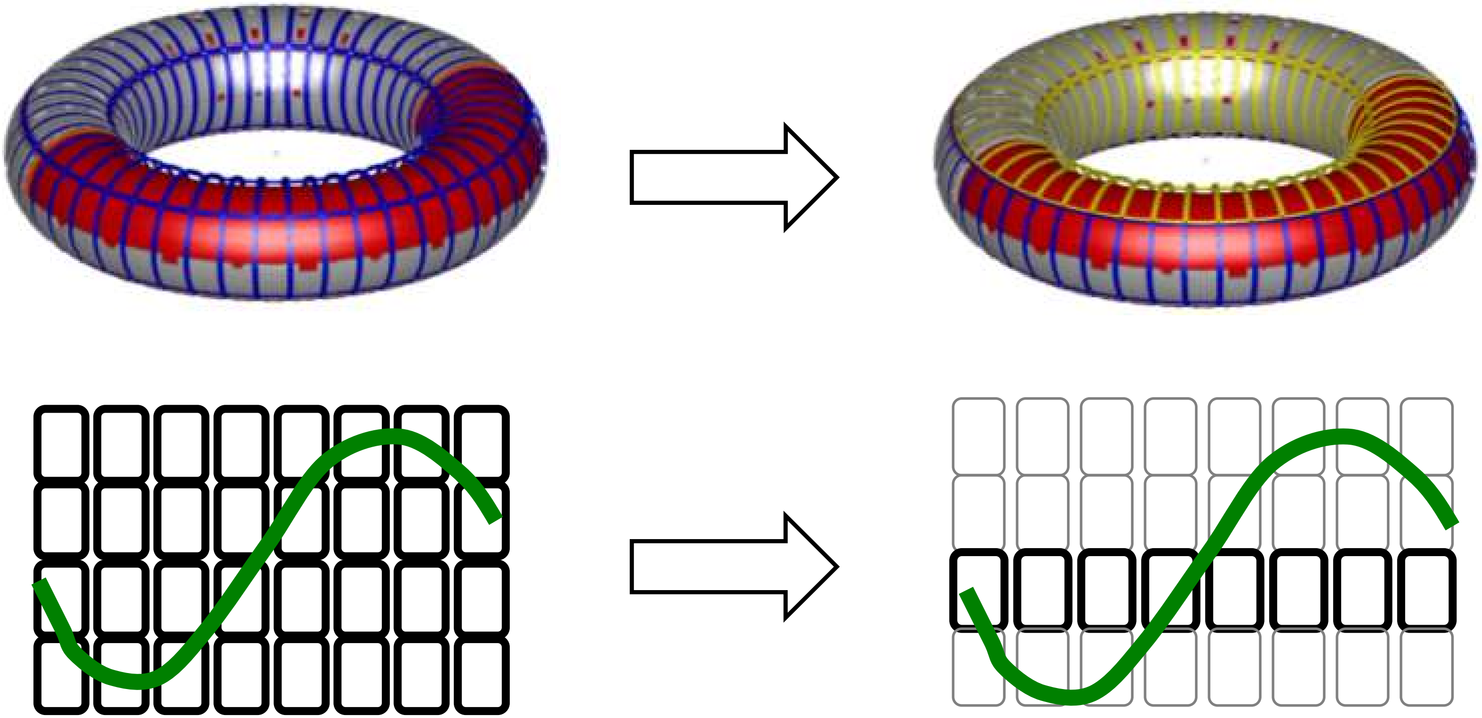
RFX-mod “quantum” for active control:

$\Delta\phi$=7.5°; $\Delta\theta$=90°.

Area covered=0.52%

Active system reconfiguration

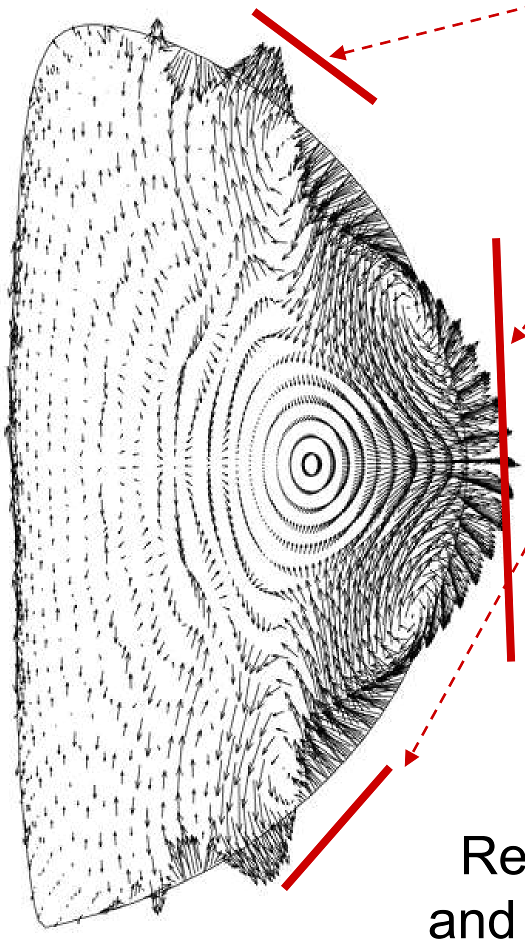
The main idea is to test on the same plasma and on the same device different active control configurations.



NB: it is a software reconfiguration, active on selected harmonics only!

This will allow to understand how much coils we need for RWM stabilization.

[T. Luce, PoP, 2011]



Installation of the high field side coils is much more easy then in the other places.

And these coils are much more effective due to the ballooning mode structure!

Number of the coils is restricted by:

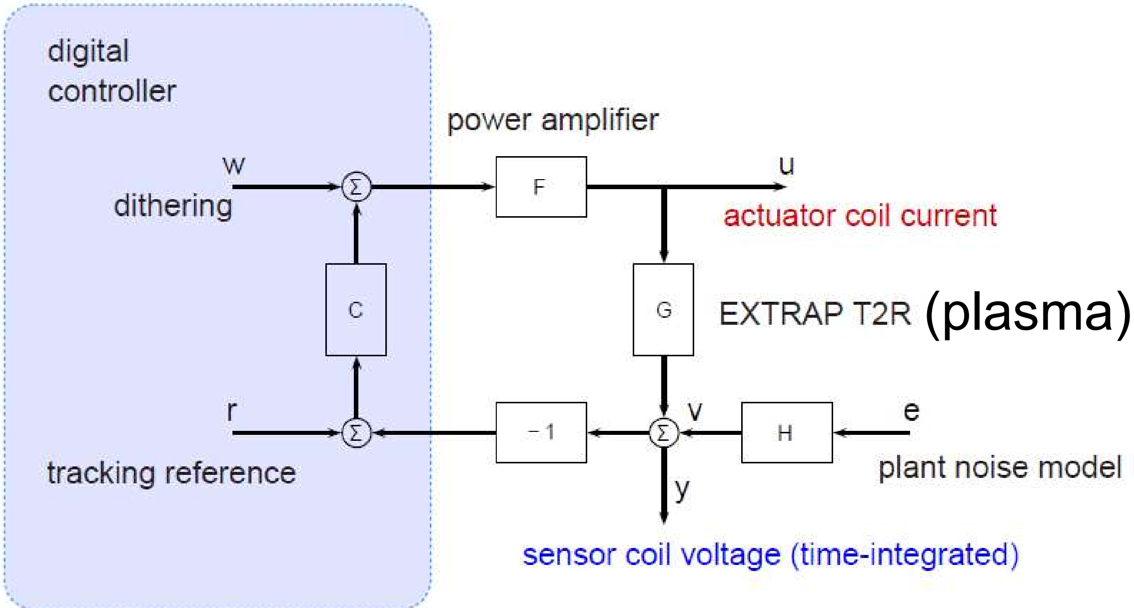
-Tokamak design

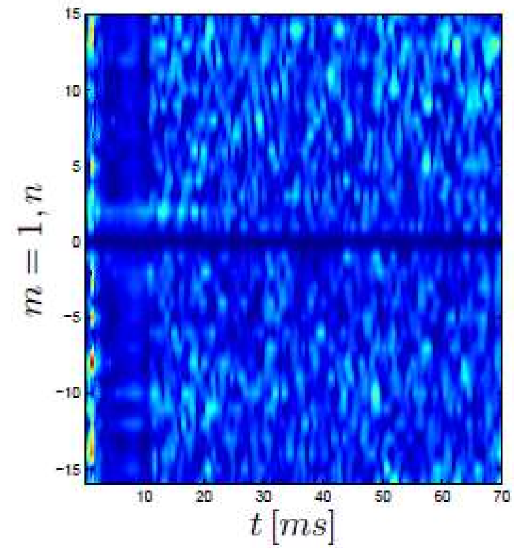
- Required currents for active control

Restricted number of coils could lead to the sideband and excitation of other modes (multiple modes control is necessary)

Close loop system identification (reversed field pinch)

From intelligent shell (SISO) to real time DFT and to dithering.



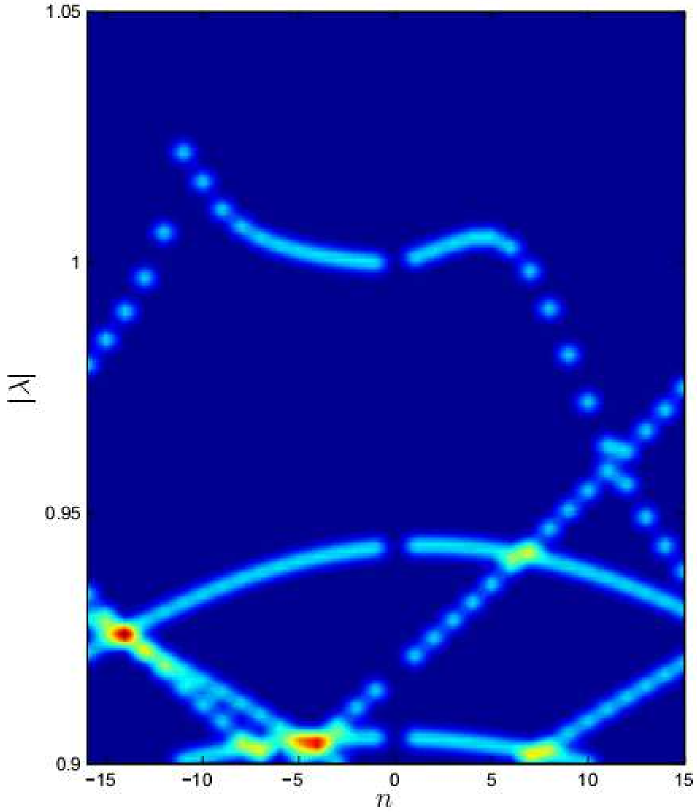


E. Olofsson et al, “Closed loop direct parametric identification of magnetohydrodynamic normal modes spectra in EXTRAP T2R reversed-field pinch,” Proceedings of the 3rd IEEE Multi-conference on Systems and Control (MSC) July 2009

E. Olofsson et al, RFX-mod programme workshop, 2011

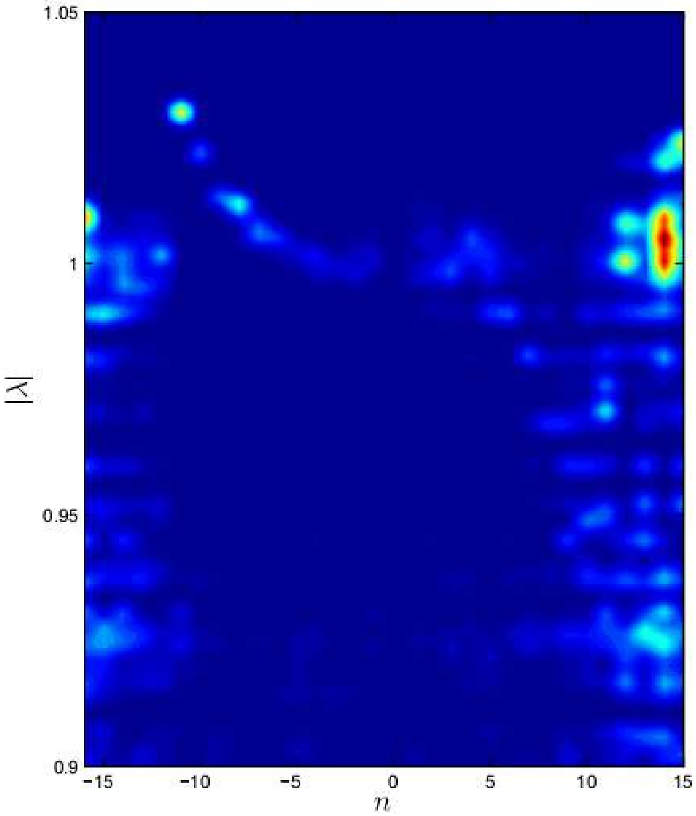
Cylindrical stability vs. Dithering in reversed field pinch

Modeled picture



(a) Cylindrical ideal MHD resistive shell modes in theory; as seen through the discrete sensor array of T2R.

Experimental picture



(b) Growth-rate and spatial spectrum of eigenvectors of the autodetected empirical A-matrix.

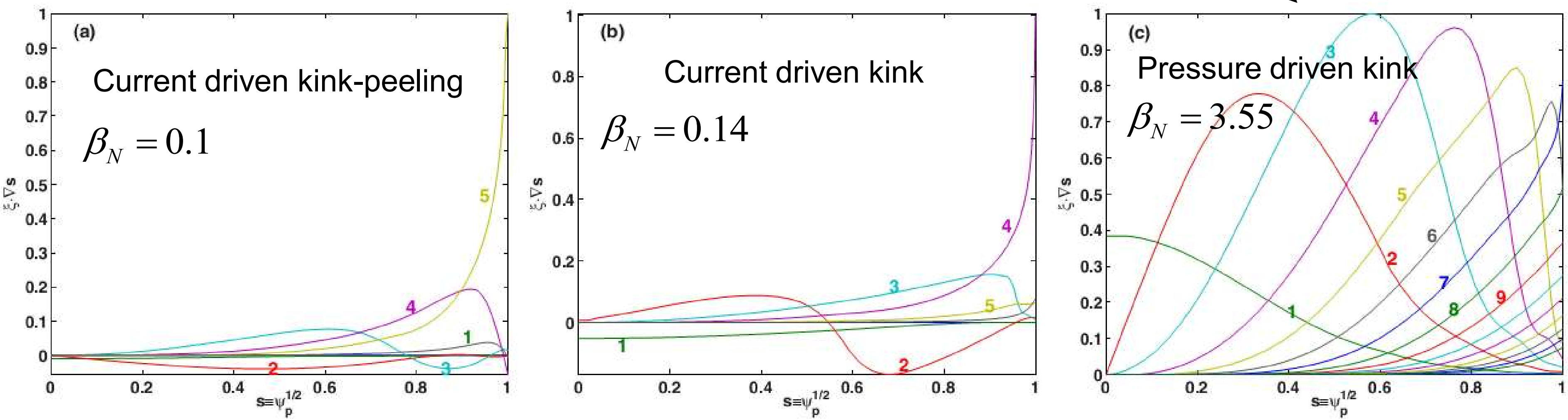
E. Olofsson et al, Plasma Physics and Controlled Fusion (53), (084003)

Difference between current driven and pressure driven RWMs

Liu *et al.* Phys. Plasmas **17**, 072510 (2010)

TABLE I. Three cases for comparison of the mode structure.

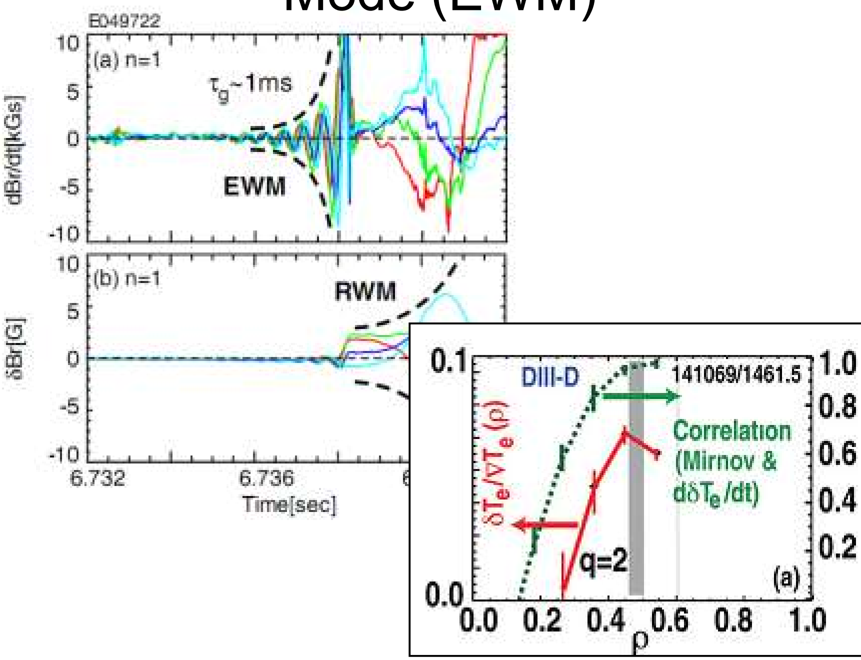
	Case no. A	Case no. B	Case no. C
$\langle J_\phi \rangle\vert_a$	>0	$=0$	>0
q_{min}	2.38	1.78	2.16
q_a	4.61	3.78	5.95
β_N	0.10	0.14	3.55
$\psi_p^{(q)}$	$\psi_p^{(3,4)}=0.543, 0.898$	$\psi_p^{(2,3)}=0.332, 0.913$	$\psi_p^{(3,4,5)}=0.392, 0.708, 0.895$
Mode	Current driven kink-peeling	Current driven kink	Pressure driven kink
$\gamma\tau_A$	0.143	0.024	0.120



Interaction of <u>RWM with plasma</u> is different for current driven and pressure driven RWMs. One has to investigate pressure driven cases. RFPs expertise is not applicable here.

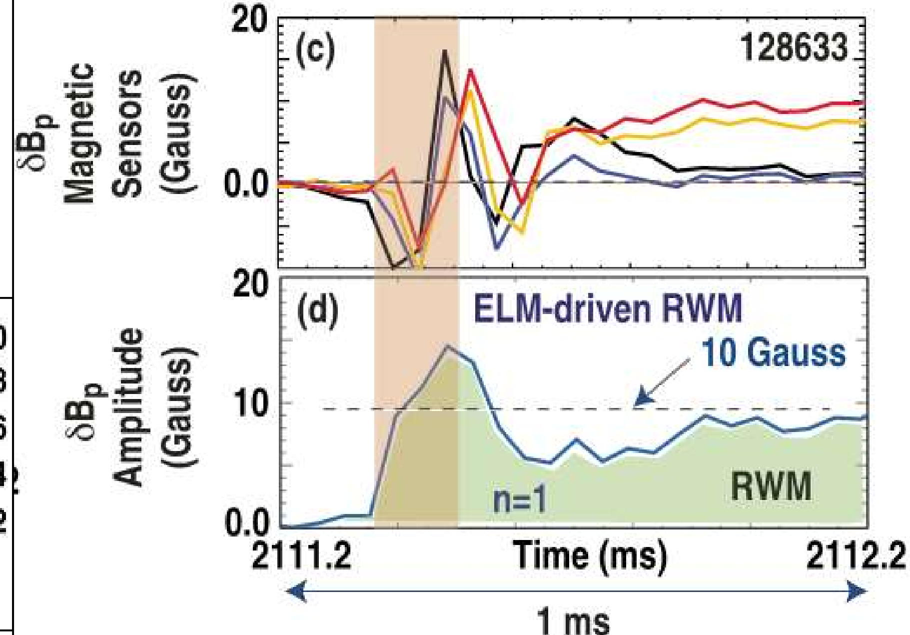
Triggers for RWM at low plasma rotation

Energetic Particle Driven Wall Mode (EWM)



[G. Matsunaga et.al., PRL, 2009 Okabayashi et.al., PoP, 2011]

ELMs



[M.Okabayashi et.al, NF, 2009]

It is important that RWM could be triggered by core (off axis fishbones) and edge (ELMs) modes. This also shows global structure of RWM.

Integrated control of different MHD modes is required to stabilize RWM.

Review papers

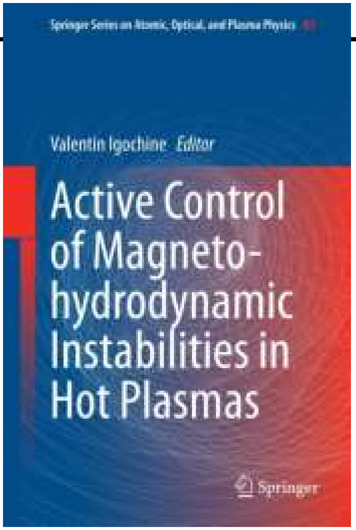
IOP PUBLISHING PLASMA PHYSICS AND CONTROLLED FUSION

Plasma Phys. Control. Fusion **52** (2010) 123001 (102pp) doi:10.1088/0741-3335/52/12/123001

TOPICAL REVIEW

Stabilization of the external kink and the resistive wall mode

M S Chu[1] and M Okabayashi[2]



IOP PUBLISHING and INTERNATIONAL ATOMIC ENERGY AGENCY NUCLEAR FUSION

Nucl. Fusion **52** (2012) 074010 (13pp) doi:10.1088/0029-5515/52/7/074010

SPECIAL TOPIC

Physics of resistive wall modes

V. Igochine

MPI für Plasmaphysik, Euratom-Association, D-85748 Garching, Germany

E-mail: valentine.igochine@ipp.mpg.de

Conclusions

RWMs may limit our operations close to the ……….. limit.

Conclusions

RWMs may limit our operations close to the pressure limit.

RWM stability is affected by interactions with …………..

Conclusions

RWMs may limit our operations close to the pressure limit.

RWM stability is affected by interactions with resistive wall, external fields, fast particles and plasma rotation.

Conclusions

RWMs may limit our operations close to the pressure limit.

RWM stability is affected by interactions with resistive wall, external fields, fast particles and plasma rotation.

Stabilization at low rotations (comparable and less to what is expected for ITER) is achieved, but self consistent modeling is still a problem.

Recent modeling shows that RWMs could be stable in ITER without external feedback well above the no wall limit because of …….

Conclusions

RWMs may limit our operations close to the pressure limit.

RWM stability is affected by interactions with with resistive wall, external fields, fast particles and plasma rotation.

Stabilization at low rotations (comparable and less to what is expected for ITER) is achieved, but self consistent modeling is still a problem.

Recent modeling shows that RWMs could be stable in ITER without external feedback well above the no wall limit because of kinetic effects.

Other modes are able to trigger RWMs at low plasma rotation: …

Conclusions

RWMs may limit our operations close to the pressure limit.

RWM stability is affected by interactions with with resistive wall, external fields, fast particles and plasma rotation.

Stabilization at low rotations (comparable and less to what is expected for ITER) is achieved, but self consistent modeling is still a problem.

Recent modeling shows that RWMs could be stable in ITER without external feedback well above the no wall limit because of kinetic effects.

Other modes are able to trigger RWMs at low plasma rotation: Energetic Particle Modes, ELMs

Conclusions

For RWM control we need:

- …….

Conclusions

For RWM control we need:

- Sensors (magnetic coils for n=1 detection)
- Actuators (large magnetic coils which would mimic ideal wall or other actions)
- control strategies and identification tools.