3D Effects on Resistive Wall Mode and its Control

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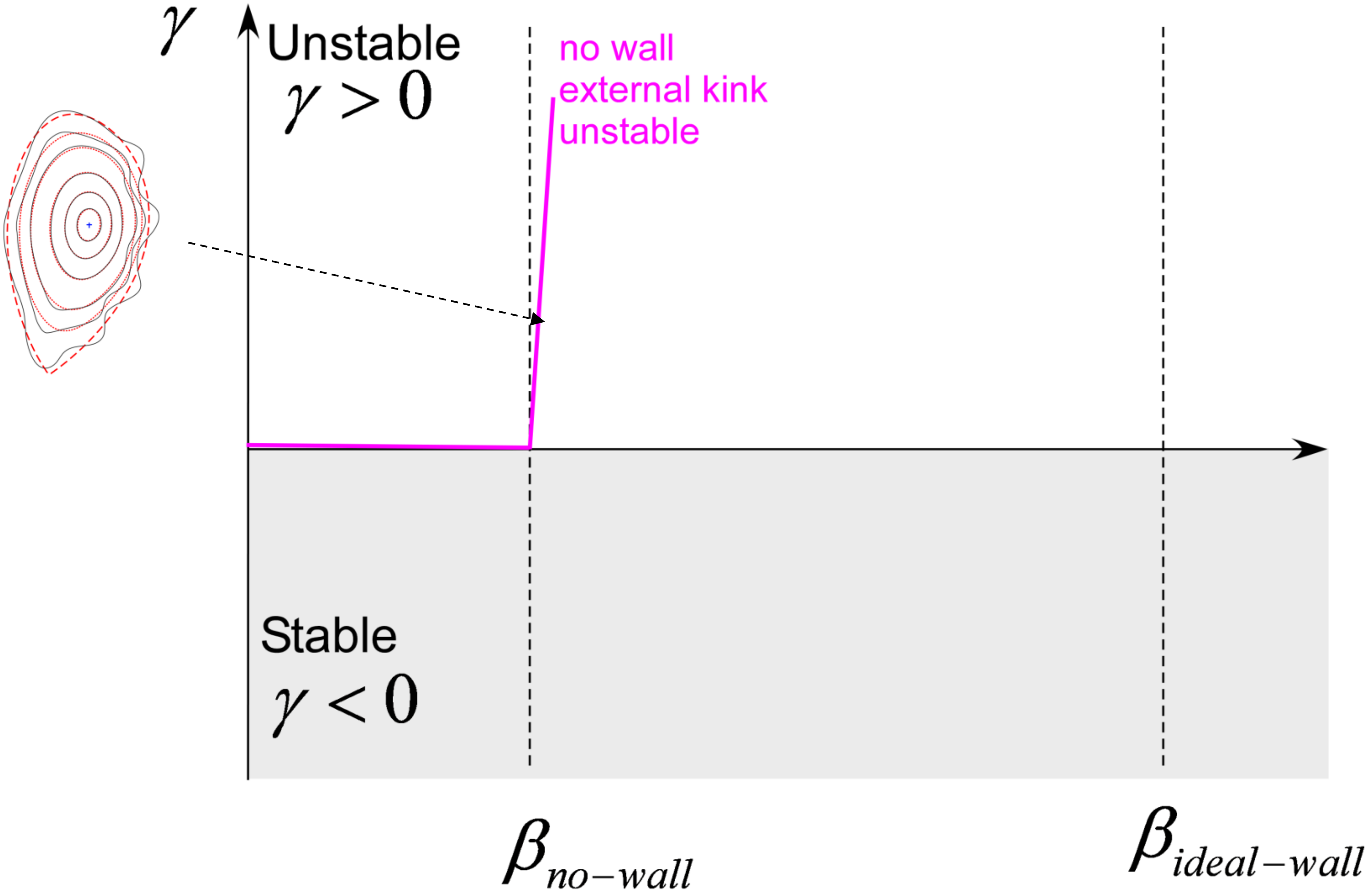
Outline

- Introduction
  - Definition of the beta limits and motivation
  - RWM structure in tokamak

- Physics of the RWM and 3D effects
  - Electromagnetic part
  - Kinetic part

- Control of RWM and importance of 3D effects
  - Control system
  - Control methods

Definitions of the beta limits



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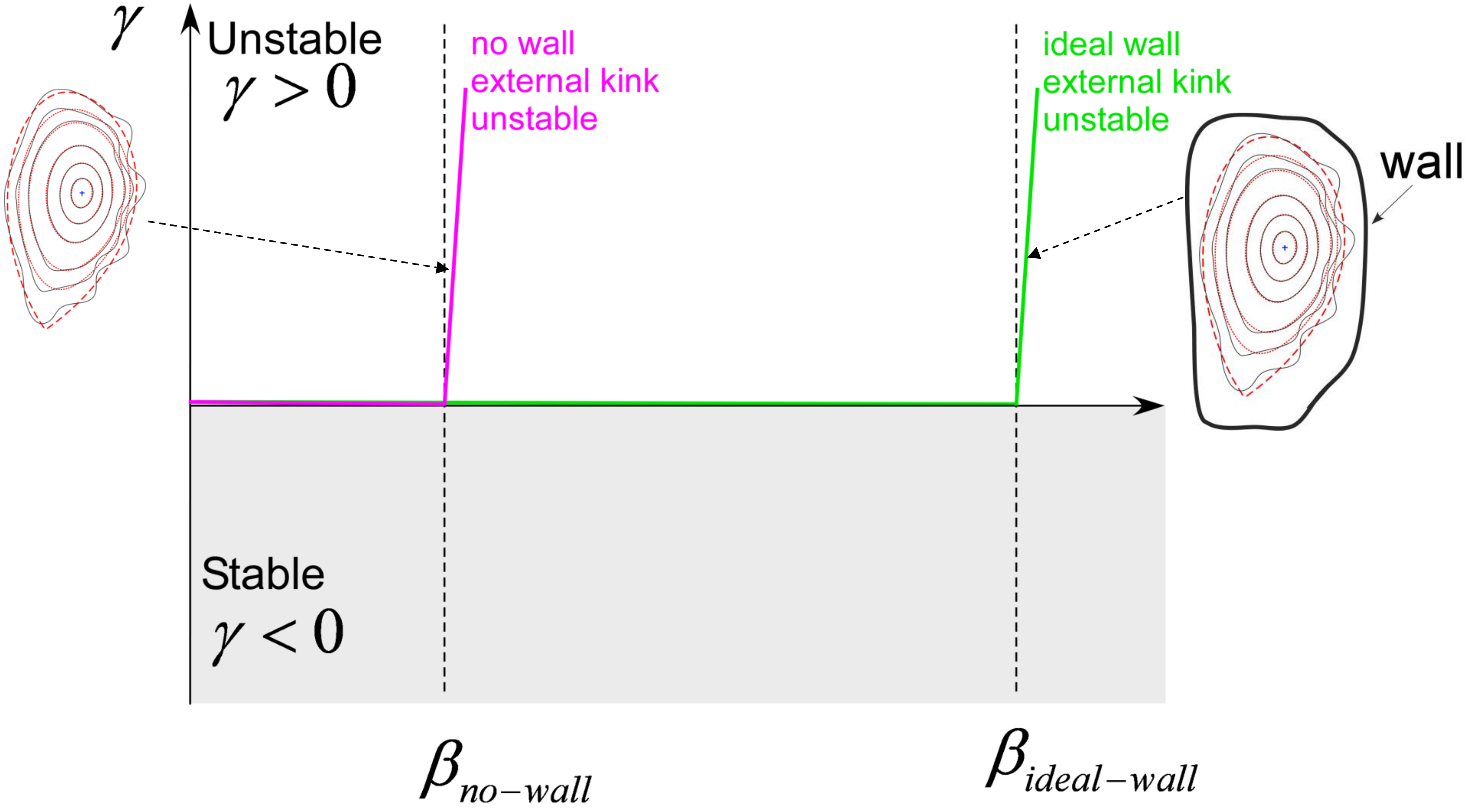


γ

Unstable

$\gamma > 0$

no wall
external kink
unstable

ideal wall
external kink
unstable

wall

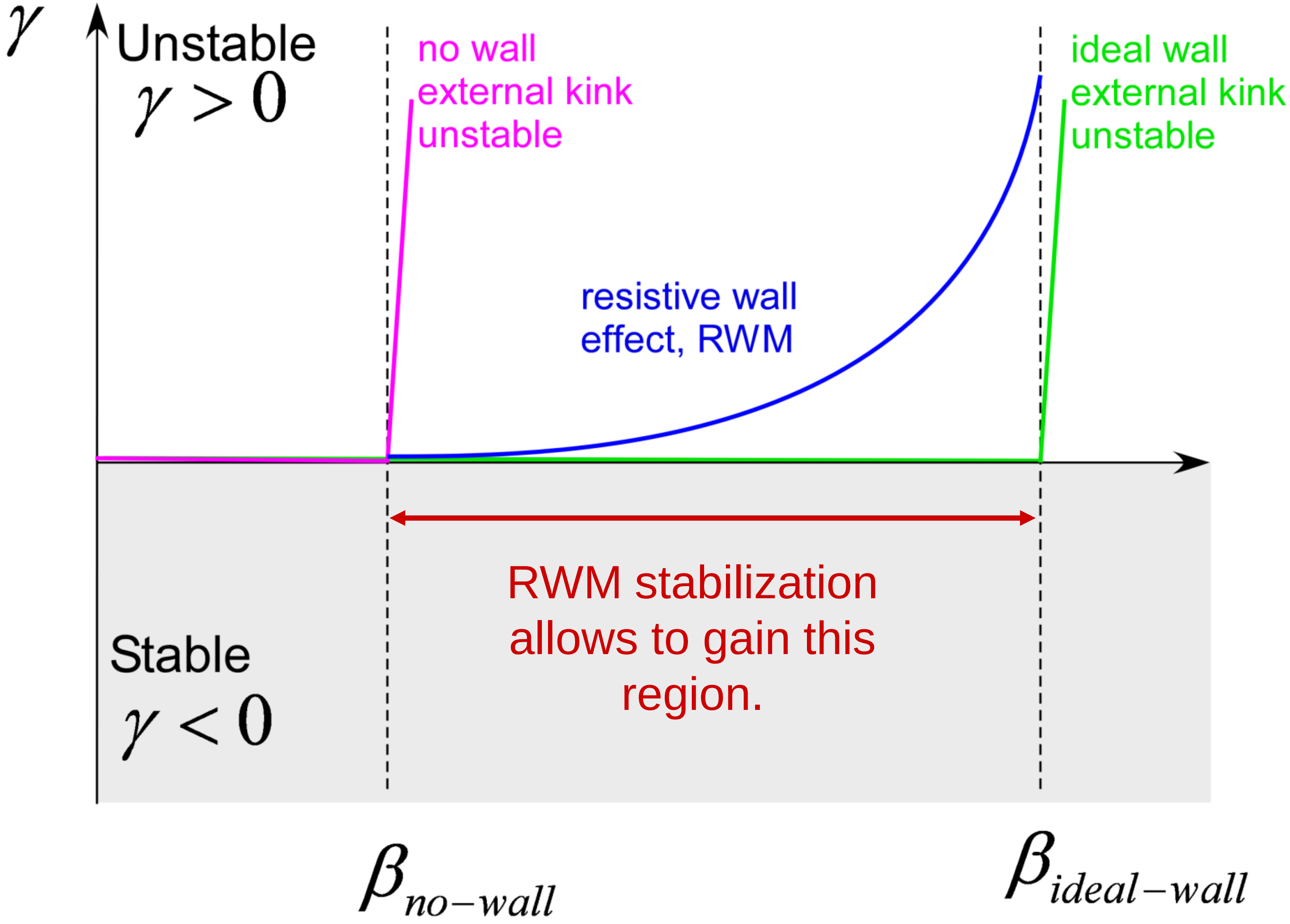
Stable

$\gamma < 0$

$\beta_{no-wall}$

$\beta_{ideal-wall}$

Definitions of the beta limits

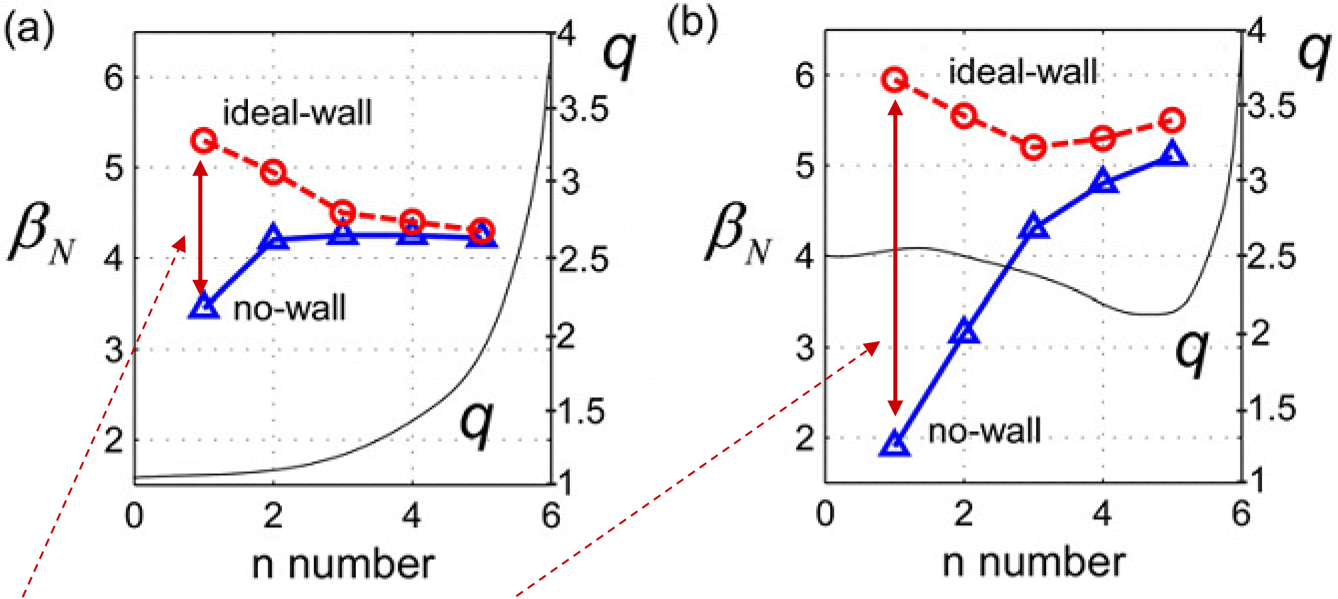


RWM stabilization allows to gain this region.

When the RWM stabilization is important?

Conventional scenario
(moderate improvements)

Advanced scenario
(crucial improvements)



V. Igochine Nucl. Fusion **52** (2012) 074010
Manickam J. *et al* 1994 *Phys. Plasmas*

RWM stabilization allows to gain this region.

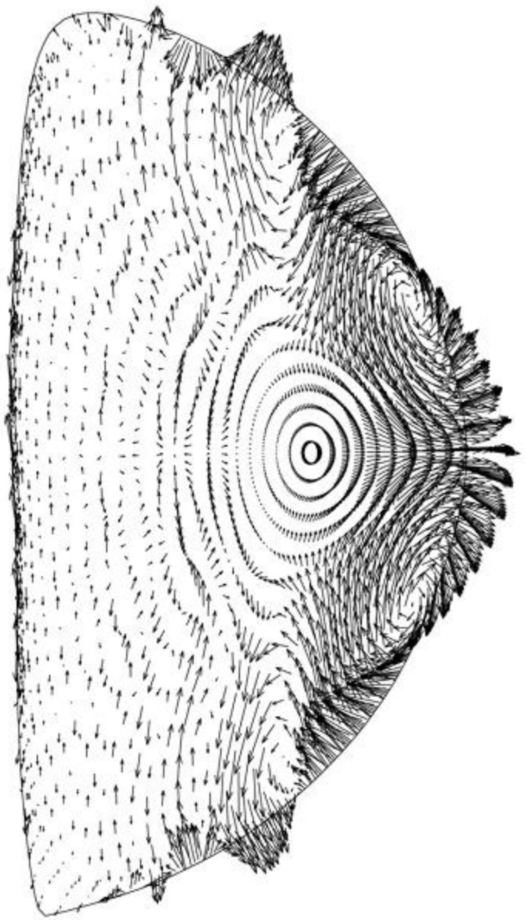
Stabilization is really important only in the advanced scenario for low n.

Resistive Wall Mode structure in tokamak

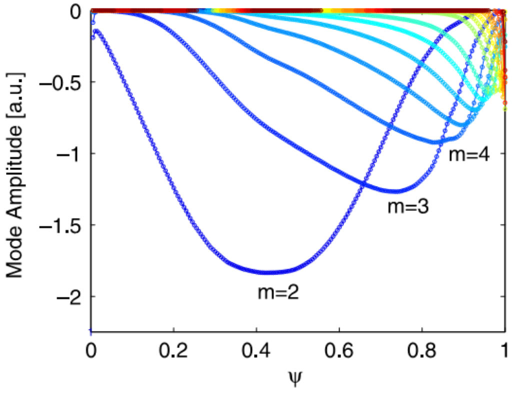
- Resistive wall mode is an external kink mode which interacts with the resistive wall.

- 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]

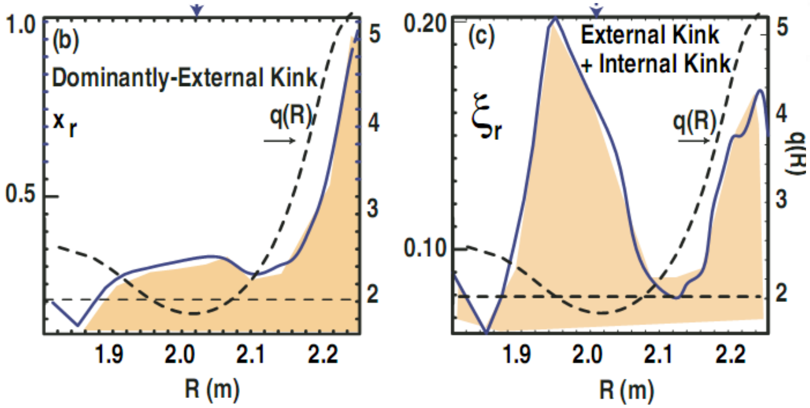


JET



[I.T.Chapman, PPCF, 2009]

DIII-D



[M.Okabayashi, NF, 2009]

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

Physics of RWMs and 3D effects

RWM physics in tokamak

RWM physics in tokamaks

RWM interaction with externally produced magnetic fields

- resistive wall (**destab**.)
- error fields (**destab**.)
- control coils (**stab**.)

+

RWM interaction with plasma

- plasma rotation (**stab**.)
- fast particles (**stab**.)
- thermal particles (**stab**.)

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Mode can be represented as a surface currents

Physics: **electromagnetism**

Wave-particle interaction

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

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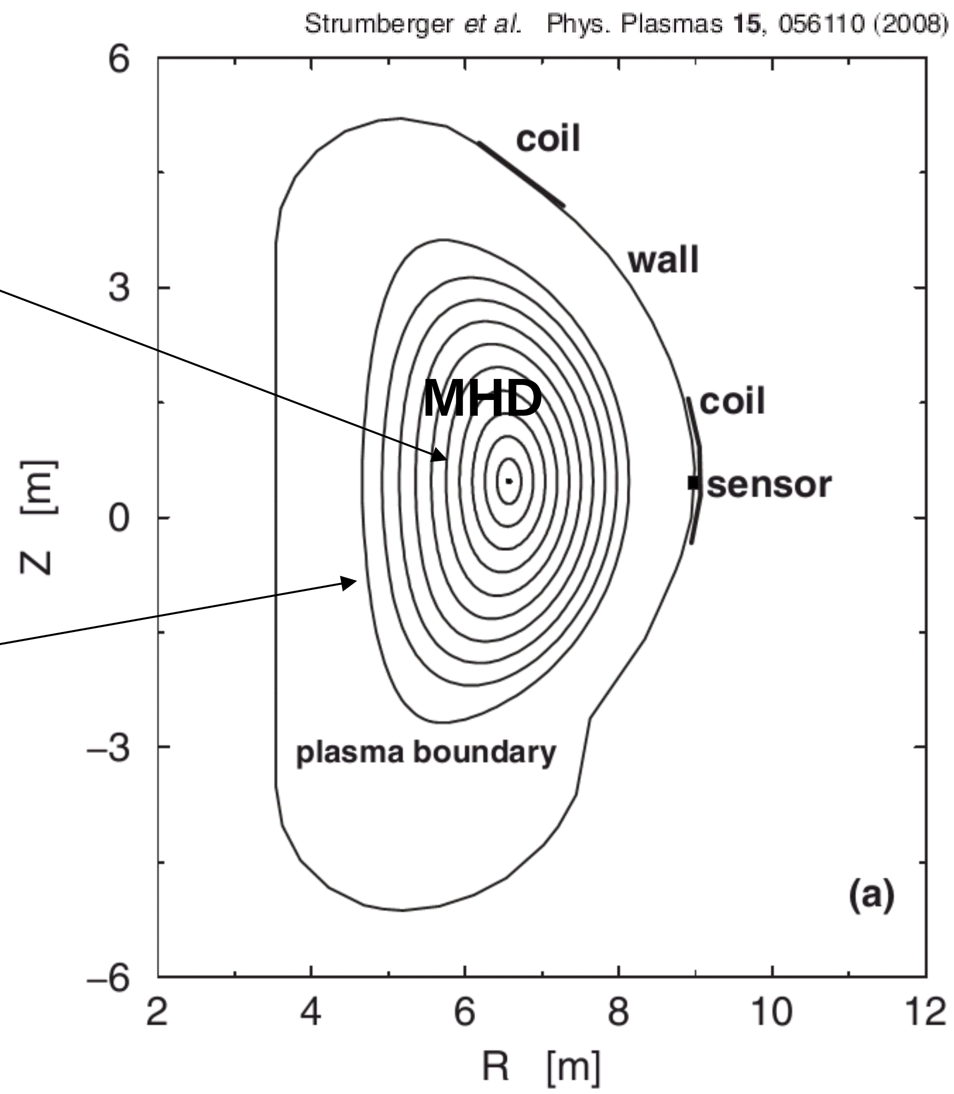
Real plasma shape, real wall,…

Plasma region is calculated with a linear MHD code: MARS, CASTOR, etc (all interactions between plasma and the mode is hidden inside the code)

Connection to the external part via boundary conditions at the coupling surface (just outside or at the plasma boundary).


Strumberger *et al.* Phys. Plasmas **15**, 056110 (2008)

Effects of the 3D wall structure (1)

Growth rate of the RWM is strongly different in 2D and 3D cases if holes in the wall are big (the low field side holes are especially important)

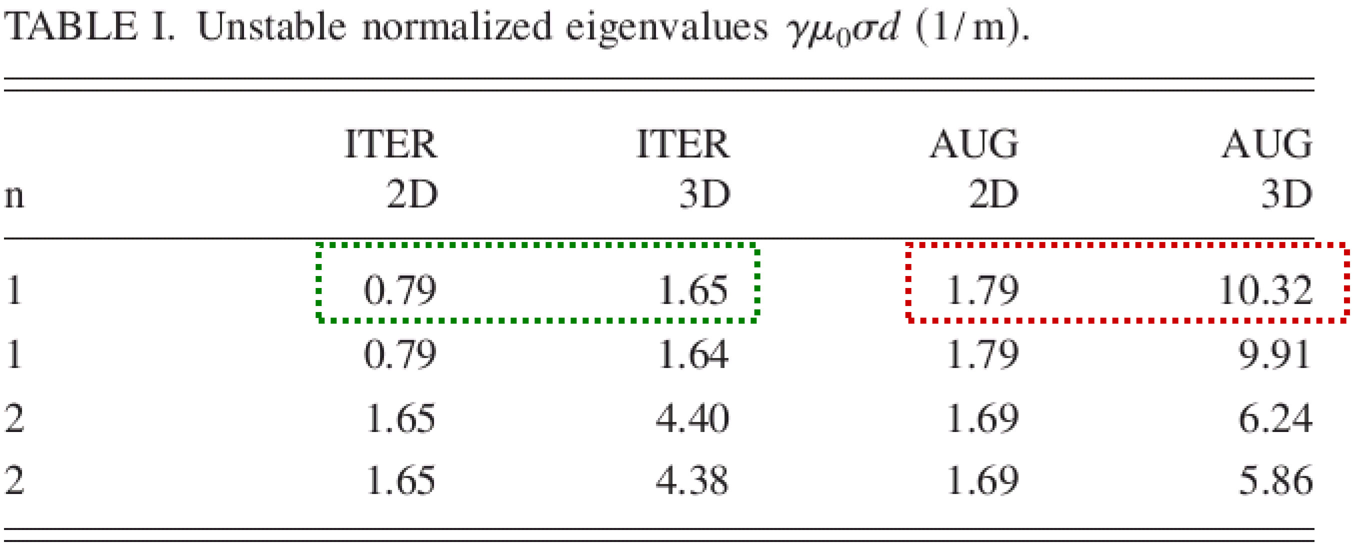
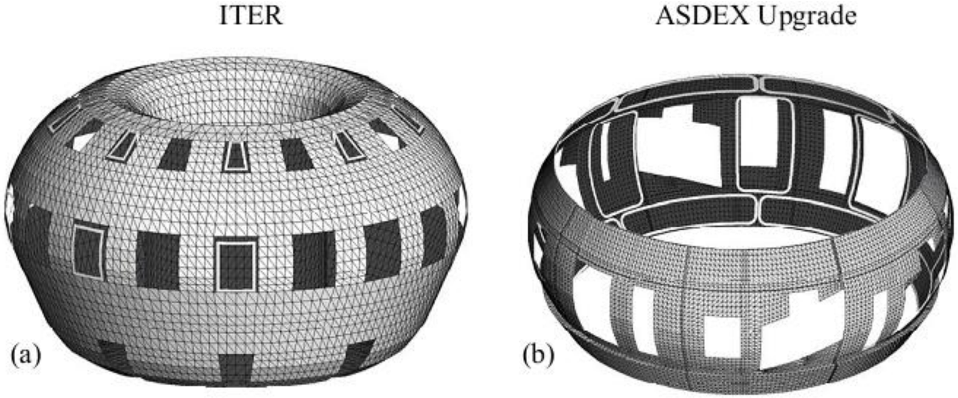


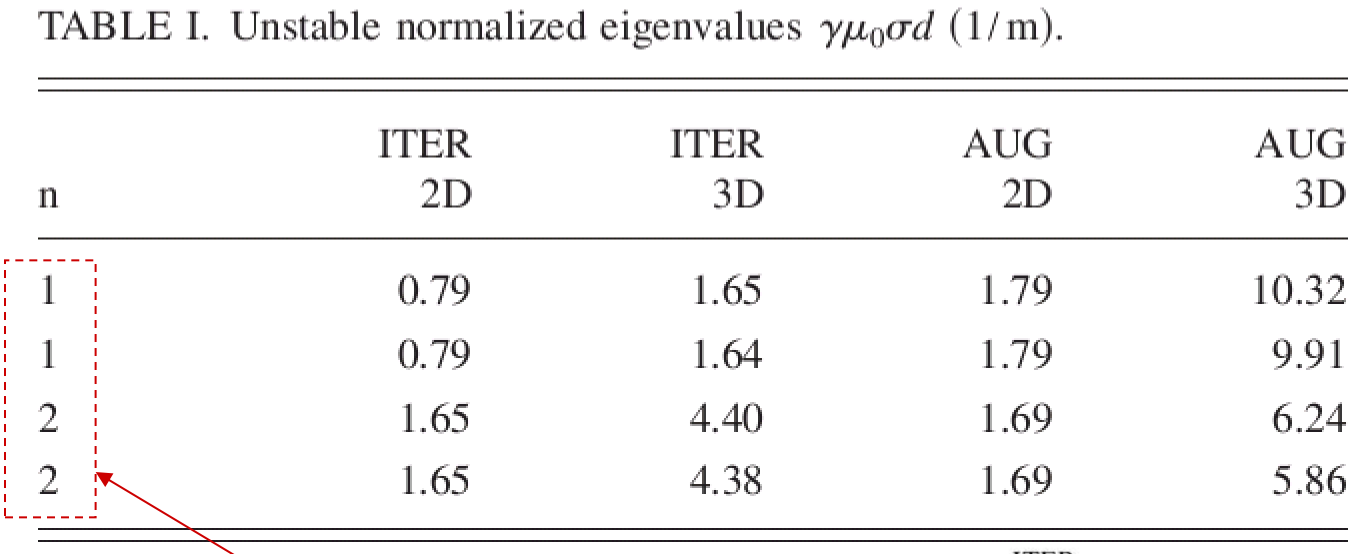
TABLE I. Unstable normalized eigenvalues $\gamma\mu_0\sigma d$ (1/m).

n	ITER 2D	ITER 3D	AUG 2D	AUG 3D
1	0.79	1.65	1.79	10.32
1	0.79	1.64	1.79	9.91
2	1.65	4.40	1.69	6.24
2	1.65	4.38	1.69	5.86



Effects of the 3D wall structure (2)

Growth rate of the RWM is strongly different in 2D and 3D cases if holes in the wall are big (the low field side is especially important)



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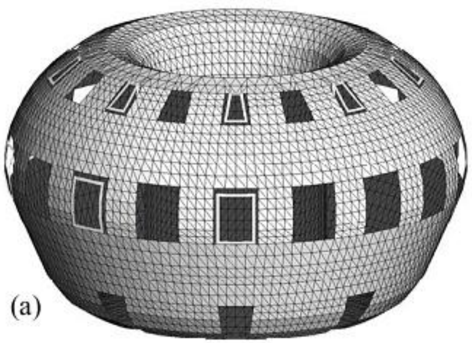
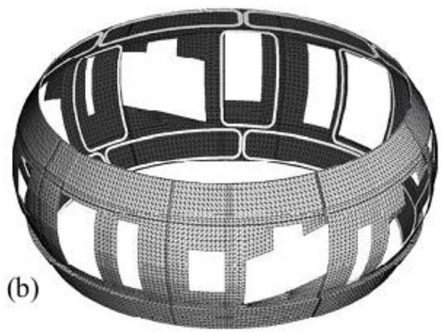
2	1.65	4.38	1.69	5.86

- Different toroidal mode numbers are coupled through the 3D wall (this is pure result of the 3D problem!)
- Different locking positions have slightly different growth rates for the same n-number

ITER



ASDEX Upgrade



Effects of the 3D wall structure on the growth rate in RFX

Growth rates are close to the measured values if one takes into account 3D effects (RFX-mod)

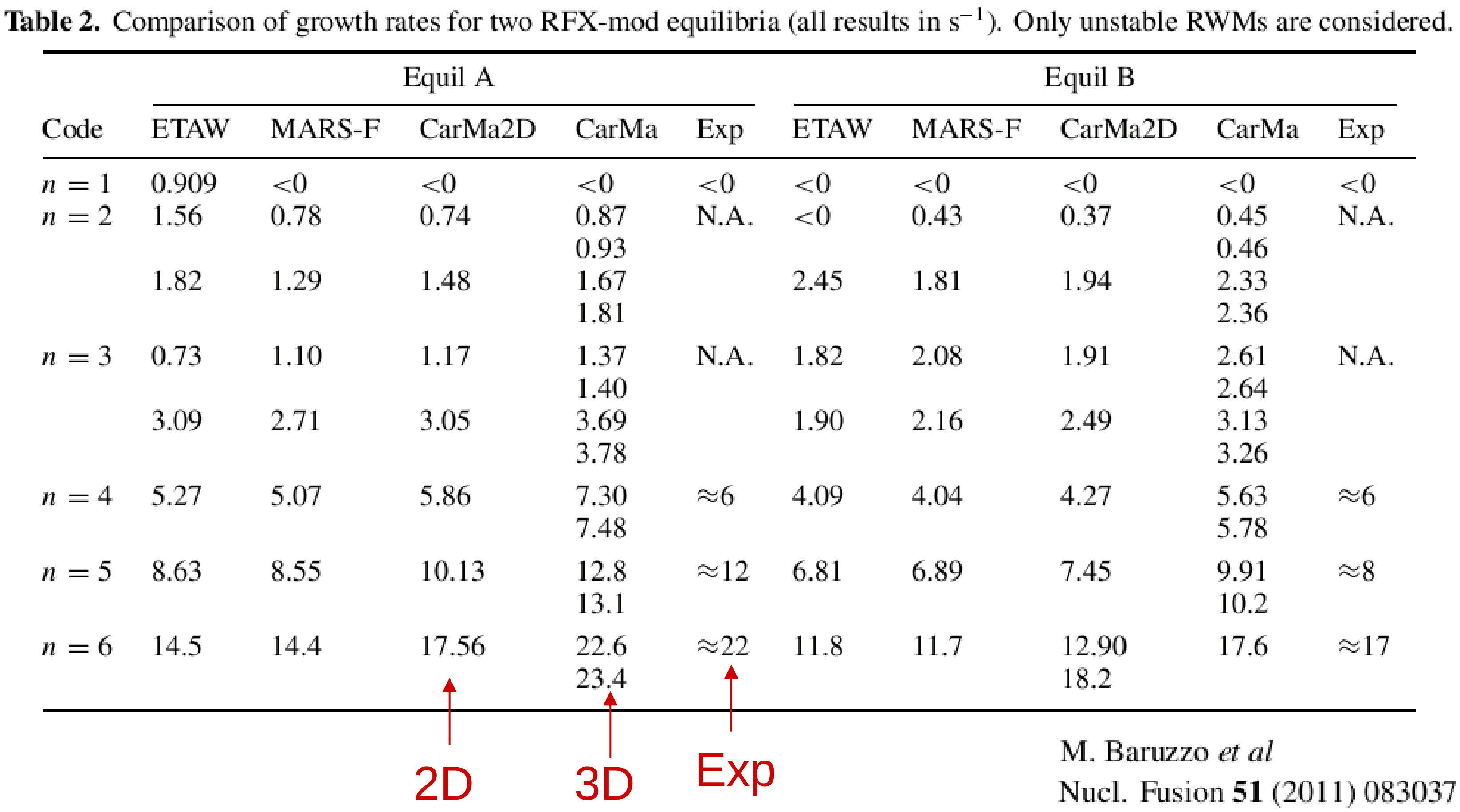


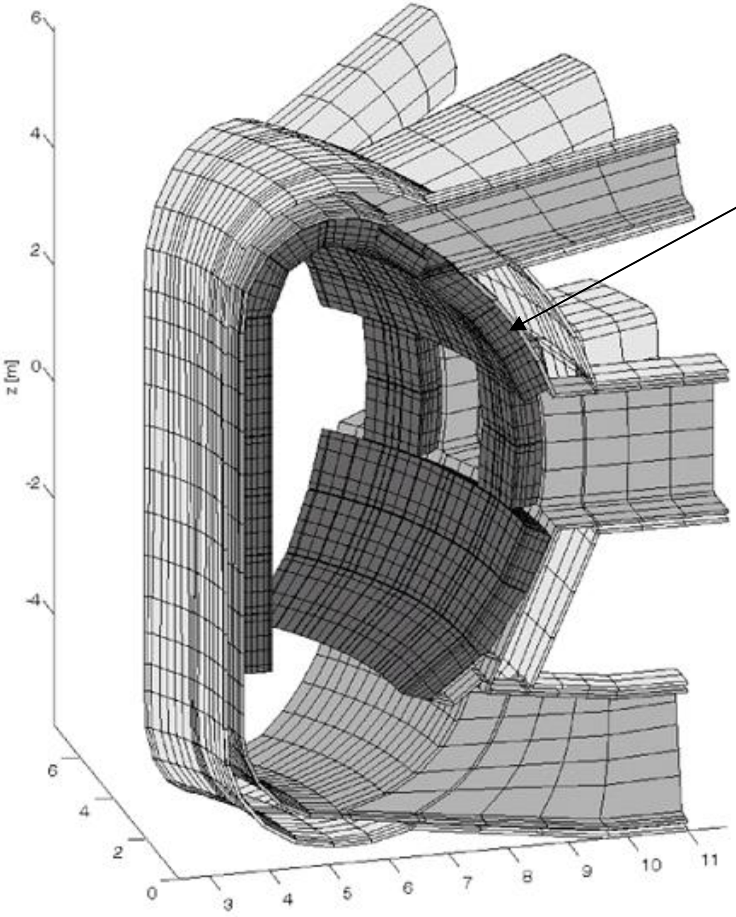
Table 2. Comparison of growth rates for two RFX-mod equilibria (all results in s^{-1}). Only unstable RWMs are considered.

	Equil A					Equil B				
Code	ETAW	MARS-F	CarMa2D	CarMa	Exp	ETAW	MARS-F	CarMa2D	CarMa	Exp
$n = 1$	0.909	<0	<0	<0	<0	<0	<0	<0	<0	<0
$n = 2$	1.56	0.78	0.74	0.87	N.A.	<0	0.43	0.37	0.45	N.A.
				0.93					0.46	
	1.82	1.29	1.48	1.67		2.45	1.81	1.94	2.33	
				1.81					2.36	
$n = 3$	0.73	1.10	1.17	1.37	N.A.	1.82	2.08	1.91	2.61	N.A.
				1.40					2.64	
	3.09	2.71	3.05	3.69		1.90	2.16	2.49	3.13	
				3.78					3.26	
$n = 4$	5.27	5.07	5.86	7.30	≈6	4.09	4.04	4.27	5.63	≈6
				7.48					5.78	
$n = 5$	8.63	8.55	10.13	12.8	≈12	6.81	6.89	7.45	9.91	≈8
				13.1					10.2	
$n = 6$	14.5	14.4	17.56	22.6	≈22	11.8	11.7	12.90	17.6	≈17
				23.4				18.2		

M. Baruzzo *et al*
Nucl. Fusion **51** (2011) 083037

Effects of blanket modules (BM) on RWM stability

Not only the wall, but also other elements can be important RWM stability.



F. Villone *et al* Nucl. Fusion **50** (2010) 125011

<u>Blanket modules in ITER provide beneficial effect</u> on growth rates which largely compensates the detrimental effect due to the presence of ports and port extensions, leading to growth rates close to the 2D case

	Case 1	Case 2	Case 3	Case 4
β_N^{nw}	2.600	2.600	2.578	2.585
β_N^{iw}	3.579	3.361	3.408	3.859

2D vessel

3D vessel with holes

3D vessel with port extensions

3D vessel with port extensions and BM

RWM physics in tokamak

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**

+

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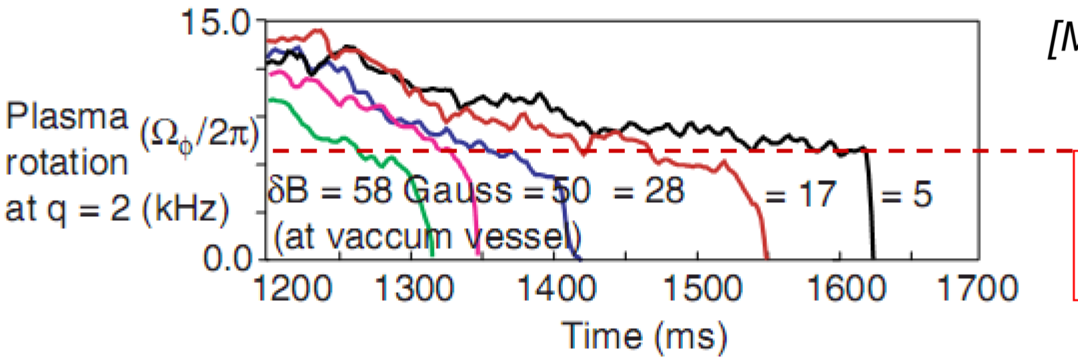
Possible variants of modeling



[M. Okabayashi et. al. PPCF 2002]

RWM is unstable if rotation drops below critical value

Self-consistent modeling (MARS,…)

Linear MHD + approximation for damping term

- (**+**) rotation influence on the mode eigenfunction

- (**-**) damping model is an approximation

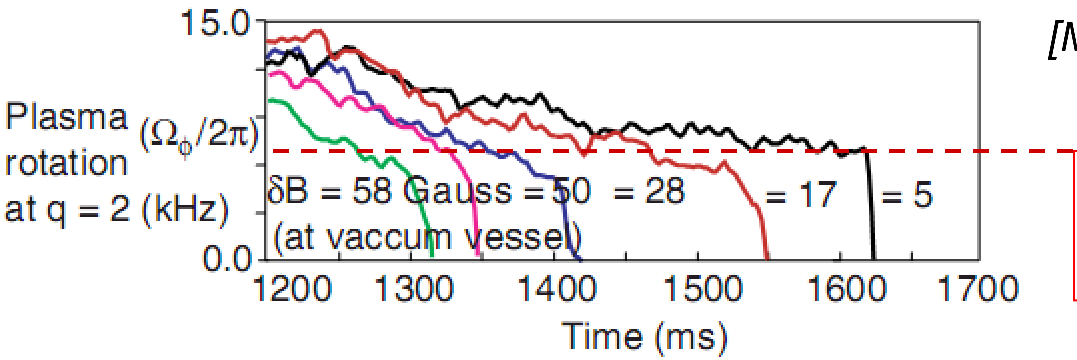
Perturbative approach (Hagis,…)

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

Possible variants of modeling



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- (+) damping is correctly described in kinetic code

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

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

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

Kinetic effects are inside the pressure

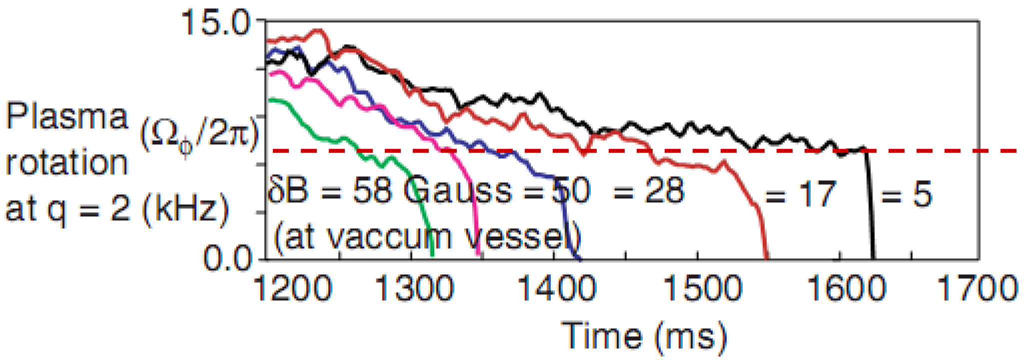
$$
\mathbf{p} = p\mathbf{I} + p_{\|}\hat{\mathbf{b}}\hat{\mathbf{b}} + p_{\perp}(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}),
$$

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

- 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.

Possible variants of modeling



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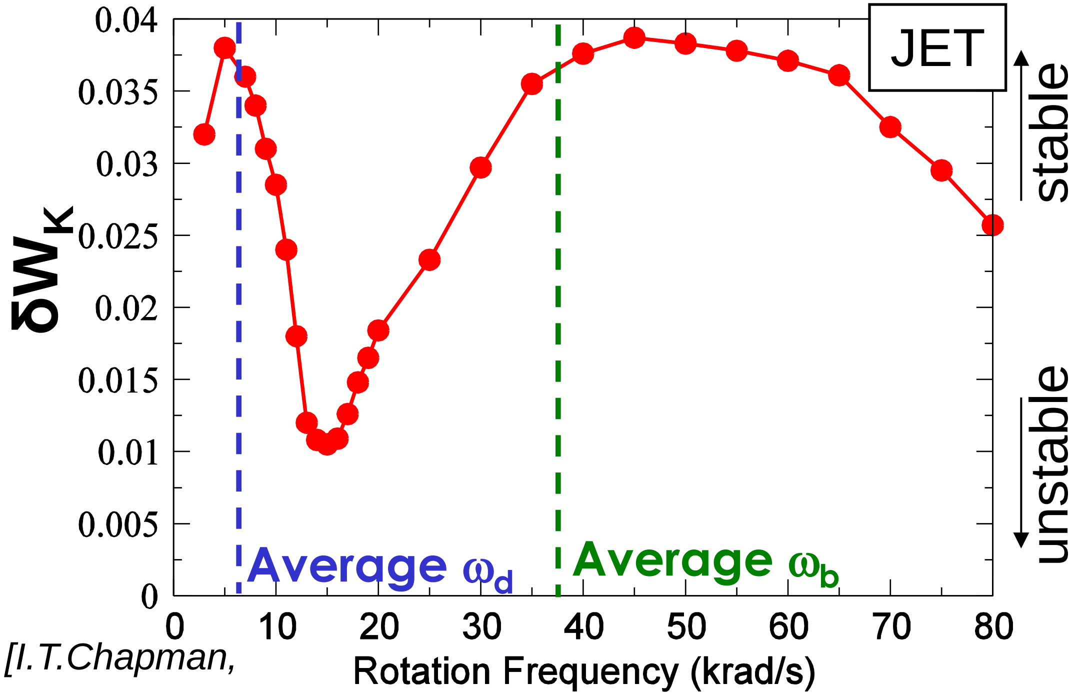
Perturbative approach. Influence of the resonances



[I.T.Chapman, PPCF, 2009]

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

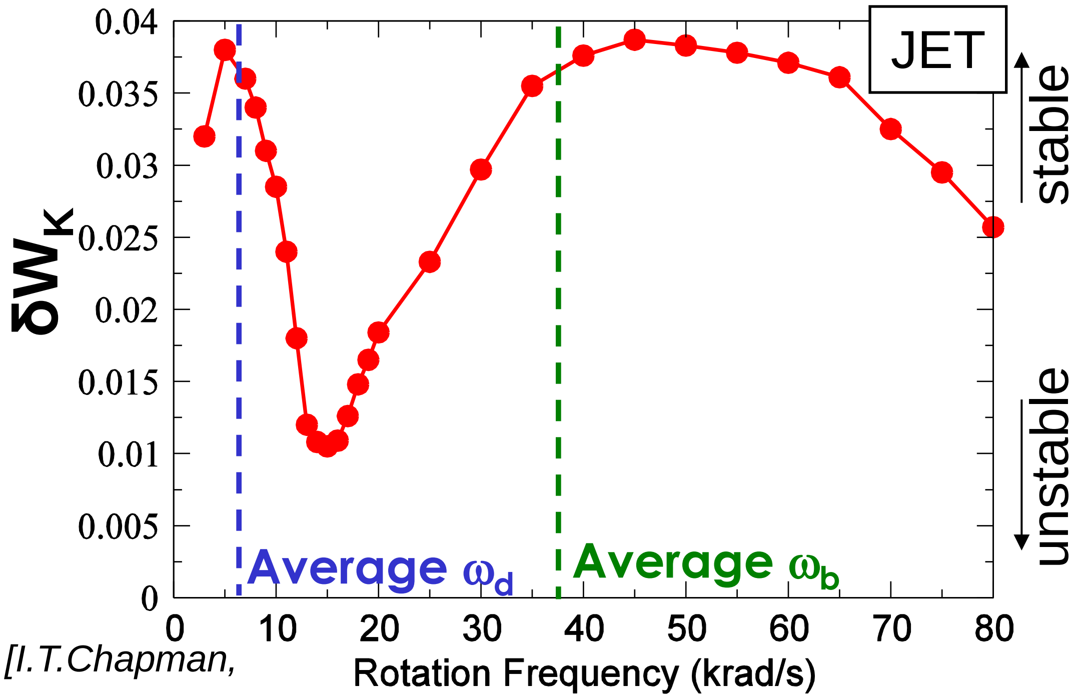
Change in mode energy has a term which contains several different resonances

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

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

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



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$$\omega_d << \omega_b < \omega_t$$

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

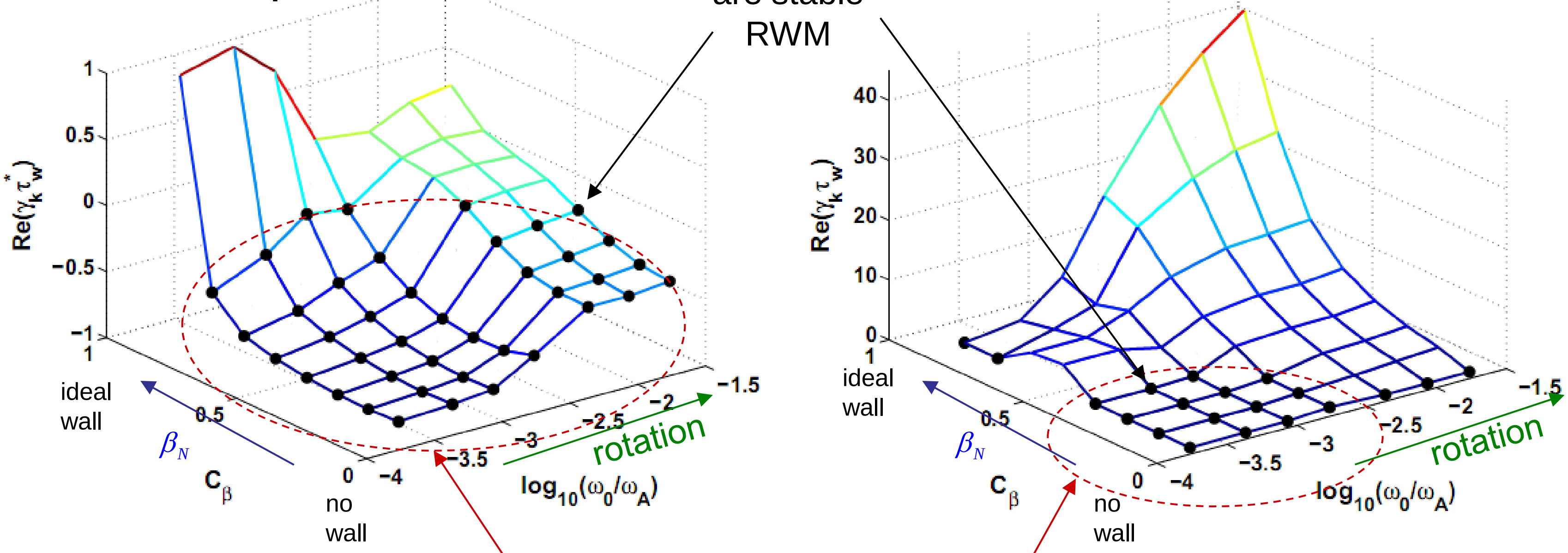
Bounce Frequency $\omega_b \sim \sqrt{r/R}\,(v_{th}/R)$

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

Different resonances are important! & Low frequencies are important!

Application of both models for ITER

[Liu, NF,2009, IAEA, 2010]



perturbative

self-consistent

black dots
are stable
RWM

Stable at low rotation

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

Application of both models for ITER

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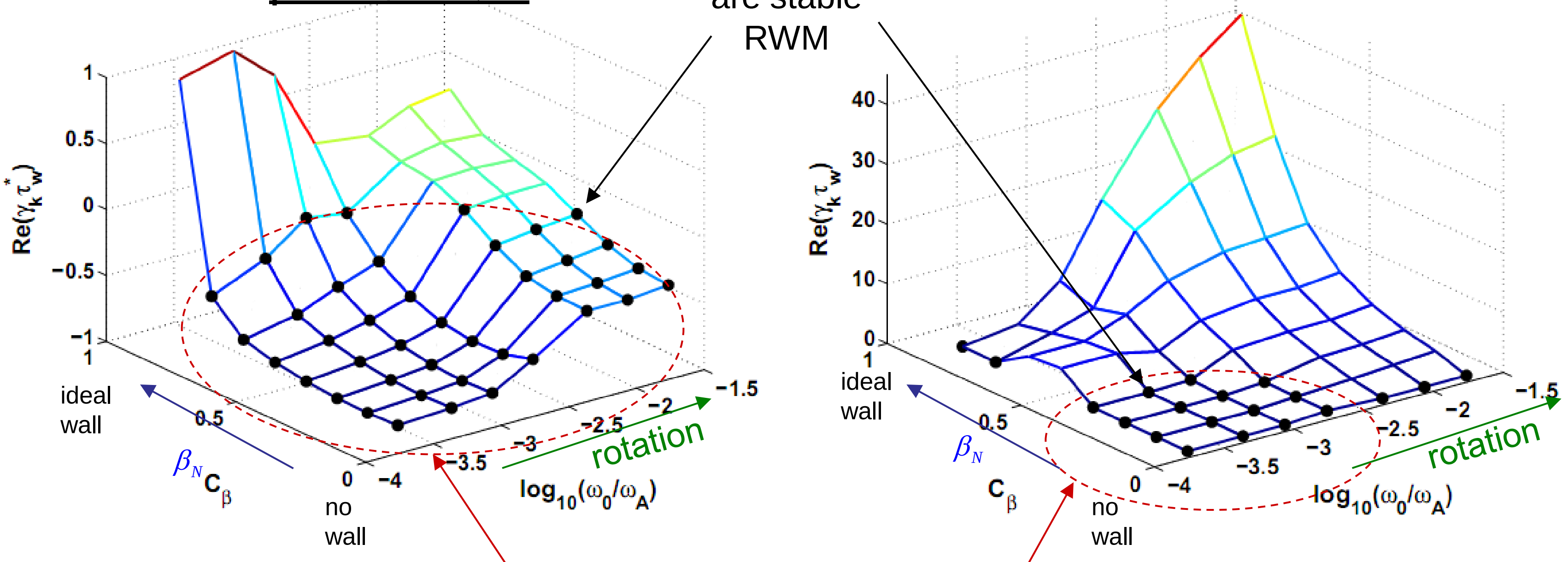


<u>perturbative</u>

<u>self-consistent</u>

black dots are stable RWM

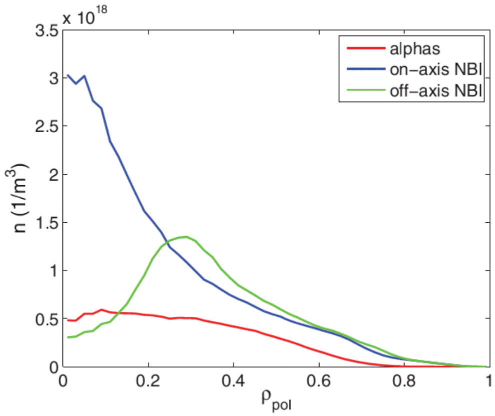
Stable at low rotation

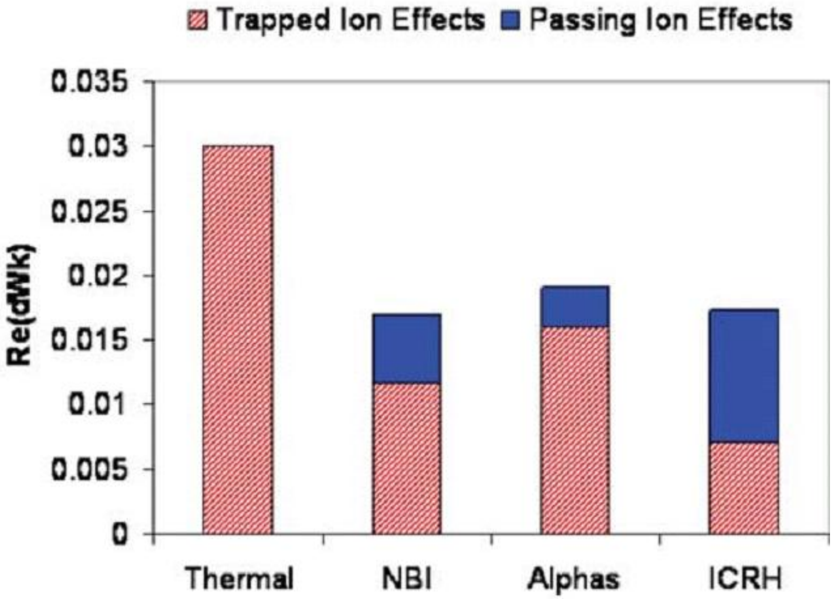
RWM is stable at low plasma rotation up to $C_\beta \leq 0.4$ without feedback due to mode resonance with the precession drifts of trapped particles.

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

Particle effects in ITER (3D perturbative approach)

ASCOT code
Particle distributions in 3D





Chapman *et al.* Phys. Plasmas **19**, 052502 (2012)

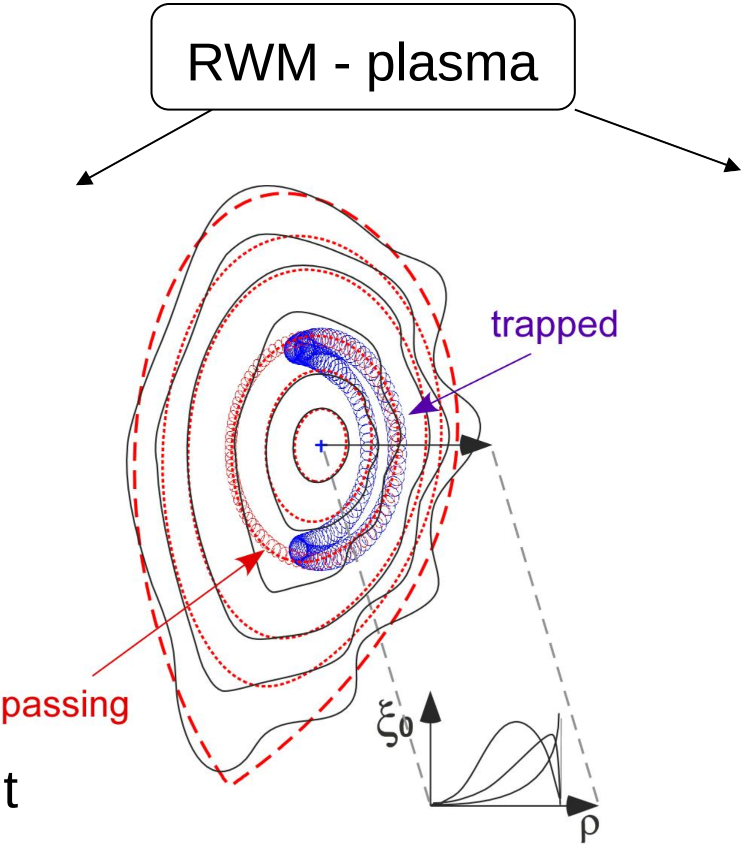
HAGIS (particle-orbit code) follows the guiding centre motion of the particles (all the relevant resonances with particle motion are included rigorously). Collisions are neglected.

$$\delta W_K = -\frac{1}{2}\int \xi_\perp^* \cdot (\nabla \cdot \widetilde{\mathbb{P}}_K)\,dV$$

perturbed pressure tensor which can be found by taking moments of the perturbed distribution function, which itself can be found by solving the linearised drift kinetic equation

Real distributions has to be taken into account!

Summary: RWM interaction with plasma



Landau damping, resonant interaction

Main resonances:
- precession drift frequency
- bounce frequency

Mainly thermal particles are important

- Conservation of magnetic flux through the particle orbit, non-resonant interaction
- Finite orbit width effects

Mainly fast particles are important

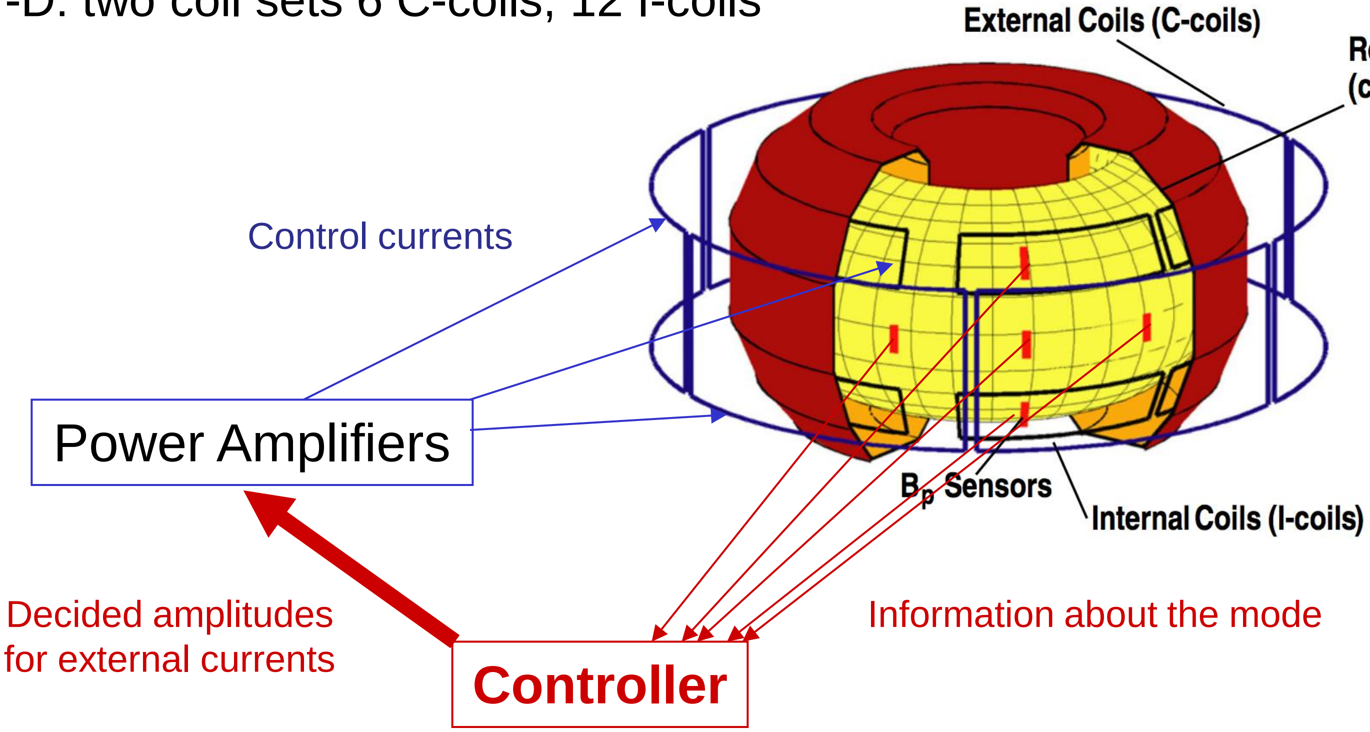
$$\omega_{RWM} \approx n\omega_{resonance}$$

$$\omega_{RWM} << \omega_{particle}$$

Control of RWMs and 3D effects

Control by external magnetic coils

DIII-D: two coil sets 6 C-coils, 12 I-coils



Control currents

Power Amplifiers

Decided amplitudes
for external currents

Controller

Information about the mode

Control algorithm

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

RWM physics in tokamak

Reversed Field Pinch:
- small plasma rotation
- small particle effects

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~~

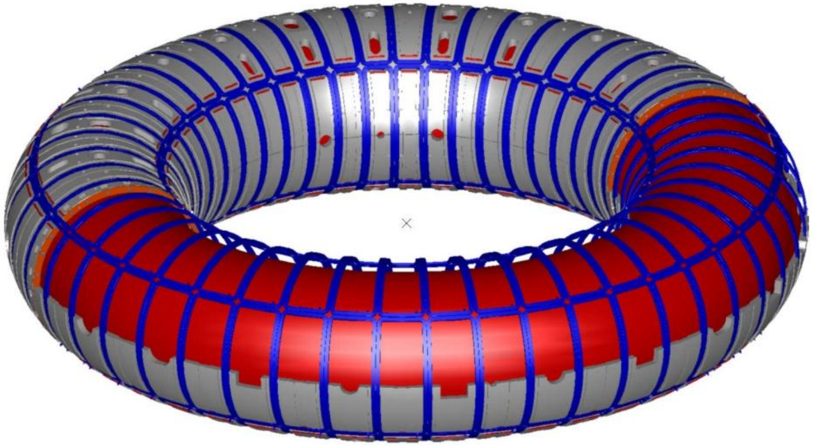
~~Wave-particle interaction~~

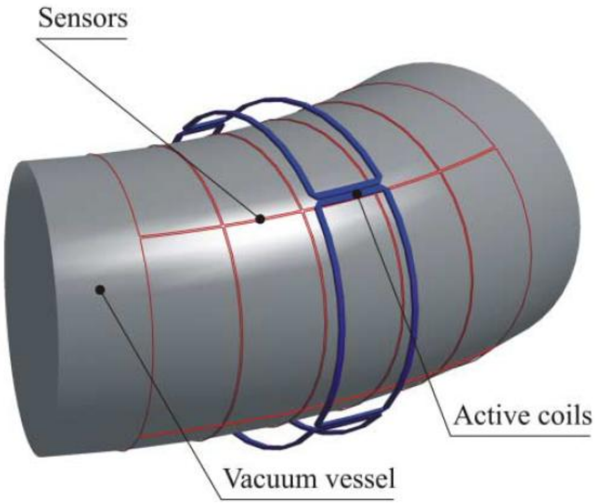
~~Physics: **kinetic description of the plasma-wave interaction**~~

Why the RFPs for RWM study?

The main advantages for RWM study:

- full coverage of the surface
- large number of coils
- flexible control of the coils currents
- possibilities to run tokamak configuration (current driven RWMs)

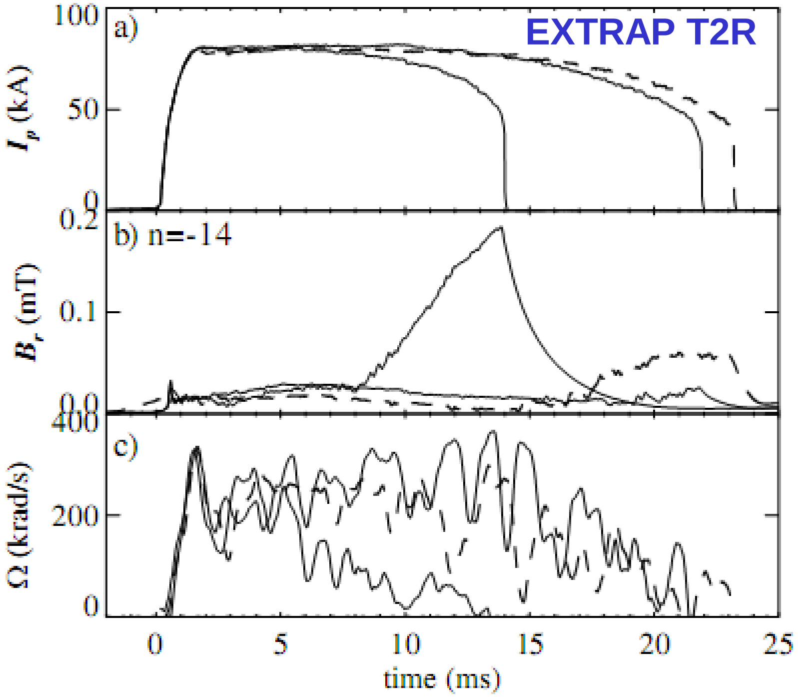




RFX-mod control system is made by 192 active saddle coils, each independently fed. 100% coverage of the plasma surface.

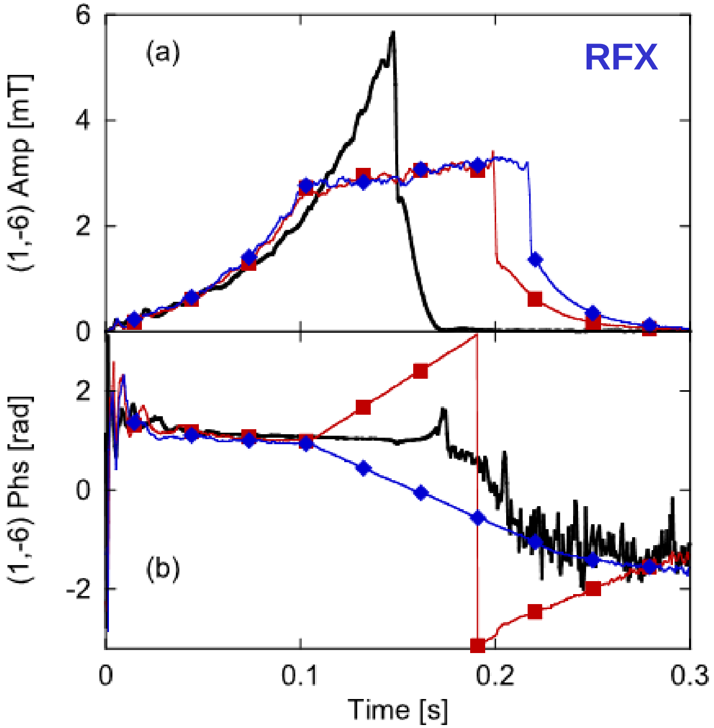
What one can achieve in RFPs with external coils ?

Feedback Stabilization of Multiple Resistive Wall Modes



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

Decoupling and active rotation of a particular RWM

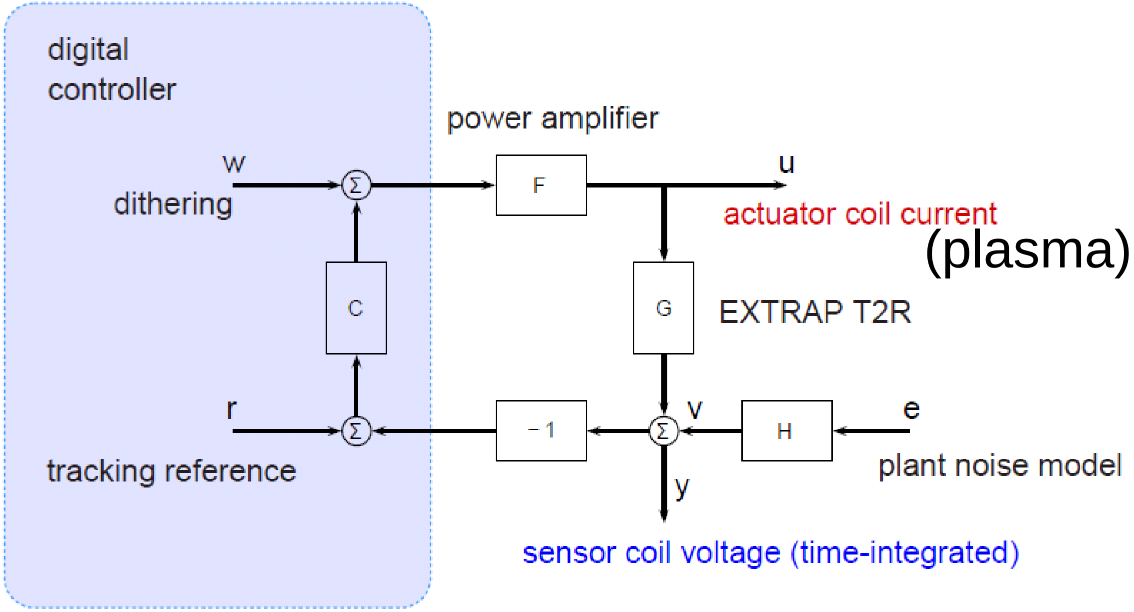


[T. Bolzonella, V. Igochine, et.al., PRL, 2008; V. Igochine, T. Bolzonella, et.al., PPCF, 2009]

Close loop system identification (reversed field pinch)

<u>Control theory has deeply developed tools which can be applied to MHD control.</u>

Example: Dithering technique in EXTRAP T2R



digital controller

power amplifier

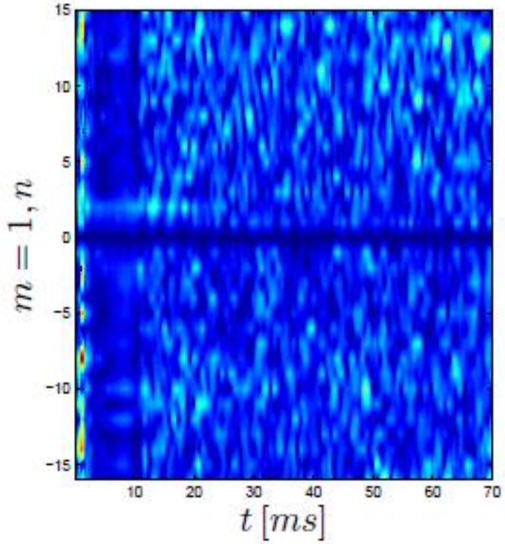
actuator coil current

(plasma)

EXTRAP T2R

plant noise model

sensor coil voltage (time-integrated)

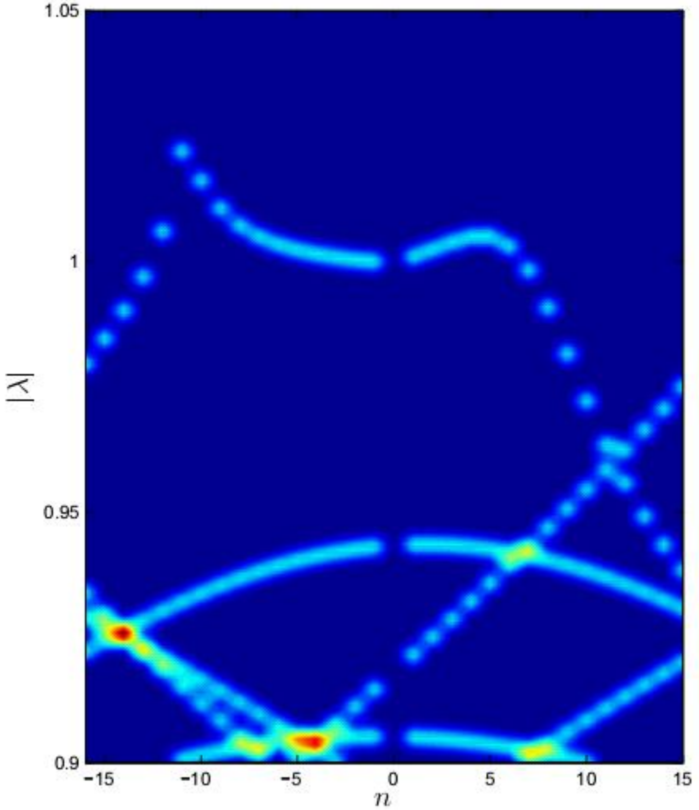


E. Olofsson et al, “Closed loop direct parametric identification of magnetohydrodynamic normal modes spectra in EXTRAP T2R reversed-field pinch,” Proceedings of the 3rd IEEE Multi-conference on Systems and Control (MSC) July 2009

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

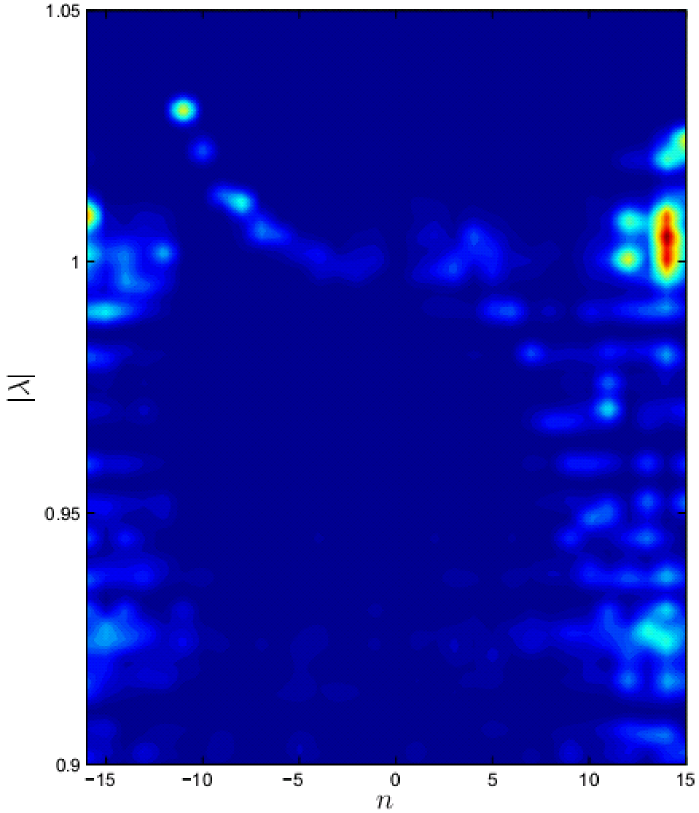
Cylindrical stability vs. Dithering in reversed field pinch

Modeled picture



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

Experimental picture

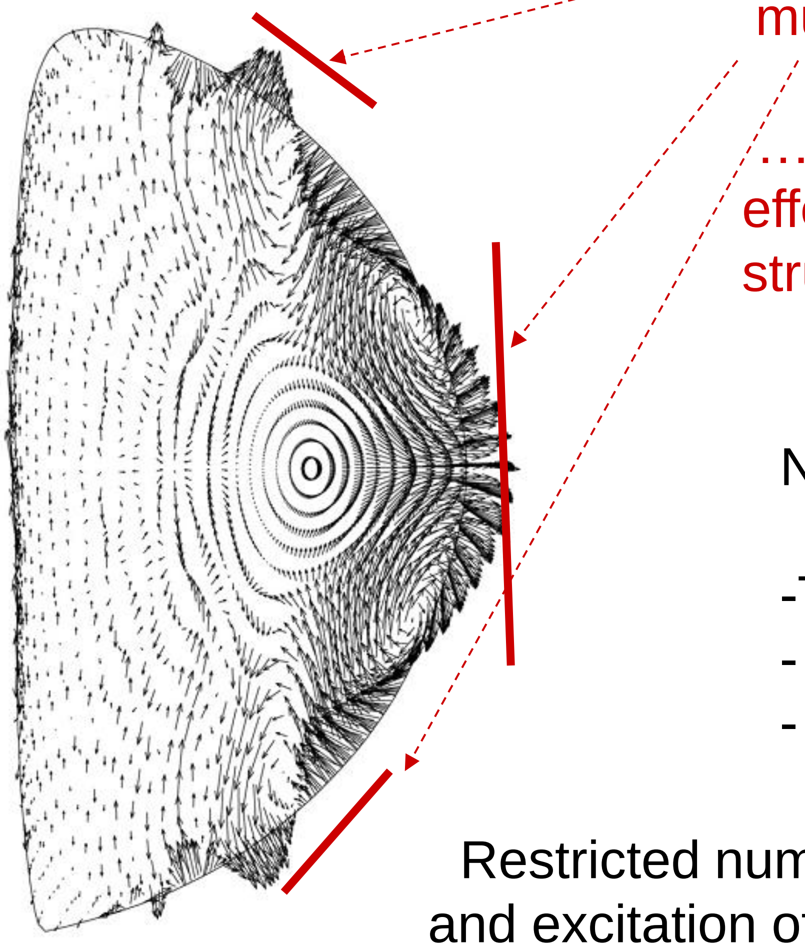


(b) Growth-rate and spatial spectrum of eigenvectors of the autodetected empirical A-matrix.

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

Resistive Wall Mode (RWM)

[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.

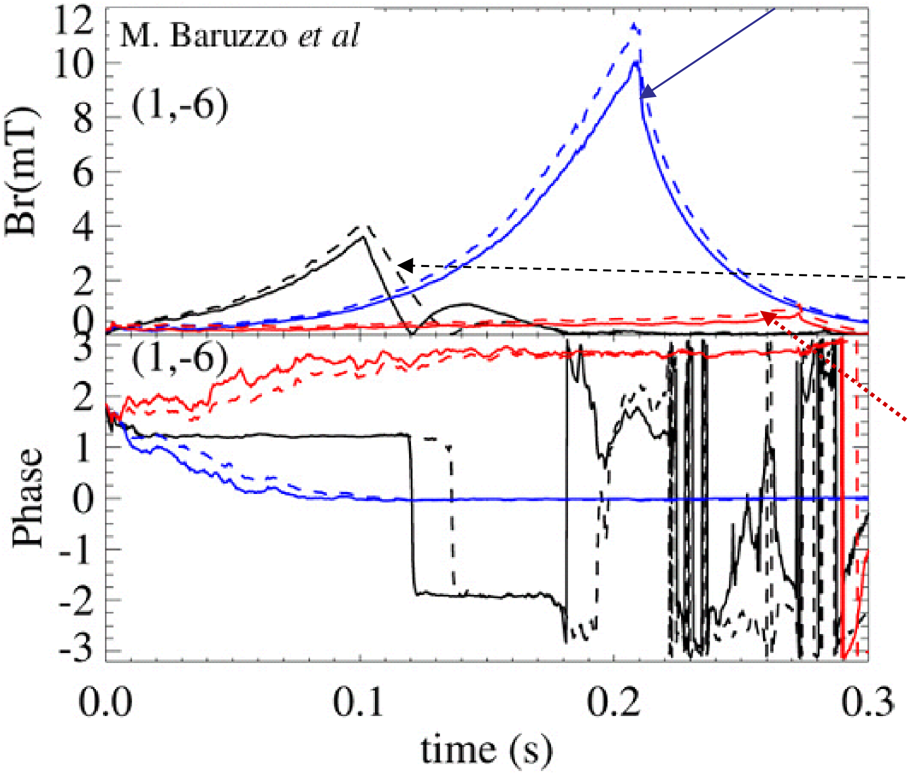
Number of the coils is restricted by:

-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)

Reduced set of control coils: limitations

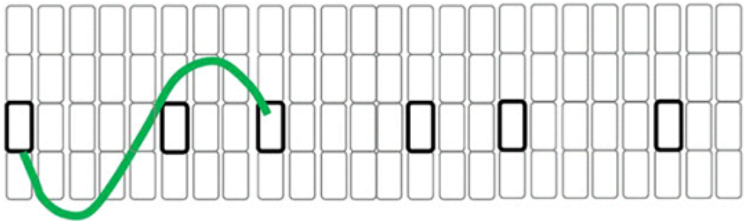
control with 12x1 coils, evenly spaced coils



The mode moves towards a minimum of feedback action, and then grows.

(m=1,n=-6) reference free growth until 0.1s and then full control

control with 12x1 coils, unevenly spaced coils



Reduced set of coils:

- provide sidebands (could excite other resonances)
- require much higher gains for stabilization (limits for coil current system)

Details in D Yadikin et al. Plasma Phys. Control. Fusion 48 (2006) and M. Baruzzo et al Nucl. Fusion 52 (2012)

Difference between current driven and pressure driven RWMs

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

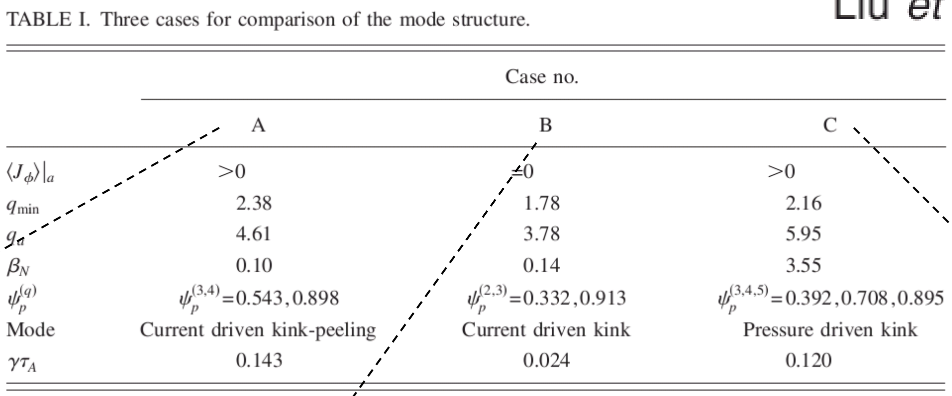
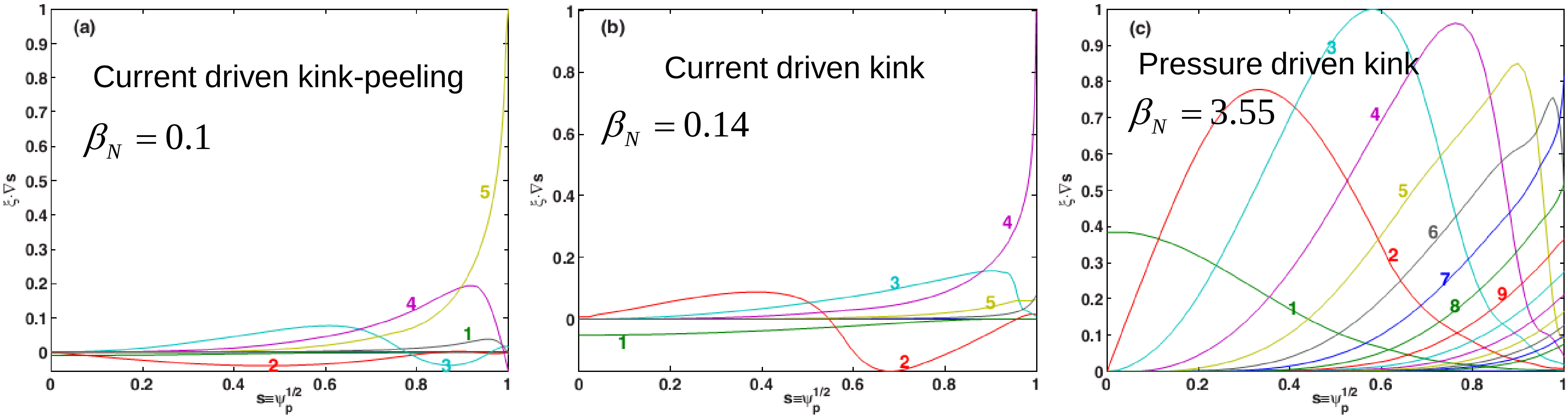


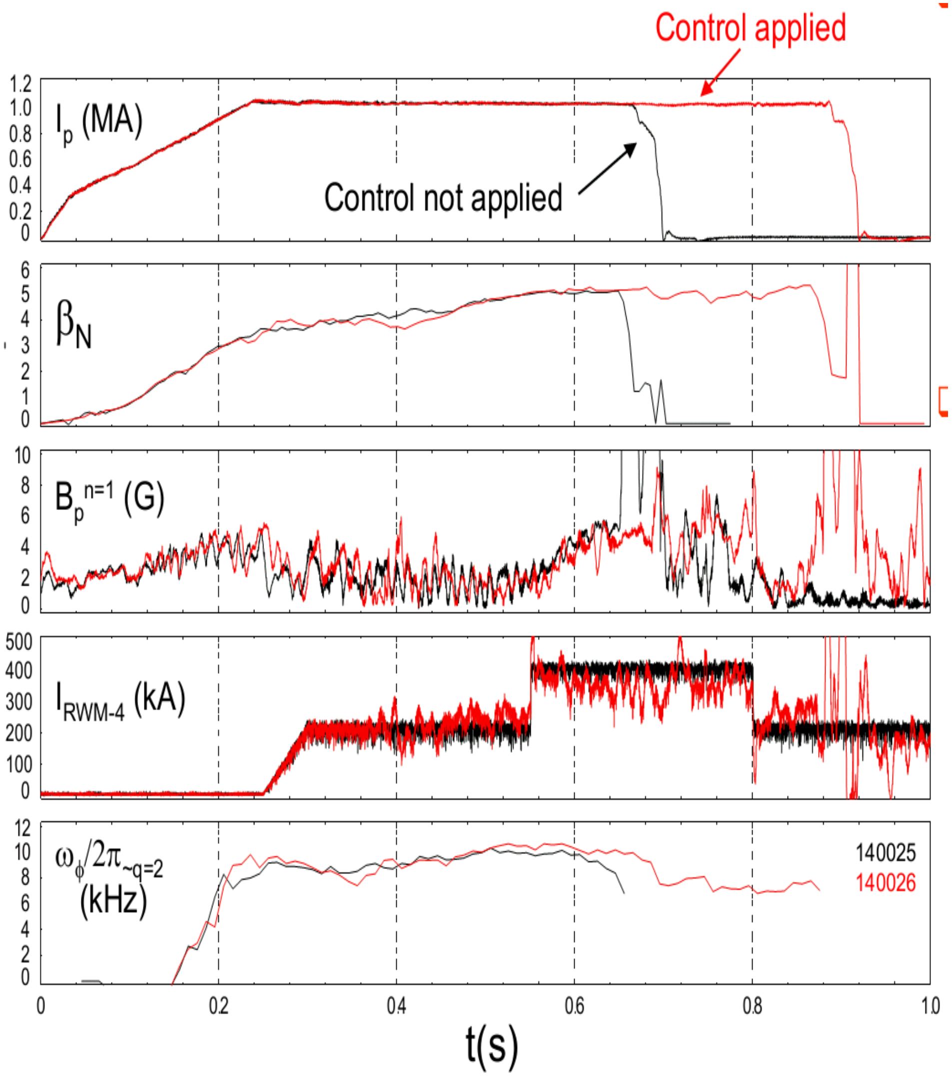
TABLE I. Three cases for comparison of the mode structure.

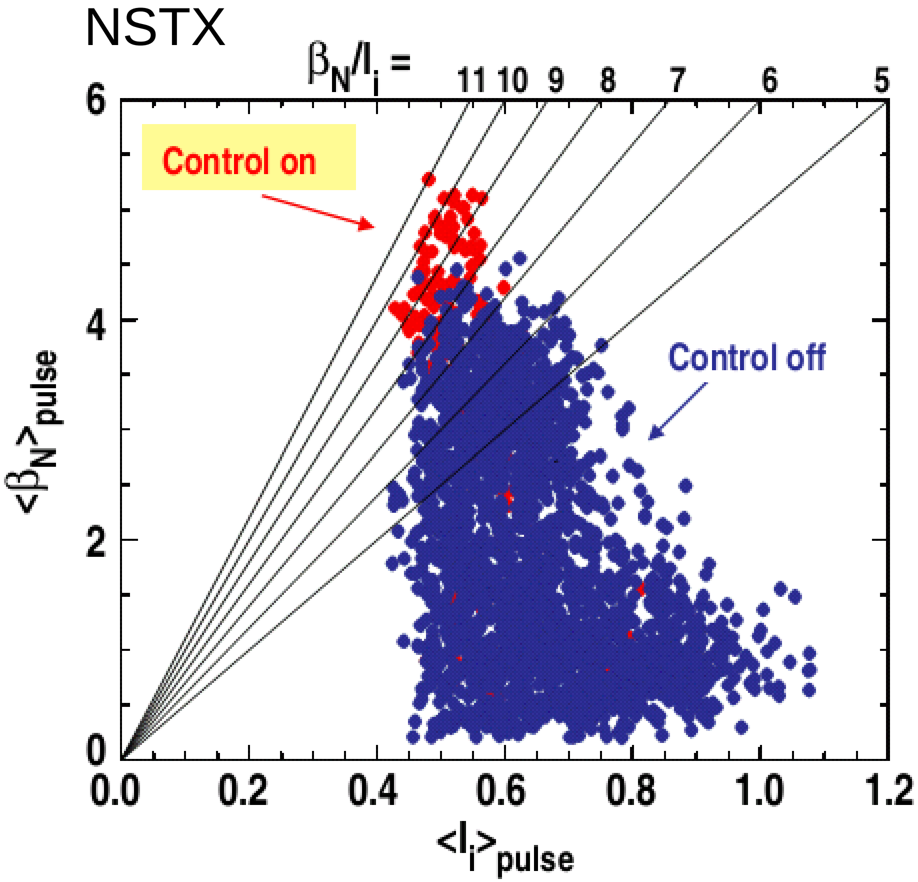
	Case no.		
	A	B	C
$\langle J_\phi \rangle \vert_a$	>0	$=0$	>0
$q_{\min}$	2.38	1.78	2.16
q_a	4.61	3.78	5.95
β_N	0.10	0.14	3.55
$\psi_p^{(q)}$	$\psi_p^{(3,4)}=0.543, 0.898$	$\psi_p^{(2,3)}=0.332, 0.913$	$\psi_p^{(3,4,5)}=0.392, 0.708, 0.895$
Mode	Current driven kink-peeling	Current driven kink	Pressure 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 for ITER. RFPs expertise is not applicable here!

Importance of the n=1 control close to the pressure limit

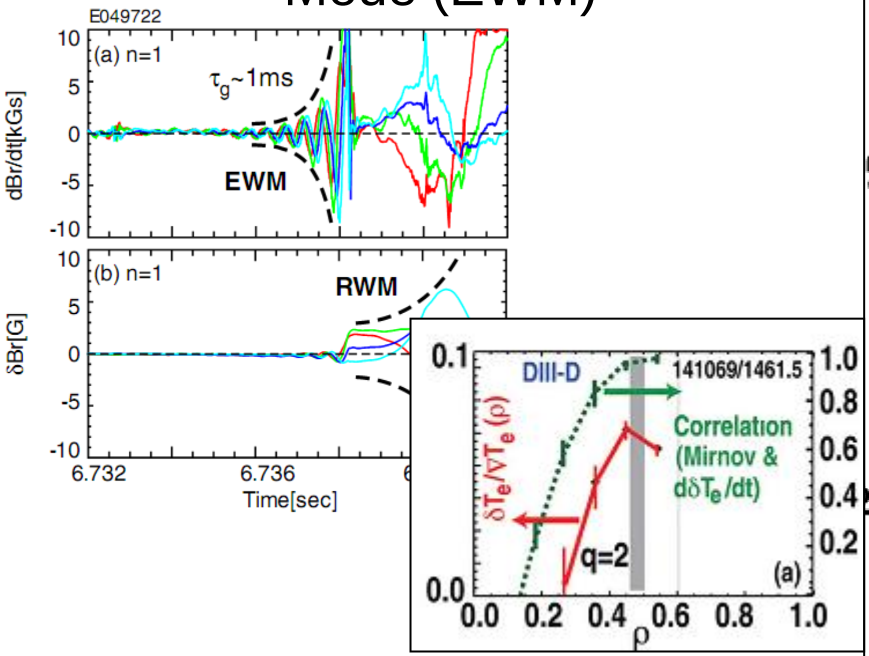




2010 *Nucl. Fusion* **50** 025020

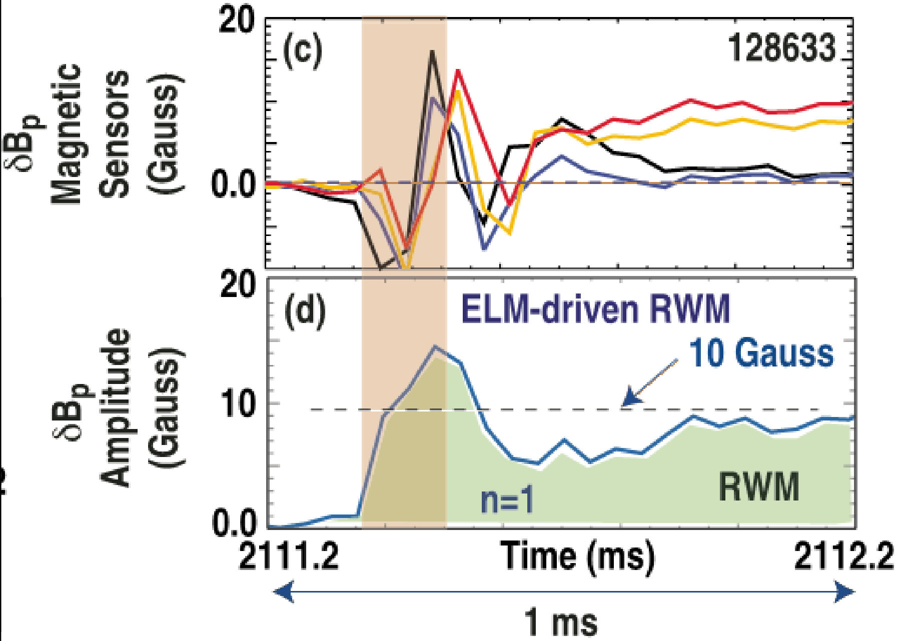
Triggers for RWM at low plasma rotation

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.

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

Conclusions

3D effects are important both for interaction of the RWM with the wall and with the plasma.

Realistic 3D geometry is required to describe RWM.

Predictions for RWM stability in tokamaks has to be based on:

- self-consistent calculations of RWM stability
- assume proper kinetic interaction with the plasma
- include 3D geometry for the wall and particle distributions