RWM control on EXTRAP T2R using various controller configurations.

See reference [1] for details of material in this presentation

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Abstract

This paper describes recent experiments in EXTRAP T2R [references 1-3].

Various controllers (P, PD, PI, and PID) have been used.

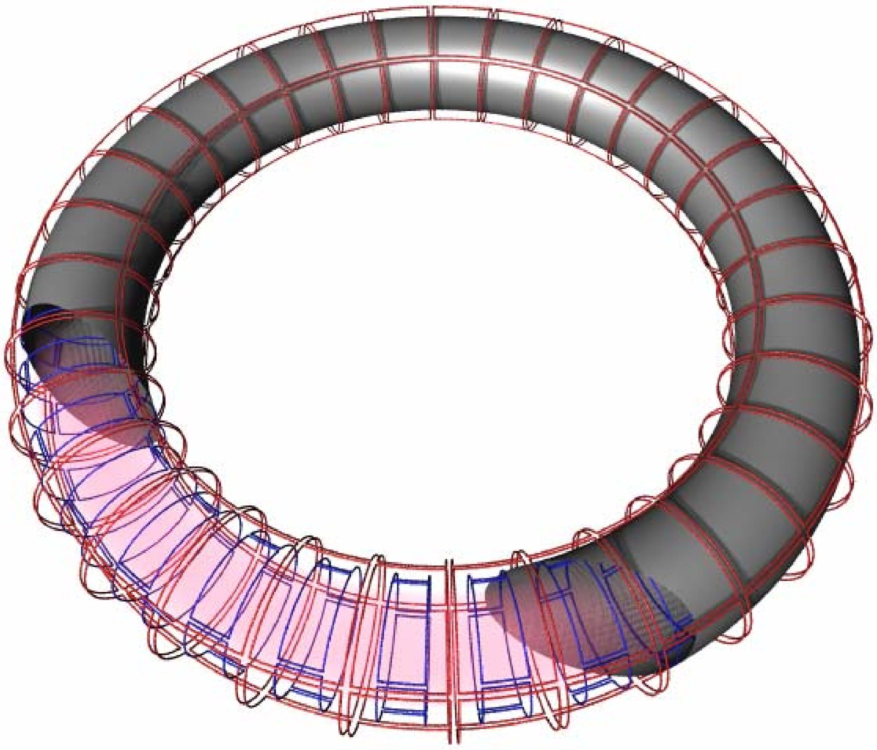
Aim is to study the improvement in the level of RWM suppression as a function of the controller configuration and gains.

Features and Characteristics of EXTRAP T2R reversed-field pinch that are important when considering contributions to the general RWM control database [4]

- High aspect ratio RFP (R/a = 6.6)
- Shell penetration time = 6.8 ms.
- There are about 10-12 unstable RWMs modes in the in the range $-11<n<+6$.
- Feed back control of RWMs and field errors is possible for the range in the range $-16<n<16$.
- A first order linear model for the plasma works for simulation of the controller dynamics.

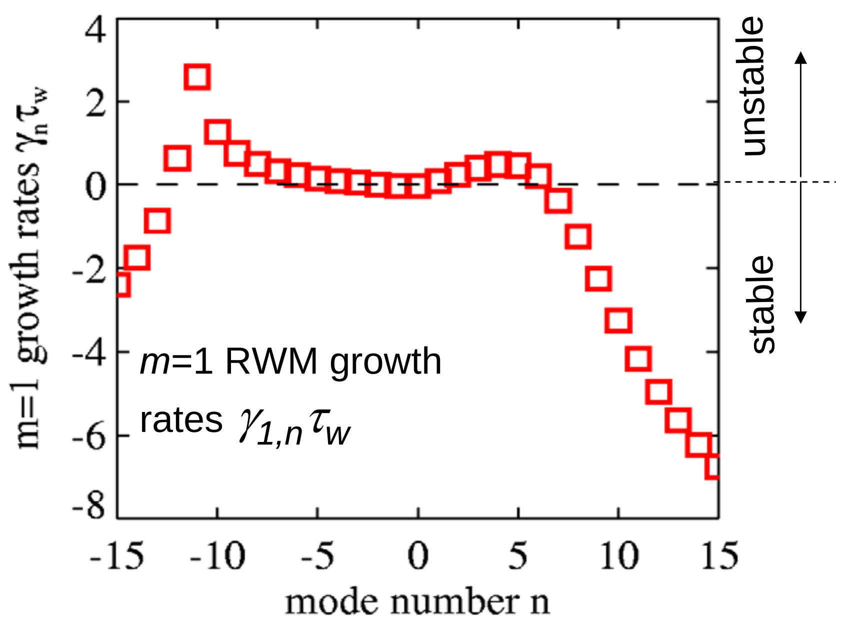
EXTRAP T2R Sensor coil array and actuator coil array [4]

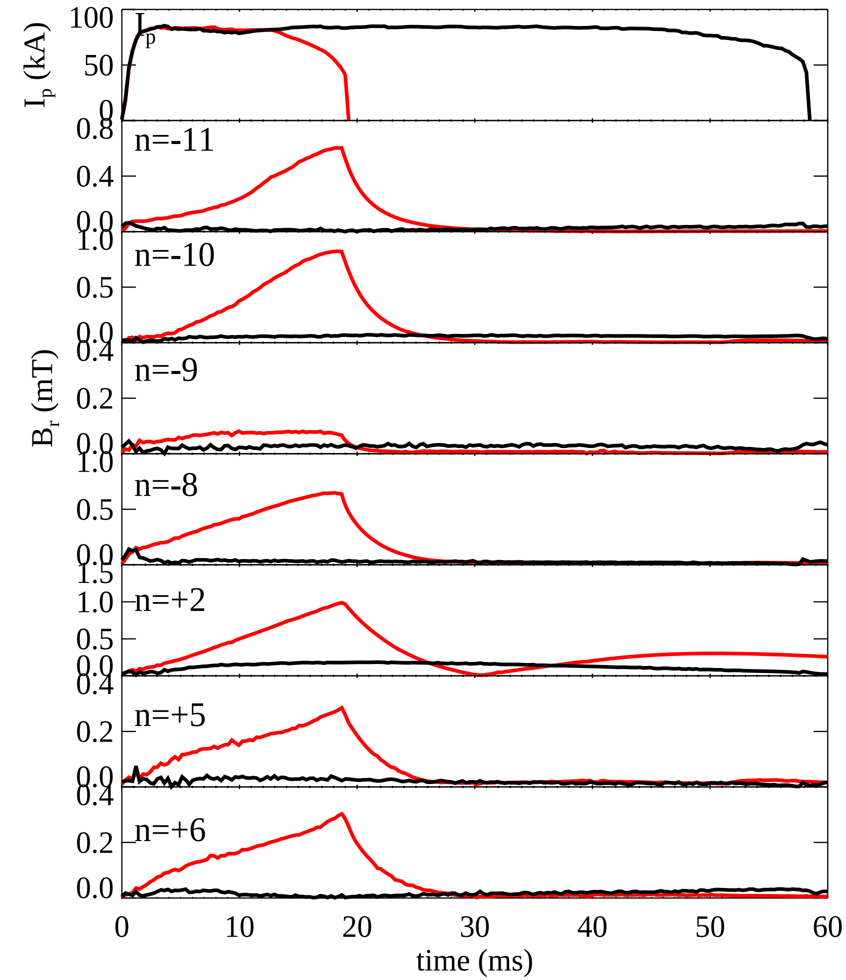
- 128 active saddle coils at 4 poloidal and 32 toroidal positions outside shell at c/a=1.3.
- 128 radial field flux loop sensors, installed at the internal surface of the shell
- Active coils (and sensor loops) are m=1 series connected.
- 64 m=1 B-radial sensor inputs to controller.
- 64 active coil current sensors.
- 64 active coil amplifier control voltages.
- Cycle time is 0.1 ms.



Intelligent Shell Feedback [5, 6]

- Full coverage with saddle coils is sufficient for stabilisation of all the unstable RWMs.
- Each active coil and coincident radial field sensor coil form a subsystem.
- Full PID controller action is incorporated.





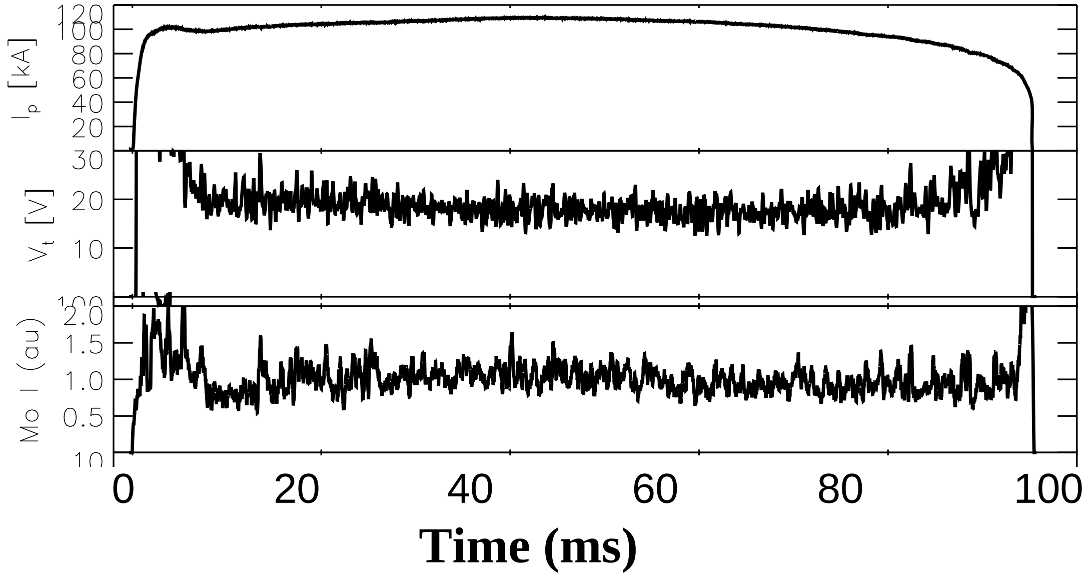
Discharges with and w/o feedback.
The panels are as follows: plasma current, modes m=1, n=-11, -10, -9, -8, +2, +5, +6.

96-ms pulse

Current (105 kA max)

Loop voltage (17 V min)

Mo I line radiation (au)



Digital PID controller

PID controller performs the following action:

$$u(t) = K\left\{e(t) + \frac{1}{T_I}\int e(t)dt + T_D\frac{de(t)}{dt}\right\}$$

$u(t)$ controller output voltage, ***e(t)*** error input signal to controller

K proportional controller gain

$K_I = K/T_I$ integral controller gain

$K_D = KT_D$ derivative controller gain

The "DC" loop gain

$$G_0 = G_{amp} \times \frac{1}{R_{coil}} \times M \times \frac{1}{RC} \times G_{pre} \times K_{contr} = 6.5 \times 10^{-2} \times K$$

Where

$G_{amp} = 8.5$ amplifier voltage gain

$R_{coil} = 2.1\,\Omega$ coil resistance

$M = 1.0 \times 10^{-5}\ \mathrm{H}$ mutual inductance coil-sensor

$RC = 6.25 \times 10^{-4}\ \mathrm{s}$ sensor voltage integrator RC time

$G_{pre} = 10$ or 25 sensor signal pre-amplifier gains (for each signal)

K_{contr} controller gain

And

$K = G_{pre} \times K_{contr}$ is the controller gain setting, reference for the next slide.

P controller with increasing K-proportional gains

Color code:

Black: w/ FB

Red: Kp = 10

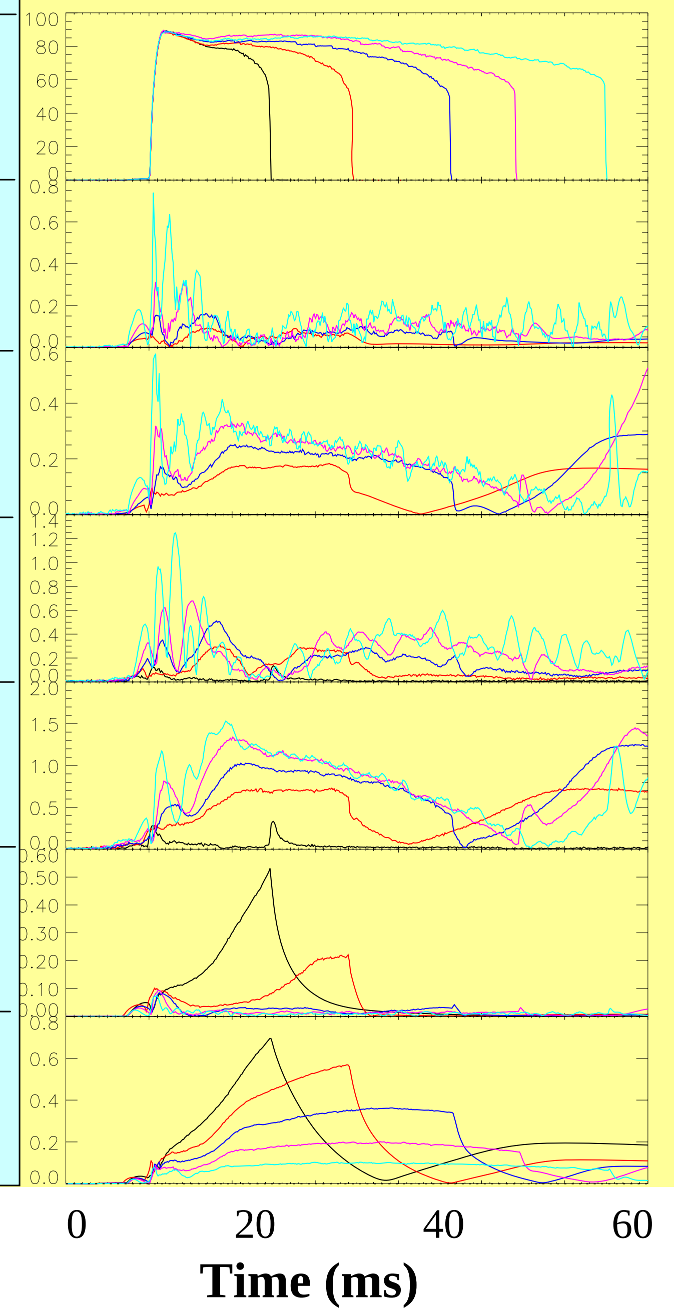
Blue : Kp = 20

Magenta: Kp = 40

Cyan: Kp = 80

Controller unstable with Kp = 160

Plasma current
n = -11 controller output voltage (V)
n = +2 controller output voltage (V)
n = -11 coil current (A)
n = +2 coil current (A)
n = -11 sensor radial field (mT)
n = +2 sensor radial field (mT)



PD controller with increasing K-derivative gains

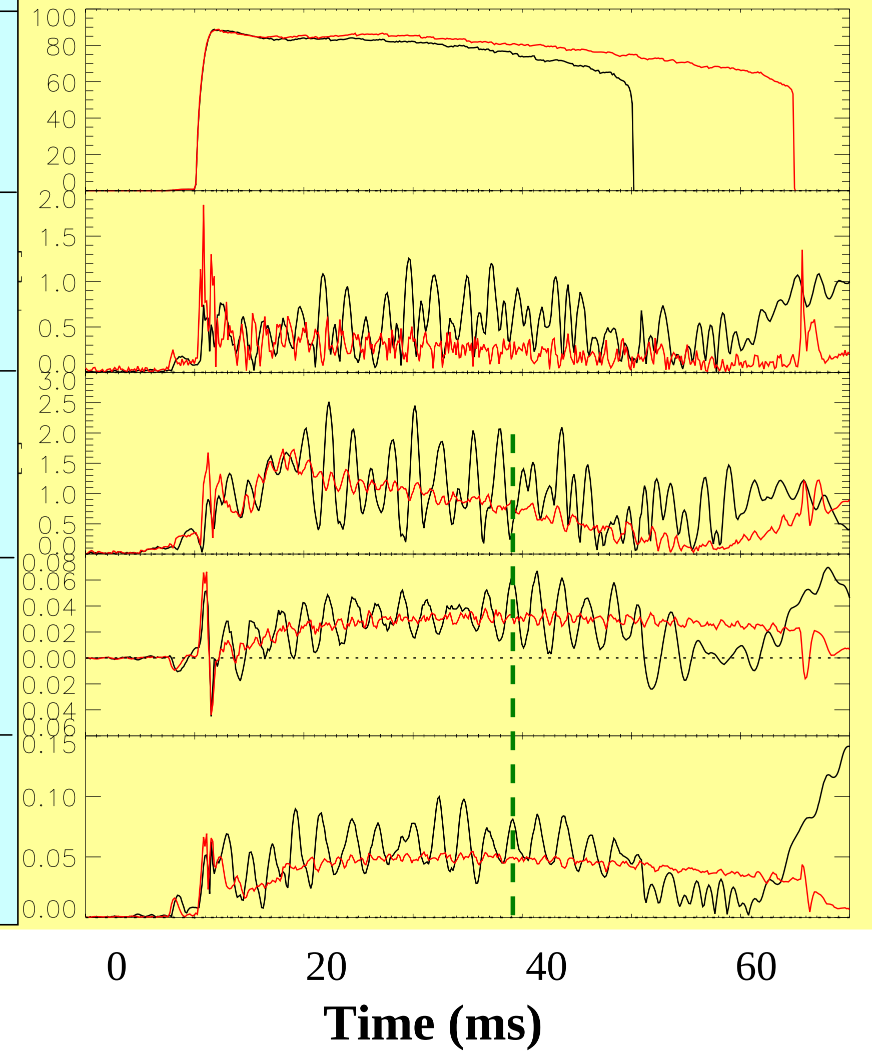
Color code:

Black:
Kp = 160
Kd = 0

Red:
Kp = 160
Kd = 0.04

Note the oscillation period is about 2.3 ms.

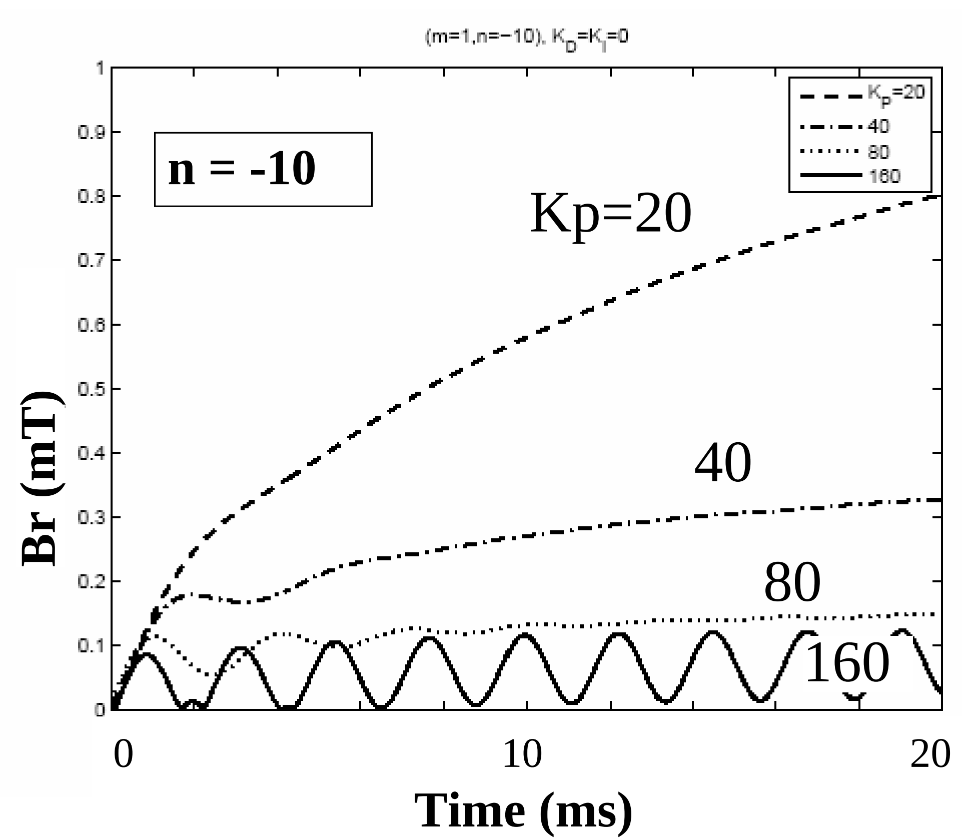
Plasma current
n = +2 controller output voltage (V)
n = +2 coil current (A)
n = +2 sensor radial field cosine (mT)
n = +2 sensor radial field (mT)



Comparison of unstable P controller with simulation based on MHD model

Erik Olofsson's presentation at this workshop will show results of simulations of the control dynamics for the actual EXTRAP T2R plant (i.e. MHD plasma 1st order DE, T2R shell, coils, controller, etc.)

Simulated controller unstable with Kp = 160



Oscillation period is about 2.3 ms.

PI controller with increasing K-Integral gains

Color code:

Kp =20 for all shots.

Black: KI = 0

Red: KI = 1000

Blue : KI = 2000

Magenta: KI = 4000

Cyan: KI = 8000

Plasma current

n = -10 controller output voltage (V)

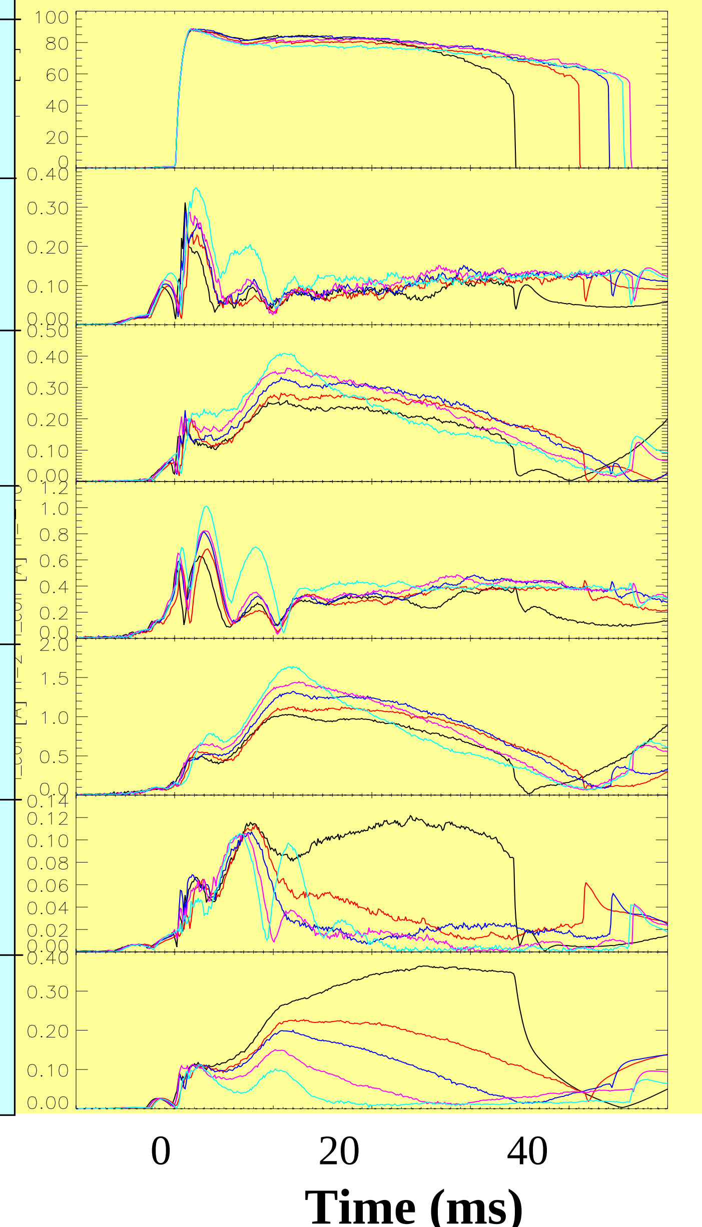
n = +2 controller output voltage (V)

n = -10 coil current (A)

n = +2 coil current (A)

n = -10 sensor radial field (mT)

n = +2 sensor radial field (mT)



PID controller with increasing K-integral gains

Color code:		
Kp = 160 Kd = 0.04 for all shots	Plasma current	
Black: **KI = 0** **Red:** **KI = 2000** **Blue:** **KI = 4000** **Magenta:** **KI = 8000** **Cyan:** **KI = 1600** **Green:** **KI = 32000**	n = +2 controller output voltage (V) n = +2 coil current (A) n = +2 sensor radial field	

Ziegler-Nichols rule of thumb [7]

Qualitative comparison of the "good" gain settings obtained in the present study with the "rule-of-thumb" for setting PID controller gains known as the Ziegler-Nichols rules, shown in Table 1.

K_o is the K_p gain where oscillations start

T_o is the oscillation period

Z-N rule of thumb

Controller	K	TI	TD
P	$0.5\ K_o$		
PI	$0.45\ K_o$	$T_o/\ 1.2$	
PID	$0.6\ K_o$	$T_o/2$	$T_o/8$

[7] J.G. Ziegler and N. B. Nichols. Trans ASME **64**, (1942) 759.

Z-K “rule of thumb” gains for EXTRAP

Qualitative comparison of the "good" gain settings obtained in the present study with the "rule-of-thumb" for setting PID controller gains known as the **Ziegler-Nichols** rules, shown in Table 1.

K_o is the K_p gain where oscillations start (160).

T_o is the oscillation period (2.3 ms).

Z-N rule of thumb

Controller	K	TI	TD
P	0.5 K_o		
PI	0.45 K_o	T_o/ 1.2	
PID	0.6 K_o	T_o/2	T_o/8

Z-N rule of thumb for EXTRAP

Controller	K	KI =K/TI	KD =K/TD
P	80		
PI	72	38000	
PID	96	83000	0.028

Comparison of “good” gains with Z-N rule

Qualitative comparison of the "good" gain settings obtained in the present study with the "rule-of-thumb" for setting PID controller gains known as the Ziegler-Nichols rules, shown in Table 1.

K_o is the K_p gain where oscillations start

T_o is the oscillation period

Z-N rule gains for EXTRAP

Controller	K	KI =K/TI	KD =K/TD
P	80		
PI	72	38000	
PID	96	83000	0.028

“Good” gains for EXTRAP

Controller	K	KI	KD
P	80		
PI	80	8000	
PID	160	16000	0.04

Summary (1)

- For intelligent shell feedback control with a P controller, mode suppression improves continuously up to the system stability limit where periodic oscillations appear.
- With a PD-controller, the stability limit is raised, allowing operation with higher proportional gain.

Summary (2)

- For a PI controller, mode suppression improves with increasing integral gain up to a limit where large slow oscillations appear, indicating the system instability threshold is reached.
- The PI controller is useful for the suppression of a mode (n=2) that is driven by an external resonant field error.
- Other modes, such as the more unstable n=-10 tend to over-shoot at higher integral gains.

Summary (3)

- The empirical values for the PID gains have been compared with those obtained by the Ziegler-Nichols rule.
- The integral gain is somewhat lower than predicted by Z-N, but the value for the derivative gain is of the same order.
- It should be pointed out that the gains were varied in large steps and the results above must be considered as preliminary, a <u>true optimization of the PID feedback gains have not yet been carried out</u>.

Summary (4)

Simulations of the PID control dynamics for the actual EXTRAP T2R plant (i.e. MHD plasma 1st order DE, T2R shell, coils, controller, etc.) agree very well with the experimental observations.

Acknowledgements

- The authors express their gratitude to the RFX team for providing the integrated digital controller module and controller software used in the present experiments on EXTRAP T2R.

References

[1] P.R. Brunsell, et al *Resistive wall mode feedback control in EXTRAP T2R with improved steady-state error and transient response*, has been published online today, 10 October 2007, in Physics of Plasmas (Vol.14, No.10)

[2] P. R. Brunsell, et al., Phys. Rev. Lett. 93, 225001 (2004).

[3] P. R. Brunsell, et al., Plasma Phys. Controlled Fusion 43 (2001) 1457

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[6] D. Yadikin, et al., Plasma Phys. Control. Fusion 48 (2006) 1-14.

[7] T. Glad and L. Ljung, Reglerteknik, Studentlitteratur, Lund, Sweden, 1981, p. 49