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Resistive wall mode feedback control experiments in EXTRAP T2R

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Introduction

The reversed field pinch (RFP) uses a conducting wall for external kink mode stabilization, which for thin shell devices gives rise to unstable resistive wall modes (RWM). For the RFP, a range of modes are unstable. Suppression of multiple RWMs was successfully demonstrated for the first time in the EXTRAP T2R reversed field pinch device [1]. This paper describes recent experiments in EXTRAP T2R using various controllers (P, PD, PI, and PID) in order to improve the level of RWM suppression.

Active MHD mode control system in EXTRAP T2R

EXTRAP T2R (major radius R=1.24 m, plasma minor radius a=0.183 m) has a thin shell (b/a=1.08) with a vertical field penetration time of 6.3 ms, the discharge length is larger than the shell time, and the growth of several independent unstable resistive wall modes (RWM) is observed. For a typical magnetic equilibrium there are unstable, non-resonant RWMs with m=1 and $-11 \leq n \leq +6$. Recent experiments on RWM feedback stabilization in EXTRAP T2R utilize an array with 128 active saddle coils at 4 poloidal and 32 toroidal positions, fully covering the conducting wall surface [2, 3]. There is a similar array of 128 flux loop sensors measuring the radial field at the wall. The sensor loops are installed at the internal surface of the shell, while the active coils are located outside the shell (c/a=1.3). Active coils (and sensor loops) are m=1 series connected in pairs (outboard-to-inboard, top-to-bottom). A digital feedback controller inputs 64 m=1 flux loop sensor signals, 64 active coil current measurements, and outputs 64 active coil amplifier control voltages. The cycle time of the digital controller is 100 μs. In the present experiments, the "intelligent shell" feedback scheme is used, which minimizes the total radial magnetic flux in the sensors. Intelligent shell experiments with a set of analog controllers and a smaller number of active coils have previously been reported [4]. In this study a digital proportional-plus-integral-plus-derivative controller (PID) is used.

The PID controller computes the output signal as follows:

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

Here $u(t)$ is the PID-controller output voltage, $e(t)$ the error input signal to controller, $K_P = K$ is the proportional gain, $K_I = K/T_I$ is the integral gain, and $K_D = KT_D$ is the derivative gain. The "DC" loop gain G_0 for only proportional control is $G_0 = 6.5\times10^{-2}\times K$

Intelligent shell feedback with P and PD controllers

Several series of discharges with intelligent shell feedback control were made, keeping the programming of the OH power supply unchanged. In the first series, only proportional (P) control was used, varying the gain ($K_p = 0,10,20,40,80,160$).

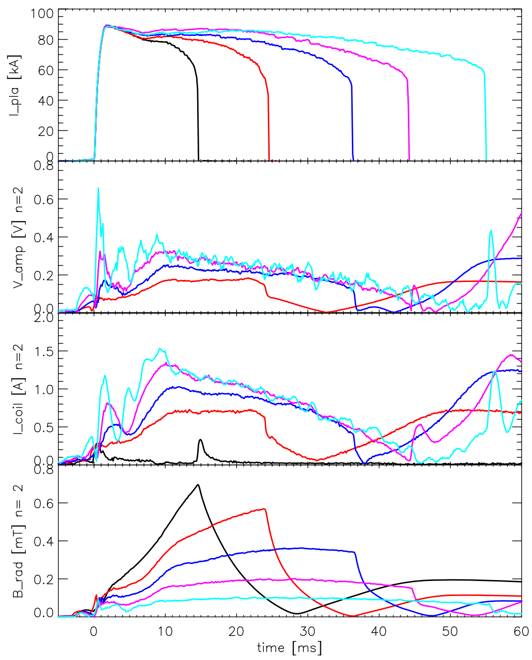

Figure 1. Intelligent shell feedback with P controller. From top: Plasma current, m=1,n=2 Fourier amplitude of controller output voltage, coil current, sensor radial field. Discharges with varying proportional feedback gain:
#20442: w/o fb (black)
#20443: K_P =10 (red)
#20444: K_P =20 (blue)
#20445: K_P =40 (magenta)
#20446: K_P =80 (cyan)

The discharge length increased continuously with the increase of the feedback gain, from 15 ms without intelligent shell feedback control to 55 ms with the feedback gain $K_p = 80$, as is shown in Figure 1. The prolongation of the discharge is coincident with better suppression of the RWM amplitudes, especially the m=1, n=2 mode. Suppression of the n=2 mode improves up to $K_p = 80$. Although the n=2 is marginally stable, is has a high amplitude due to a resonant external field error. Unstable modes that have higher RWM growth rates, such as n=-11, but low external field errors are suppressed at lower gain. At the gain $K_p = 80$, oscillations start to appear in the controller output voltage and coil current. At the highest gain $K_p = 160$ (not shown), these oscillations are sustained at large amplitude. The oscillations indicate that the feedback system is close to the stability limit, determined by the total gain margin of the system. Operation with $K_p = 160$ is possible for a proportional-plus-derivative action controller (PD). A series of PD-controller discharges with fixed proportional gain $K_p = 160$ and varying derivative gain ($K_d = 0.01, 0.02, 0.04, 0.08$) was performed, demonstrating operation without oscillations for $K_d = 0.04$.

Intelligent shell feedback with PI and PID controllers

A series of experiments with a proportional-plus-integral controller (PI) was carried out with the proportional gain fixed at $K_p = 80$ and varying integral gain $K_I = 0, 4000, 8000$. The suppression of m=1, n=2 continuously improved with higher integral gain, as shown in Figure 2.

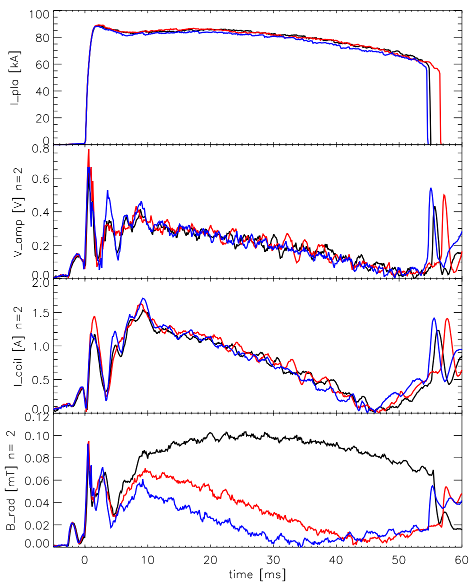

Figure 2. Intelligent shell feedback with PI-controller. From top: Plasma current, m=1,n=2 Fourier amplitude of controller output voltage, coil current, sensor radial field. Discharges with fixed proportional feedback gain (K_P=80) and varying integral gain:
#20446: K_P=80, K_I =0 (black)
#20465: K_P=80, K_I =4000 (red)
#20466: K_P=80, K_I =8000 (blue)

The n=2 mode is driven by a slowly varying external resonant field error, and it is apparent that the integral gain is useful in order for the feedback system to compensate this error field. Other modes, such as the more unstable n=-10 tend to show oscillations at higher integral gains. The simultaneous use of derivative and integral gains in a proportional-plus-integral-plus-derivative controller (PID) resulted in the best mode suppression. A series of discharges was made with fixed proportional and derivative gain $K_p = 160$ $K_d = 0.04$ and increasing integral gains $K_I = 0, 2000, 4000, 8000, 16000, 32000$, shown in Figure 3. In order to compare the performance of the various controllers, the maximum amplitude of n=2 after the initial transient behavior (t>5 ms), is measured for P, PI and PID controllers with "good" gain settings. The amplitude is reduced from $B_{1,2} \approx 0.7$ mT without feedback to $B_{1,2} \approx 0.1$ mT (14%) with P-control ($K_P = 80$), and further to $B_{1,2} \approx 0.05$ mT (7%) with PI-control ($K_P = 80, K_I = 8000$), and finally to $B_{1,2} \approx 0.02$ mT (3%) with PID control ($K_P = 160, K_I = 32000, K_D = 0.04$).

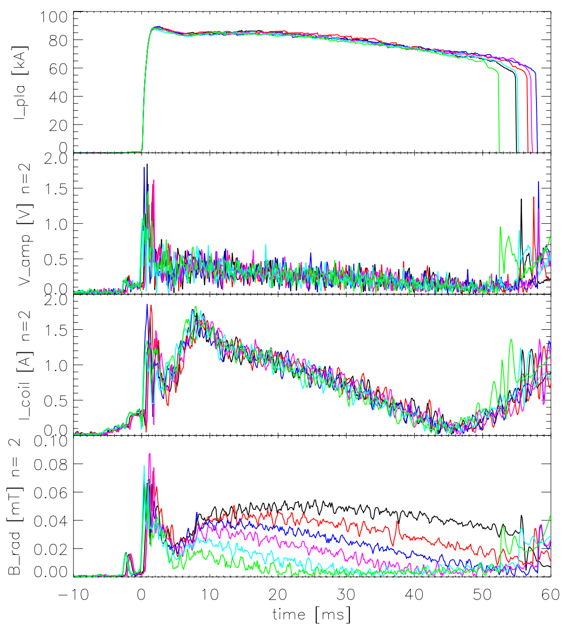

Figure 3. Intelligent shell feedback with PID-controller.
From top: Plasma current, m=1, n=2 Fourier amplitude of controller output voltage, coil current, sensor radial field. Discharges with fixed proportional and derivative feedback gains (K_P=160, K_D=0.04) and varying integral gains K_I:
#20450: K_I=0 (black)
#20453: K_I =2000 (red)
#20454: K_I =4000 (blue)
#20455: K_I =8000 (magenta)
#20456: K_I =16000 (cyan)
#20457: K_I =32000 (green)

Summary

Experiments in EXTRAP T2R on RWM stabilization using intelligent shell feedback with a P-controller showed that mode suppression improves with increasing gain up to the system stability limit. A PD-controller gives faster response and allows operation with higher gain. The PI-controller is useful for suppression of modes driven by external resonant field error. Best mode suppression was in the present study achieved with a PID-controller.

References

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