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# Intelligent shell feedback control of resistive wall modes in EXTRAP T2R

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## 1 Introduction

An active feedback system is required for suppression of resistive wall modes (RWMs) in the reversed field pinch (RFP) device because of non-rotating nature of RWMs[1]. An array of discrete active coils distributed in the toroidal and poloidal directions is used in the active feedback system. A general feature of the feedback system with discrete active coils is the side band effect [2], when infinite number of a side band modes is produced in order to stabilize selected perturbation.

A spectrum of unstable RWMs is present in EXTRAP T2R RFP device[3] with poloidal mode number $m = 1$ and a range of toroidal mode numbers $n$[4]. They are converted from non-rotating non-resonant ideal MHD kink modes as a resistive wall is placed close to the plasma column. The growth time of unstable RWMs is of the order of the resistive wall time $\tau_w$. An active feedback system with discrete active coils is used in recent experiments on the EXTRAP T2R to suppress unstable RWMs[5]. The intelligent shell[6] is one of the feedback schemes used for the RWM suppression. It was found during experiments that two unstable RWMs were coupled by the side band effect making it difficult to suppress them simultaneously by the intelligent shell. Therefore it is important to study the appearance of the side band effect during feedback. Active feedback systems with different number of active coils in the toroidal and poloidal directions having different side band effect is studied here. The relation between side band modes is obtained for the intelligent shell feedback scheme.

## 2 Experimental setup

The EXTRAP T2R[3] is a medium sized RFP device with aspect ratio $R/a = 1.24\ m/0.183\ m$. A resistive shell is installed at the minor radius $r_w = 0.198$. The shell has a vertical magnetic field penetration time $\tau_w = 6.3\ ms$. The RFP equilibrium is defined by the parameters $\Theta = B_\theta(a)/ < B_\phi >$ and $F = B_\phi(a)/ < B_\phi >$, where $B_\theta(a), B_\phi(a)$ are the edge values of the poloidal and toroidal magnetic fields respectively and $< >$ is the average over the plasma column.

Radial perturbed magnetic field is measured by a diagnostic array of 256 flux loops placed at the minor radius $r_s = 0.197\ m$ just inside the shell. The array is distributed at 4 poloidal and 64 toroidal positions. The width of the single sensor is $\Delta\theta_s = 90°$ poloidally and $\Delta\phi_s = 5.625°$ toroidally giving $100\%$ coverage of the toroidal surface by the diagnostic array. For these experiments sensors at one toroidal position are connected to form cosine (in-out) and sine (top-bottom) $m = 1$ pairs. Using the diagnostic array, modes with poloidal mode number $m = 1$ and toroidal mode numbers $n = -31..32$ are resolved.

A feedback system is installed in EXTRAP T2R in order to actively control unstable RWMs. The active part of the feedback system is an array of 128 saddle coils distributed at 4 poloidal and 32 toroidal positions. Coils are placed at the minor radius $r_c = 0.238\ m$ outside the shell. The width of the single active coil is $\Delta\theta_c = 90°$ poloidally (same as the sensor width) and $\Delta\phi_c = 11.25°$ toroidally (twice the sensor width). This gives $100\%$ coverage of the toroidal surface by the active coil array. Active coils at one toroidal position are connected to form cosine and sine $m = 1$ pairs similar to the diagnostic array. The sensor part of the feedback system is a subset of the diagnostic array having 128 sensors distributed at 4 poloidal and 32 toroidal positions coincident with the active coils.

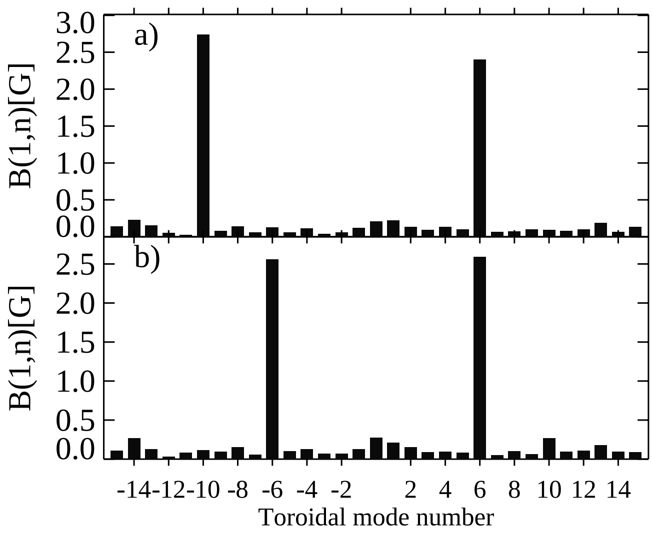


**Figure 1** *The vacuum mode spectrum of* $m = 1$ *RWMs; a)* $4 \times 16$ *active coil configuration; b)* $2 \times 32$ *active coil configuration. A current harmonic with* $m = 1, n = 6$ *is created in the active coil array.*

For these experiments, half of the active coils are used giving $50\%$ coverage of the toroidal surface. Two active coil configurations are studied here: $M \times N = 4 \times 16$ configuration having $M = 4$ active coils in the poloidal and $N = 16$ coils in the toroidal direction; $M \times N = 2 \times 32$ configuration having $M = 2$ coils in the poloidal and $N = 32$ coils in the toroidal directions.

The intelligent shell feedback scheme with analog PID controllers [7] is used in these studies. The proportional, integral and derivative gains of the analog controller is set to $K_p = 50,\ K_i = 0.5 \cdot 10^5,\ K_d = 0.5 \cdot 10^{-2}$ respectively. The proportional gain value corresponds to a total loop gain [5] of around $G = 50$.

# 3 Side band effect

The discrete active coil configuration used in the feedback system causes a side band effect [2, 8]. In order to suppress a perturbation with mode numbers $m_0, n_0$, a current distribution with the same mode numbers is created in the active coil array. Because of the discrete active coil array, the magnetic field produced by the current distribution has infinite number of side bands with mode numbers $m = m_0 \pm i \cdot M,\ n = n_0 \pm j \cdot N$ where $M, N$ is the number of active coils in the poloidal and toroidal directions respectively and $i, j$ are the arbitrary integers.

Two active coil configurations are used in these experiments with different numbers $M, N$ and therefore different sets of side band modes. The side band effect on the $m = 1$ mode spectrum is seen in figure 1. Here the vacuum spectrum of the mode amplitudes is plotted. The active feedback system is used in open loop operation to produce a stationary perturbation with $m = 1, n = 6$. Measurement is shown for $t \gg \tau_w$ to assure field penetration through the wall. Modes with $n = 6, -10$ are produced for the $4 \times 16$ configuration (figure 1a). In this case coupling is connected to the number of active coils in the toroidal direction (toroidal side band effect). Coupled modes have $\Delta n = N = 16$. For the $2 \times 32$ configuration the $m = 1$ RWM spectrum is mostly affected by the side band effect connected to the number of active coils in the poloidal direction (poloidal side band effect). Due to this effect the modes with mode numbers $1, n$ are coupled to the modes with mode numbers $-1, n$. It can be shown that $B_{-1,n} = B_{1,-n}$ where $B_{-1,n}, B_{1,-n}$ are the mode amplitudes. This relation shows the effect of the

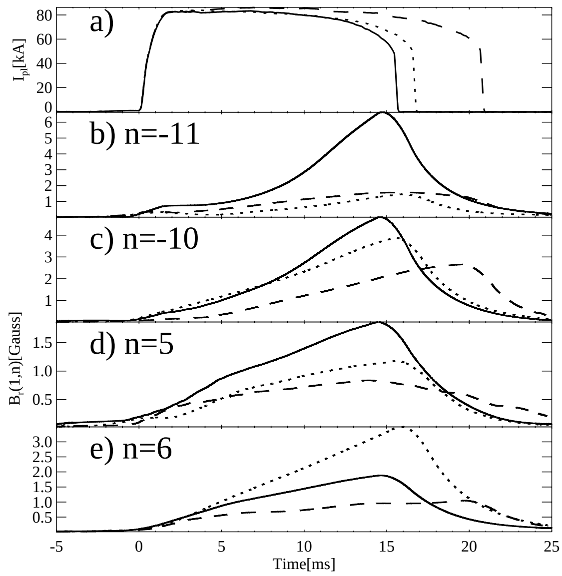


**Figure 2** *Amplitudes of the dominant RWMs; a - the plasma current; b,c - internal RWMs; d,e - external RWMs. Solid line - reference, dotted line -* $4 \times 16$ *active coil configuration, dashed line -* $2 \times 32$ *active coil configuration.*

poloidal coupling on the $m = 1$ mode spectrum. In particular, the mode $m = 1, n = -6$ is produced as a side band to the $m = 1, n = 6$ mode as shown in figure 1b.

# 4 RWM control using different active coil configurations.

The side band effect on the RWM suppression is studied for the intelligent shell feedback scheme by using different active coil configurations. The RWM dynamics in EXTRAP T2R is shot-to-shot reproducible. Initial excitation of RWMs is probably connected to the wide spectrum of intrinsic field errors present in the machine. This allows direct comparison of the mode amplitudes for the discharges without and with feedback. The mode amplitudes of dominant RWMs are shown in figure 2. Cases without feedback and with feedback using different active coil configurations are plotted. Although suppression of the mode amplitudes is seen for both configurations, modes are better suppressed for the $2 \times 32$ configuration (dashed line). It can be explained by the fact that the dominant internal $m = 1$ RWMs with $n = -11, -10$ are coupled to the dominant external RWMs with $n = 5, 6$ due to the toroidal side band effect for the $16 \times 4$ configuration (dotted line). This limits the efficiency of the feedback system and even has negative effect (further destabilization of $m = 1, n = 6$, dotted line). Suppression of both coupled modes $m = 1, n = -11, 5$ for the $16 \times 4$ configuration can be explained by the accidental phase difference of the initial field errors causing the modes to be in phase at the positions of active coils. In the case of the $2 \times 32$ configuration, $m = 1$ RWMs are coupled due to the poloidal side band effect. Dominant RWMs $m = -10, -11, 5, 6$ for this configuration are coupled to stable modes $n = 10, 11$ or to modes having lower growth rates $n = -5, -6$. This allows better simultaneous suppression of the dominant RWMs. In combination with another feature of this system (decoupled resonant and field error modes [9]) better sustainment of the plasma is achieved. Discharge time is increased and reaches a value of $4 - 5\tau_w$ with feedback.

As it is seen for both active coil configurations the mode amplitudes are not fully suppressed. This is due to the side band effect. For the intelligent shell feedback scheme, the relation between two unstable side bands is $b_{1,n_1} = -b_{1,n_2}$ [10] , where $b_{1,n_1}, b_{1,n_2}$ are the mode field harmonics at angular position of an active coil. Suppressing the dominant mode in a coupled set, a side band mode is produced with the same amplitude and the opposite sign. This limits the feedback system efficiency for suppression of both side band modes simultaneously.

# 5 Conclusions

The side band effect is studied in the EXTRAP T2R. Two active coil configurations with different number of active coils in the toroidal and poloidal directions are used. Side band effects that are seen for these configurations affect the $m = 1$ RWM spectrum. Better suppression of RWMs is obtained for the $2 \times 32$ configuration due to decoupling of two dominant RWMs. Modes are not fully suppressed due to the toroidal side band effect for the $4 \times 16$ configuration and poloidal side band effect for the $2 \times 32$ configuration, limiting the efficiency of the feedback system for suppression of couple unstable modes.

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