Active Feedback Control of the Wall Stabilized External Kink Mode*

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Abstract. Active feedback control has been used in the HBT-EP tokamak to control the growth of the n=1 resistive wall mode. These experiments were carried out using a set of thin stainless-steel wall segments with magnetic diffusion time of ~0.4 ms positioned near the plasma boundary. In plasmas that would normally exhibit a strong ideal $n = 1$ external kink mode without a nearby conducting wall, the resistive wall slows the growth of the external kink to the ~1 ms time scale where it can be stabilized by active feedback control. The approach taken in these experiments is to use a network of active feedback coils mounted on the surface of the stainless-steel wall segments and driven by an active feedback control system that simulates the electrical response of a superconducting wall and minimizes the radial flux penetration of the perturbed mode field through the wall. This implementation of the so called 'smart shell' in HBT-EP has 30 independent sensor/driver feedback loops.

1. Introduction

Control of long-wavelength MHD instabilities using conducting walls and external magnetic perturbations is a very promising route to improved reliability and improved performance of magnetic confinement fusion devices. Conducting walls are known to prevent or reduce the growth of harmful, long-wavelength MHD instabilities in tokamaks [1], and spherical tori [2], and they are essential to the operation of reversed field pinches (RFP) [3] and spheromaks. Many attractive fusion power scenarios require wall stabilization to reach high fusion power density and operate continuously with low recirculating power [4,5,6]. In toroidal devices which rely on a nearby conducting wall to stabilize the current or pressure driven external low-*n* kink mode, the lifetime and/or beta limit of these devices is set by the onset of the resistive wall mode (RWM) [7,8] which grows on the much slower time scale of the flux penetration through the conducting wall rather than the very rapid MHD Alfven time scale.

In this paper we report the first observation in a tokamak of the use of active feedback control to suppress the onset of the RWM. The approach taken in these experiments to control RWM instabilities is to use a network of active feedback coils configured so that the electrical response of the resistive wall simulates that of a perfect conductor. This so-called 'intelligent shell' or 'smart shell' was proposed by Bishop [9] and has been implemented in the HBT-EP tokamak with 30 independent sensor/driver feedback loops mounted behind a 2 mm stainless-steel resistive wall located near the plasma boundary as shown in Fig. 1.

2. Feedback Control Configuration in HBT-EP

The experiments were carried out using the HBT-EP tokamak which previously demonstrated passive wall stabilization of $n = 1$ external kink modes by adjusting the position of a segmented aluminum (Al) wall (magnetic diffusion time, τ_w ~ 65 ms) close to the plasma boundary [10]. Each wall segment can be independently positioned ($1.08 < b/a < 1.70$), allowing the position of the wall to be adjusted relative to the plasma. Half of the original thick (1.2 cm) Al wall segments were replaced with thinner (2 mm) stainless steel (SS) segments (τ_w ~ 0.4 ms) at equally spaced toroidal locations as shown in Fig. 1.

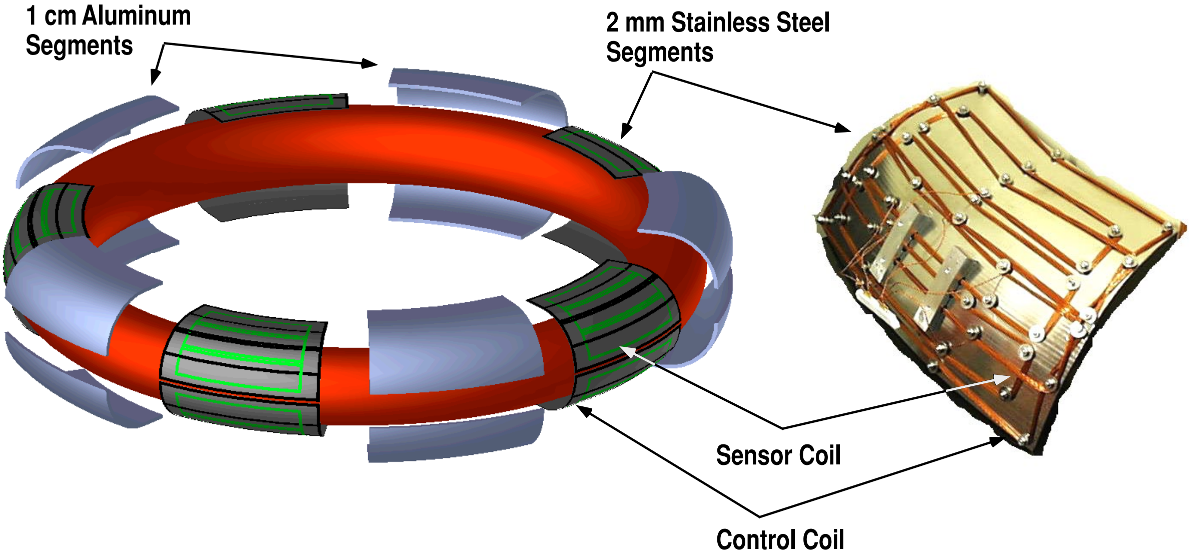

Fig. 1. HBT-EP has 20 independently adjustable conducting wall segments symmetrically arranged above and below the mid-plane. Ten of these 26° wide segments are thick Aluminum with a long (65 ms) flux penetration time. Between these are 10 thin stainless steel segments with a relatively fast flux penetration time (0.4 ms). Three flux sensors and control coil pairs are mounted on the back of each stainless steel segment as shown.

Each sensor loop and control coil pair of the active feedback system was connected to identical and independent analog feedback loops consisting of solid-state amplifiers and analog filters. The area of the sensor loop is slightly less than half the control coil area to reduce their mutual inductance. Each feedback loop applies a voltage to the control coil proportional to both the flux, Φ_s, and the time derivative of the flux $d\Phi_s/dt$ measured by the sensor. Near the center of the feedback loop's bandwidth (4 kHz) the control coil voltage was $V_c = G_p\ \Phi_s + G_d\ d\Phi_s/dt$, with G_d 31 V/V and $G_p = 5.5 \times 10^5$ V/Weber. These values allowed the feedback loop to exclude up to 85% of the penetration of radial magnetic fields through the SS wall segments up to 10 G within a bandwidth of 0.4 kHz < $\omega/2\pi$ < 11 kHz. For typical experiments the radial field applied by the control coil was approximately 1 Gauss.

3. Experimental Observations of Active Feedback Control

The plasmas which exhibit an unstable $n = 1$ kink mode in HBT-EP are prepared by a ramped current technique. After the initial formation of the plasma in a few 100 μs, the toroidal plasma current is increased at a rate of ~ 2.5 MA/sec creating a broad current profile and lower values of plasma internal inductance. In this way the edge safety factor, q_a, decreases in time and crosses $q_a = 3$ at about 2 ms where a strong external kink mode is then excited when no stabilizing wall segments are near the plasma boundary. MHD fluctuations are detected by the sensor loops of the active feedback system and by a poloidal array of Mirnov coils mounted on the inside of a thick Al wall segment.

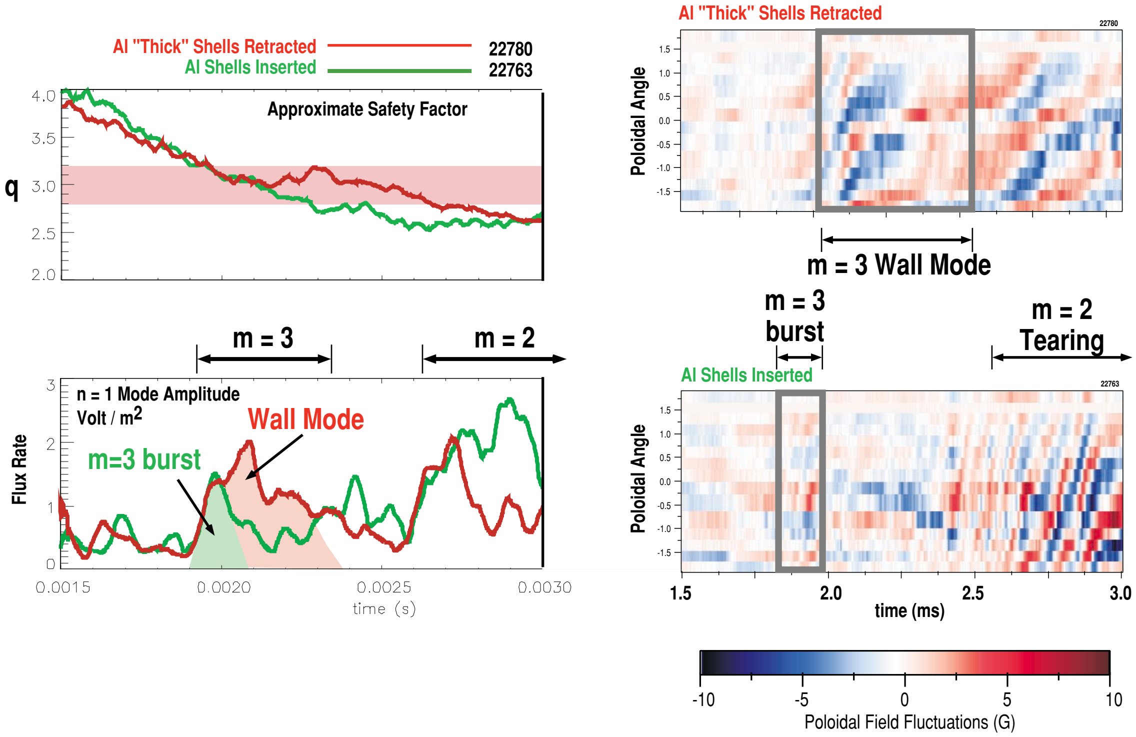

Fig. 2. Comparison of the MHD activity of two nearly identical shots, one with nearby thick Aluminum wall segments and one with the thick Aluminum wall segments retracted, leaving only the thin stainless steel segments near the plasma boundary. With the Aluminum walls retracted a slow growing wall mode is observed as shown in the flux penetration through the wall as well as the poloidal mode structure as a function of time measured by local Mirnov probes near the plasma boundary.

Shown in Fig. 2 are the effects of passive wall stabilization and the growth of the resistive wall mode in these current ramp discharges. The figure shows two plasma discharges which are nearly identical except for the arrangement and use of the adjustable wall segments. Discharge number 22763 had the thick Al wall segments fully inserted, b/a = 1.08. Discharge number 22780 had the thick Al segments fully retracted, b/a = 1.70. The thin SS wall segments were positioned near the plasma boundary (b/a = 1.08) for both plasmas. For the plasma with the thick Al wall inserted, a short burst of n = 1 activity was observed on the sensor loops as $\mathrm{q_a}$ approached and passed below 3. This was accompanied by an equally short burst of Mirnov oscillations. A simple cylindrical model of the plasma predicts that this brief period of n = 1 instability should occur as q_a crosses the integer value 3 in agreement with the observations. For the plasma with the thick Al wall segments retracted (shot 22780), the amplitude of the m = 3 oscillations characteristic of the RWM increase significantly when $q_a \sim 3$. The poloidal field perturbations, δB_θ, increase at a rate as large as 15×10^3 s^{-1} which is much less than the ideal MHD growth rate expected with the wall retracted. The growing m = 3 RWM mode initially rotates near a frequency between 5 kHz < $\Omega/2\pi$ <7 kHz. Normalized to the SS wall time, $\Omega\tau_w$ ~ 15, the normalized rate of rotation is about a factor of 6 times slower than the critical rotation rate observed to stabilize the RWM in the DIII-D device.[11]

On the next shot, the active feedback control is switched on (22781) as shown in Fig. 3. The amplitude of the m = 3 fluctuations and n = 1 flux penetration rate are observed to decrease to levels at or below those seen when the thick Aluminum wall segments are inserted. The feedback control is able to mimic the stabilizing effect of the thick aluminum shells. Later in the discharge (after ~ 2.5 ms) for all discharges equilibrium changes destabilize a rotating 2/1

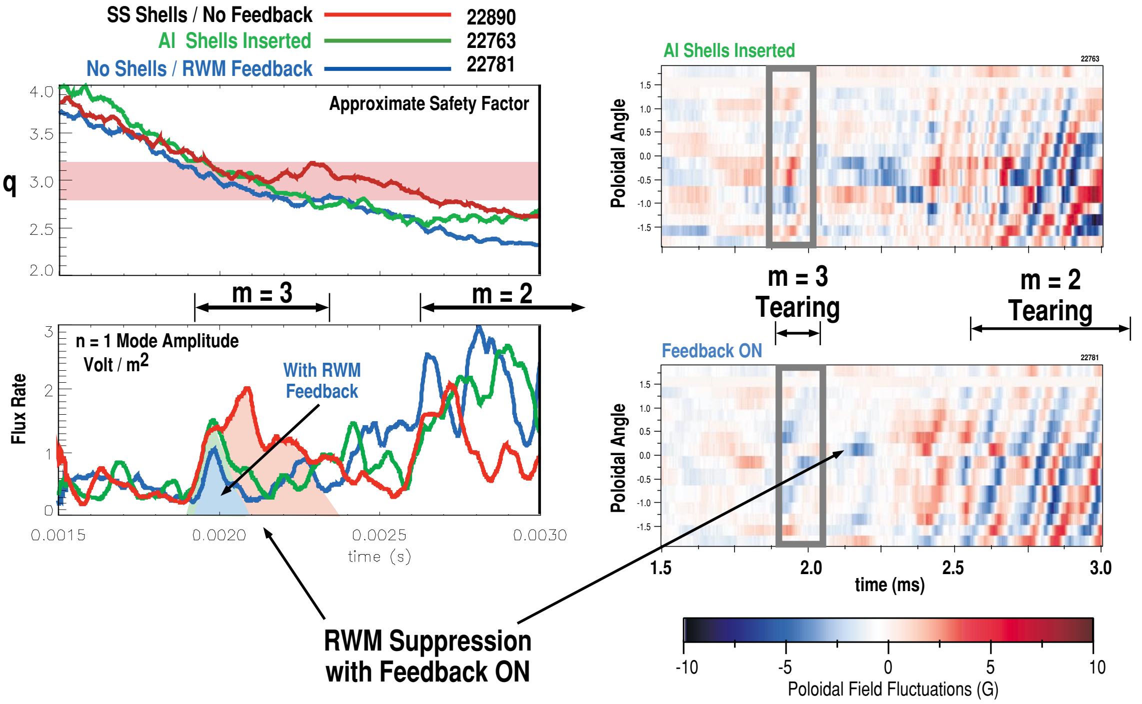

Fig. 3. Comparison of MHD activity when active feedback control is applied to a shot otherwise identical to that shown in Fig. 2.

tearing mode which can be seen in the poloidal field fluctuation plots in Fig. 2 and Fig. 3. When feedback was applied, the tearing mode rotation frequency was increased significantly. We believe this is due to the phase shift in the feedback loop (~45°), but these effects are still being investigated.

4. Modeling of Active Feedback Control

The RWM growth rate has been calculated in toroidal geometry with accurate wall geometry and resistivity using the technique developed by Boozer [12] and a 3D, finite element, electromagnetic computer code VALEN[13]. Kink mode stability is parameterized in terms of a dimensionless stability constant, $s \propto -\,\delta W/\Phi_p{}^2$, where δW is the change in the plasma energy and Φ_p is the perturbed flux on the plasma surface due to the unstable mode. Instability occurs when $s > 0$ and larger values of s correspond to stronger instability drives. VALEN includes an unstable plasma model based on the Boozer formulation and a computational model of the 3D control and sensor coils for a smart shell to predict the effectiveness of active feedback. In the experimental range $0.02 < s < 0.04$, the effect of the thick Al wall is to significantly reduce the growth rate of the RWM to a level much slower than can be seen on the time scale of the experiment. When the thick Al wall segments are retracted, the external kink mode is predicted to grow at the typical RWM rate ($\sim 10^4$ s^{-1}) in agreement with the experiment. In the VALEN simulation, when feedback is applied with G_p greater than about 10^5 V/Weber, the slowly growing RWM is predicted to be suppressed, again in agreement with experimental observations. These results are summarized in Fig. 4 which illustrates the computed growth rates of the external mode when $q_a < 3$ modeling the actual experimental wall geometries.

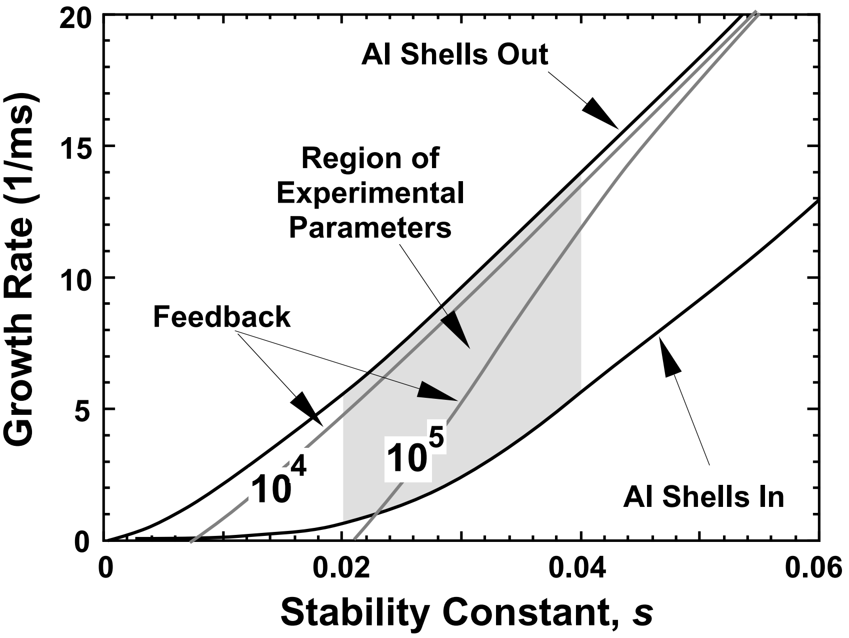

Fig. 4. The instability growth rate computed by the 3D electromagnetic VALEN code for the HBT-EP segmented conducting wall geometry both passively and with two values of feedback gain, G_p*, equal to* 10^4 *and* 10^5 *V/W. The cross hatched region indicates the range of parameters consistent with the experimental conditions. In this analysis the thin SS wall segments are always positioned near to the plasma boundary.*

5. Summary and Conclusions

The growth of resistive wall modes has been suppressed by energizing a network of active feedback control coils which mimics the response of a perfectly conducting wall. The MHD activity during application of active feedback is very similar to that observed with passive wall stabilization achieved by moving a highly conducting wall to the edge of the plasma. These results are also consistent with the 3D electromagnetic VALEN model calculations of the feedback-wall-plasma system.

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