Active Feedback Control of Kink Modes in Tokamaks: 3D VALEN Modeling and HBT-EP Experiments*

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Abstract. Significant progress in the development of active feedback control as a robust technique for the suppression of the wall stabilized external kink or resistive wall mode (RWM) in tokamaks has been achieved through a combination of modeling and experiments. Results from the application and benchmarking of the 3D feedback modeling code VALEN [1] as the primary analysis and feedback design tool on the HBT-EP [2] and DIII-D [3] experiments are in good agreement with observations, and modeling of proposed advanced control system designs on HBT-EP, DIII-D, NSTX [4], FIRE [5], and ITER are predicted to approach the ideal wall beta limit in agreement with design principles based on the simple single mode analytic theory of RWM feedback control [6]. Benchmark experiments on HBT-EP have shown suppression of disruptions at rational edge *q* values using active "smart shell" feedback control, the initiation of the first test of directly coupled coils designed to operate up to the ideal wall limit on RWM behavior, as well as observation of the plasma amplification of static resonant magnetic fields in plasmas marginally stable to the RWM in agreement with theory [7].

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 [9], and spherical tori [10], and they are essential to the operation of reversed field pinches (RFP) [11] and spheromaks. Many attractive fusion power scenarios require wall stabilization to reach high fusion power density and operate continuously with low recirculating power [12,13]. 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 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.

It is well known that control of these resistive wall slowed kink modes above the no-wall beta limit is essential to achieve bootstrap current sustained steady-state operation in a high gain tokamak fusion energy system. Accurate quantitative modeling of the active feedback stabilization of these RWMs including realistic effects of complex 3D nearby conducting structures and practically located control and sensor coils is essential for the analysis of present experiments, the design of improved feedback control configurations on current devices, and projection of these configurations to next generation burning plasma experiments and fusion power plant designs. The VALEN feedback modeling code has been developed to meet this requirement.

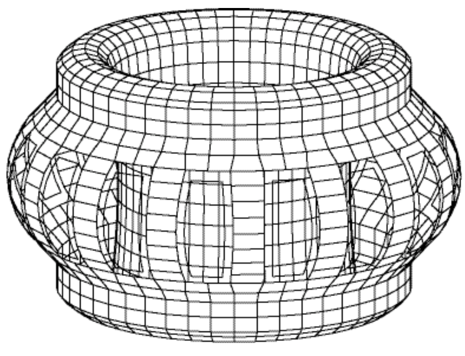

Figure 1

2. VALEN MODEL OF RWM CONTROL

A general circuit formulation of the RWM feedback stabilization problem has been developed by Boozer [6]. This circuit formulation has been implemented as the basis for the VALEN code. The code uses a finite element representation of thin shells to model arbitrary 3D conducting walls. An example 3D VALEN model of the passive conducting structure of the FIRE tokamak is shown in Fig 1. The VALEN model of the conducting structure is then combined with a circuit representation of stable and unstable plasma modes represented as 2D surface current distributions derived from the DCON [14] MHD stability code. Two RWM induced wall eddy current patterns Calculated by VALEN are depicted in figure 2*(a)* and *(b)*. Fig. 2*(a)* shows a planar map of the response of an axisymmetric model of the FIRE passive wall structure due to an unstable RWM mode. Note the clear mode localization to the low field side of the device. Fig. 2*(b)* shows the model of the actual FIRE passive wall including porthole apertures. Note the large distortion of the outboard eddy current pattern due to the presence of the portholes on the outside mid-plane. VALEN accurately accounts for such non-axisymmetric effects using its 3D finite element capability. The effect of the portholes on the passive response of the wall is presented in fig. 3 along with the behavior of an ideal wall and proposed feedback system. The use of the axisymmetric wall is seen to over estimate the stabilizing response of the wall by several orders of magnitude at high beta on the predicted mode growth rate. VALEN also accurately models arbitrary sensor and control coils including the feedback logic to provide a complete simulation capability for feedback control of plasma instabilities. To date, VALEN is the only code able to quantify these important effects in the design and evaluation of RWM passive and active control systems.

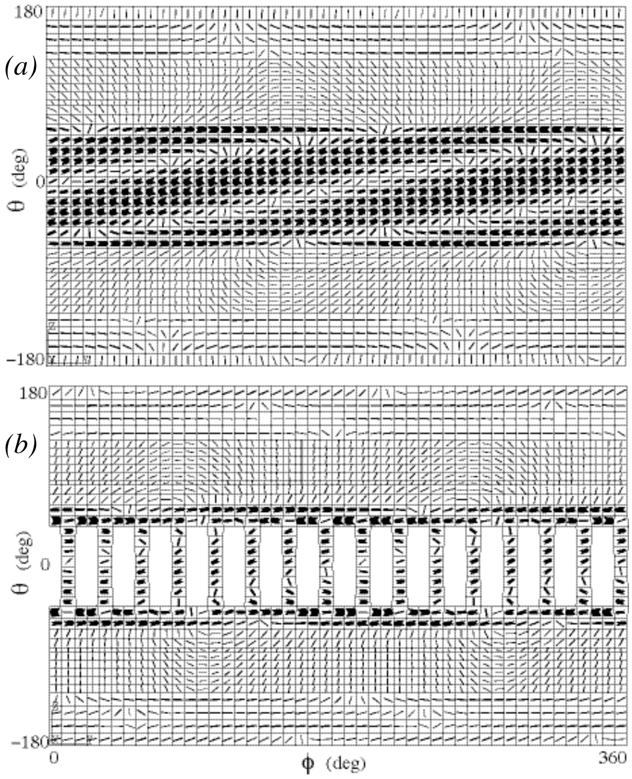

Figure 2

2. HBT-EP RWM CONTROL EXPERIMENTS

The control physics issues of optimized feedback and sensor coil layout and geometry are crucial to maximizing the efficacy of MHD instability control for fusion systems. The HBT-EP tokamak serves as a test-bed facility for investigating these issues. Using a flexible multi-element set of 30 independent sensor/driver feedback coils, RWM induced disruptions have been suppressed, and feedback effectiveness has been investigated as a function of coil coverage and feedback loop gain on the HBT-EP tokamak employing a so-called “smart shell” configuration. These studies are important to on-going efforts to optimize active mode control systems. We have

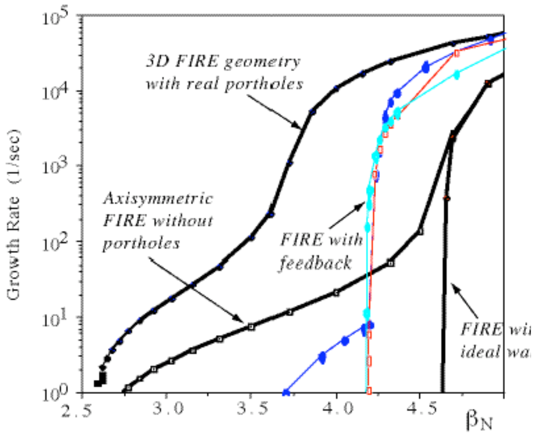

Figure 3

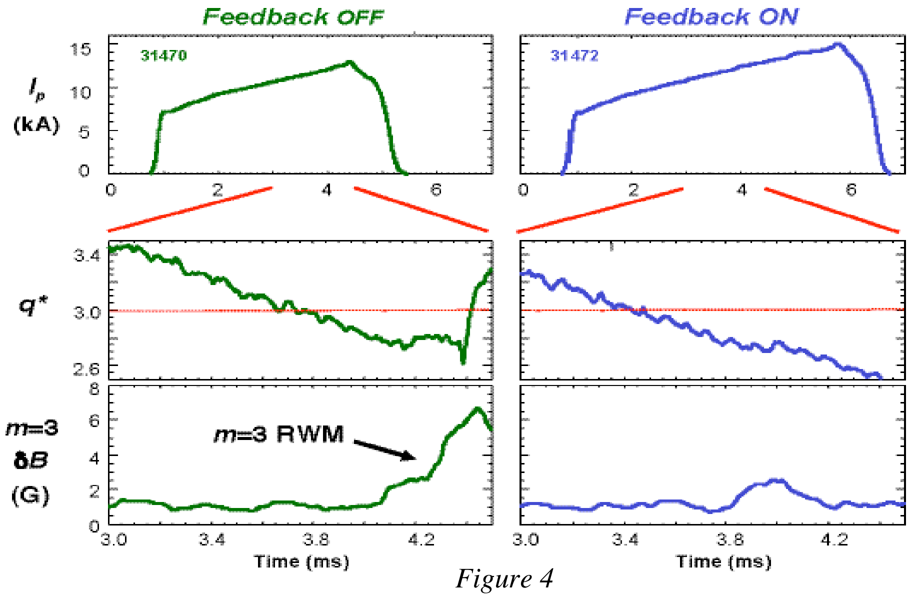

Figure 4

also investigated the response of external RWMs to pre-programmed resonant magnetic perturbations generated using a digital waveform generator to drive the smart shell coil set. Here saturated RWMs are observed to phase lock to an applied static resonant field with a paramagnetic or amplifying plasma response. In addition, we have recently installed and operated the first set of in-vessel directly coupled control coils for RWM suppression. Using this new 20-element coil set we have observed both suppression and enhancement of RWM amplitude as the phase of the applied field was varied during initial experiments. We now describe in more detail these observations.

Suppression of RWM induced disruptions and extension of the allowable edge q operating space of HBT-EP plasmas with feedback control has been extended from earlier reported feedback suppression experiments [2] due to improvements in feedback control loop circuitry that now allows cancellation of up to 94% of the mode radial flux through the resistive wall. Each sensor loop and control coil pair of the active feedback system was connected to identical and independent 200W analog feedback circuits using primarily proportional gain having a magnitude of $\sim 10^6$ V/Weber at 4 kHz. 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 an Al wall segment. Fig. 4 shows the effects active feedback control on the magnetic fluctuations along with a representative target plasma for comparison. The figure shows the suppression of a large amplitude m/n=3/1 wall mode that later disrupts the plasma discharge in the case of no applied feedback. As seen the application of feedback suppresses the external m=3 mode amplitude and inhibits the hard disruption as the $q^*=3$ surface enters the vacuum. Feedback control has allowed lower q higher plasma current operation.

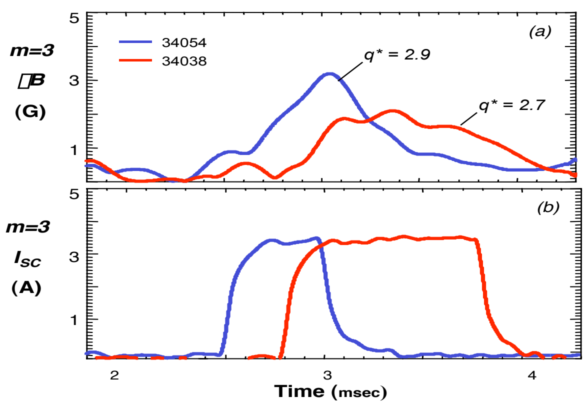

Figure 5

Feedback control was applied to a series of current-ramp up experiments (dI/dt~2MA/s) that produce strong disruptive RWM activity of 4/1 modes at the q^*~4 transition in addition to the 3/1 mode shown in fig. 4 at the $q^*\sim 3$ transition. At the q^*~4 transition plasmas were normally observed to be 50% disruptive and application of feedback completely suppressed these RWM induced disruptions. At the q^*~3 transition the plasmas were normally observed to be 60% disruptive, and application of feedback at that same gain reduced the RWM induced plasma disruption rate to about 10%. When these experiments were repeated with a reduction in gain by a factor of 10, no feedback suppression of the disruptions was observed in agreement with VALEN modeling for HBT-EP.

Finally, fig. 5 shows the effect of an applied static, predominantly m/n=3/1, external resonant magnetic perturbation to a rotating saturated RWM. The observed plasma response has a phase locked growing m=3 poloidal mode structure. This response is observed to be paramagnetic or amplifying relative to the magnitude of the applied vacuum field [7,8]. The observed plasma response is shown to depend upon the stability limit of the resistive wall mode as indicated by slower decay of the plasma response to the external resonant magnetic perturbation when q^* is reduced further below the rational value of 3 where the mode is more weakly damped.

3. OPTIMIZED FEEDBACK: APPROACHING THE IDEAL WALL LIMIT

The ultimate goal of RWM feedback system suppression is to allow plasma performance up to the ideal wall stability limit. By applying VALEN to a wide variety of tokamak designs several important design principles for optimizing the effectiveness of feedback control up to the ideal wall limit for kink modes have been found:

(1) ***Mode control is superior to "smart shell" feedback.*** "Smart shell" feedback cancels out or nulls the total local magnetic field perturbation measured on a radial field sensor by energizing a concentric control coil. This control/sensor coil geometry can only approach the performance of an ideal wall under the area of the "smart shell" control coils. Using mode control feedback that seeks to cancel out the radial mode flux at the plasma surface (not at the coil) by application of an externally generated field proportional to the mode amplitude (not total flux) the feedback loop can reach a performance level equivalent to the entire passive stabilizing wall behaving as an ideal conductor

(2) Poloidal field sensors are superior to radial field sensors. Poloidal field sensors are better able to distinguish between the plasma mode and applied control coil fields than radial sensors allowing higher feedback loop gain. This sensor property is due to two effects: (*i*) poloidal sensors have minimal mutual inductive coupling to the applied radial feedback coils, and (*ii*) poloidal sensors have greater mode amplitude sensitivity to rotating magnetic perturbations in the presence of a conducting wall boundary condition.

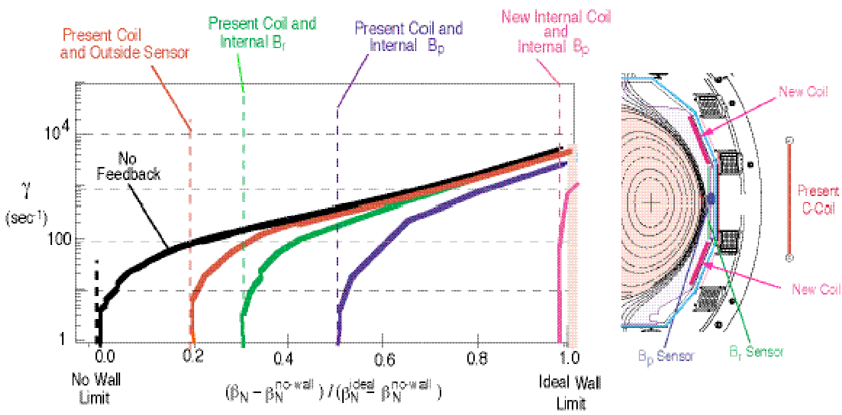

Figure 6

(3) Inboard conducting walls are ineffective for passive stabilization. The effect of the outer passive stabilizer is dominant in setting performance limits at high β for both advanced and low aspect ratio tokamaks. This is a property of the larger mode-wall coupling due to the longer outboard poloidal wavelength of the perturbation

(4) In-vessel control coils are superior to external coils. Simple theory[6] predicts that control coils that couple more strongly to the passive stabilizing wall (as in the "smart shell" configuration) than the plasma are not able to reach the ideal wall performance limit. This effect has been demonstrated for several realistic configurations using VALEN (HBT-EP, DIII-D, NSTX, FIRE, and ITER), where ideal wall limit performance is reached when the control coils could couple directly to the plasma mode. VALEN has been applied to a series of existing and proposed control coil configurations on DIII-D as shown in fig. 6 for both radial field sensor coils, poloidal field sensor coils, and in vessel control coils showing projected performance relative to normalized beta, β_N. Using the above outlined design principles ideal wall limit feedback performance is achieved with the proposed poloidal field sensors and in-vessel control coil system. An optimized feedback configuration with control coils located in the gaps of the passive stabilizing wall on HBT-EP has been installed and the first tests of VALEN predictions of ideal wall level performance for directly coupled control coils on RWM suppression are underway.

4. SUMMARY

In conclusion, the design and development of active feedback systems for RWM control in tokamaks using the VALEN feedback modeling code [1] have expanded the operational parameter space of existing experiments on HBT-EP and DIII-D [3] in q and β. Experiments on HBT-EP have shown disruption suppression using "smart shell" feedback, initiated the first test of directly coupled control coils and observed the amplification of asynchronous resonant magnetic perturbations by external MHD activity. The insight gained in the operation and modeling of these feedback loops has allowed the design and development of a new improved generation of control systems predicted to operate at the ideal wall limits of performance offering the advanced tokamak the possibility of further high β performance improvement.

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