Control of External Kink Modes Near the Ideal Wall Limit Using Modular Internal Feedback Coils*

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Abstract. We report on the first experimental demonstration of feedback suppression of rotating external kink modes near the ideal wall limit in a tokamak [1]. This was achieved using an optimized control system employing a low latency digital controller and directly coupled modular feedback coils. The magnitude of plasma dissipation affecting kink mode behavior has also been experimentally quantified for the first time using measurements of the radial eigenmode structure of the poloidal field fluctuations associated with the rotating kink mode. New capabilities of the VALEN code [2] are also reported. These include the ability to simulate multiple plasma modes, mode rotation, transfer function and Nyquist analysis, and the inclusion of realistic noise and time delays in the model of the feedback control loop.

1. INTRODUCTION

The improved understanding and control of long-wavelength kink instabilities that grow on the resistive time scale of a nearby conducting wall, τ_w, is a key issue for tokamak-based fusion reactors. These resistive wall modes (RWMs), appear when opposing fields from eddy currents in the wall prevent growth of fast ideal modes [3]. When the RWM is controlled, tokamaks and spherical tori can operate steadily with a high plasma pressure that exceeds the no-wall, beta-limit and makes possible advanced scenarios having good confinement and low current drive power requirements [4-6]. The RWM is stabilized either by sustained plasma rotation [7] or by active feedback control [8, 9].

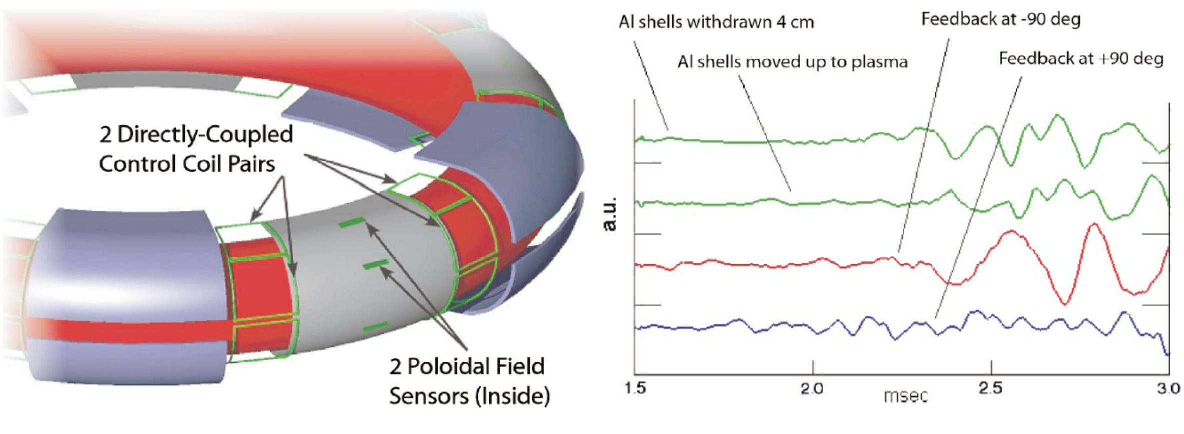

Figure 1. Left: The mode control system layout showing the sensor and control coils. Right: m=3 selecting Rogowski coil signals show a m/n=3/1 kink mode with no feedback (green), amplified by positive feedback (red), and suppressed by negative feedback (blue).

2. HBT-EP RWM CONTROL EXPERIMENTS

The successful suppression of rotating m/n=3/1 kink modes near the ideal wall performance limit (see Fig. 1) was achieved on the HBT-EP tokamak, which serves as a test-bed for various passive and active kink mode stabilization schemes. It was accomplished using a highly optimized feedback system employing poloidal sensors and radial control coils that couple directly to the plasma but have minimal magnetic coupling to each other, and the passive stabilizing wall. The feedback algorithm is implemented on a versatile high-speed digital (FPGA) processor capable of loop rates of 100 kHz and latency of only 10μsec. Such low latency is necessary to stabilize fast rotating and growing kink modes with complex growth rate of order $(3+i2\pi5)\text{x}10^{-3}\ s^{-1}$ typical for kink modes at the ideal wall limit in HBT-EP. The versatility of the HBT-EP mode control system allows for a multitude of rapidly realizable experimental configurations to explore the limits of mode control feedback and digital feedback algorithms. The effects of transfer function phase shifts, loop latency, and control coil coverage have been investigated. Use of digital lead-lag compensation was found to substantially increase feedback loop ability to suppress rotating kink modes for a variety of mode rotation frequencies encountered under typical experimental conditions.

Understanding the magnitude and source of plasma dissipation that governs resistive wall mode rotational stabilization is crucial for the extrapolation of current experimental results to future burning plasma regimes of operation. To date, methods to determine the magnitude of dissipation affecting kink mode dynamics has been through the measurement of the complex damping rate of the mode using MHD spectroscopic techniques [10-12], or by detailed profile measurements of momentum loss as the kink mode evolves in time [13]. Previous measurements on HBT-EP have shown rotationally stabilized kink perturbations to be consistent with a semi-empirical viscous model of Fitzpatrick [14] in the high dissipation regime. Here we present an alternate method to quantify the magnitude of dissipation using measurements of the polodial magnetic field fluctuations associated with the kink's radial eigenfunction. A twenty element, high spatial resolution Hall sensor array [15] was used to measure the kink mode perturbed poloidal fields shown in Fig. 2. Comparison of the relative phase shift of these fluctuations as a function of minor radius with calculations of the expected structure of the kink-RWM eigensystem based on Fitzpatrick's model show a sensitive dependence upon the magnitude of dissipation allowing its quantitative characterization. Estimates of the magnitude of dissipation using these phase shift measurements are in good agreement with previous MHD spectroscopy measurements [12] made on HBT-EP.

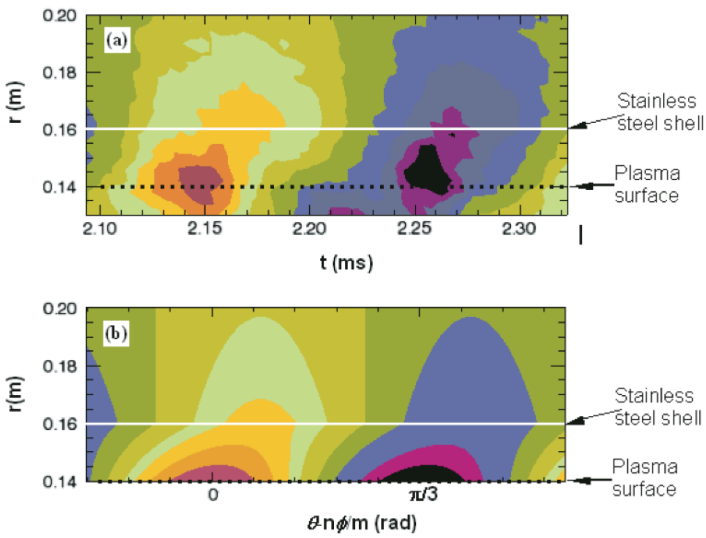

Figure 2. Top: Contour plot of 4 mm spatial radial resolution measurements of the polodial field eigenstructure of the m/n=3/1 kink mode in HBT-EP. Bottom: Model calculation [14] of the perturbed flux eigensystem showing good agreement with the measured shift as a function of radius.

3. FEEDBACK PERFORMANCE AT THE IDEAL WALL LIMIT

While theory, modeling, and experiments have established the effectiveness of magnetic control coils for active RWM feedback stabilization, these same studies show significant advantages to control coil location inside the passive stabilizing metallic walls [2]. For ITER and any future fusion tokamak power plants, it is beneficial to make these internal coils as few and small as possible without compromising the ability to feedback stabilize the RWM. To address this, a new set of shells and coils will be installed in HBT-EP, figure 3. In each of the toroidal gaps between conducting shells, a set of three overlapping control coils (5˚, 10˚, and 15˚ wide) will be installed. This arrangement spans the roughly 10˚ toroidal width of an ITER mid-plane port. The setup will allow determination of the necessary flux gain required in a modular control coil set as a function of degree of modularity and coverage compared with VALEN model predictions. A possibility of coupling control coil input to shorter wavelength toroidal modes and edge plasma Alfvén continuum modes leading to a breakdown in the basic 'rigid mode' model used in the VALEN analysis must be tested and understood to confidently extrapolate to the burning plasma experiments on ITER. The present HBT-EP feedback control coils (Figure 1) are modular enough that when operated to produce a particular helicity, eg. m/n=3/1, a significant amount of magnetic flux is inevitably expressed into other modes (sidebands). Experiments on HBT-EP have shown phenomena consistent with the excitation of sidebands [16], although this did not prevent the successful suppression of the RWM all the way to the ideal wall limit. Evidence of lack of mode rigidity during RWM feedback experiments has recently been observed in NSTX [17].

4. VALEN RWM CONTROL MODELING

A critical analysis and design tool for optimized active feedback control of the RWM is the 3D finite element electromagnetic code, VALEN [2] developed in support of active

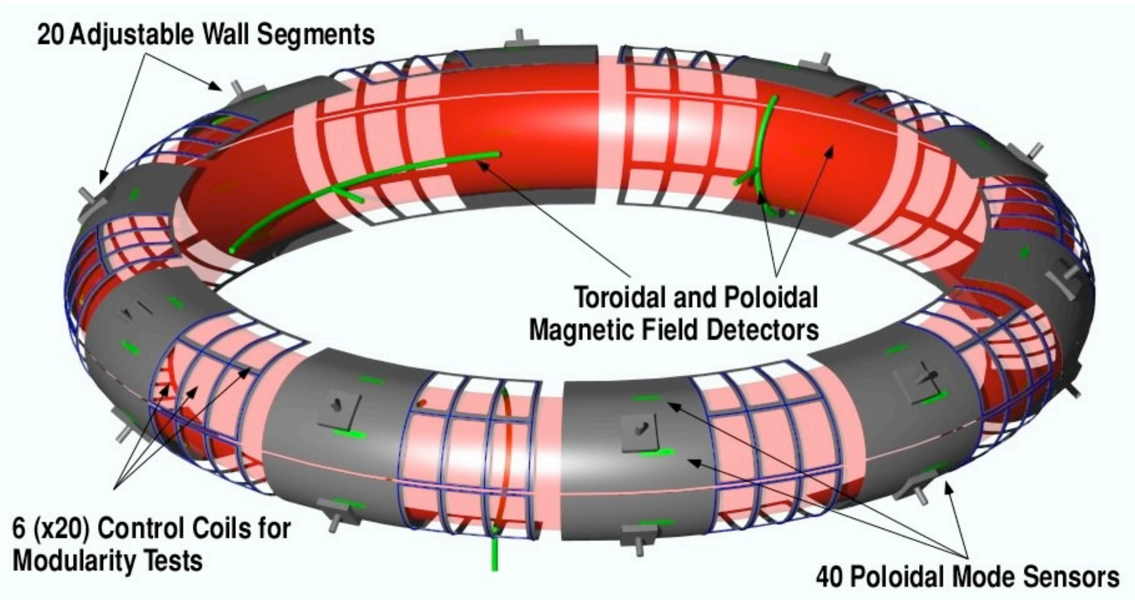

Figure 3. The new HBT-EP configuration showing sensor and control coils, new passive stabilization shells, and high resolution magnetic diagnostic arrays.

mode control work on HBT-EP and based on the lumped element resistive wall mode model of Boozer [18]. We report new capabilities of the VALEN code. It has been extended significantly to include realistic effects in the feedback control loop of finite bandwidth (high and low frequency roll-off) and overall system delay or "latency" typically encountered when a digital system is used in the feedback loop. This capability was obtained by running VALEN in the time domain as an initial value code with simple single pole L-R circuit models or time delay were added to the feedback loop as summarized in Figure 4 for the new internal control coil system installed on DIII-D near the ideal stability limit.

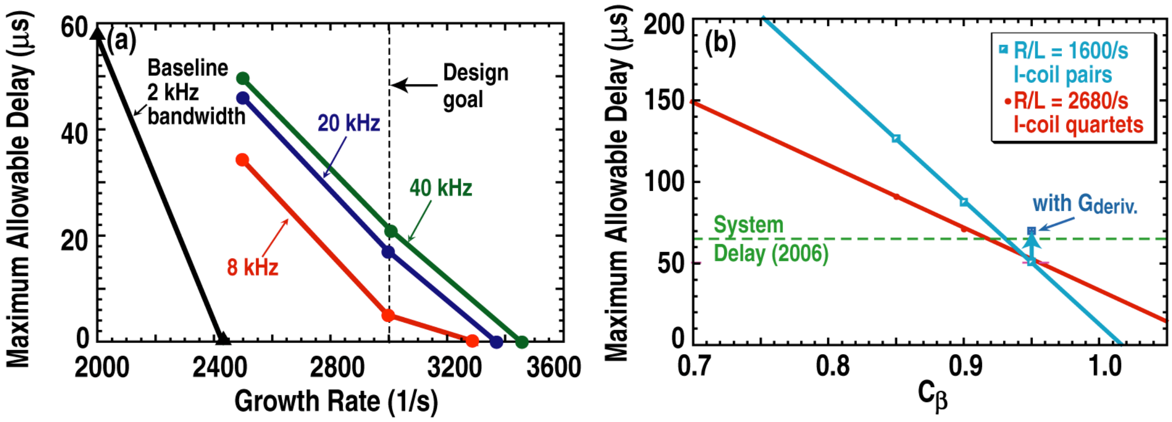

Figure 4. VALEN modeling of maximum allowable delay as a function of RWM growth rate (a), and C_β (b) for the new internal-coil control system on DIII-D. Addition of derivative gain to the feedback circuit is shown for one case, allowing larger maximum delay. R/L represent typical values of resistance and inductance for the feedback power system.

To determine the amplifier power required in real experimental feedback control systems, a full noise model capability was developed for VALEN including both broadband "white" noise as well as correlated MHD events like ELMs. Also, VALEN has been extended in its capability from analysis of a single mode to the treatment of multiple plasma modes (both stable and unstable). The first practical application of this was to include 2 degenerate n = 1 RWMs shifted 90° in toroidal phase so as to model a rotating RWM in HBT-EP as shown in Figure 5. The rotating mode model in VALEN is formulated using the parameters proposed

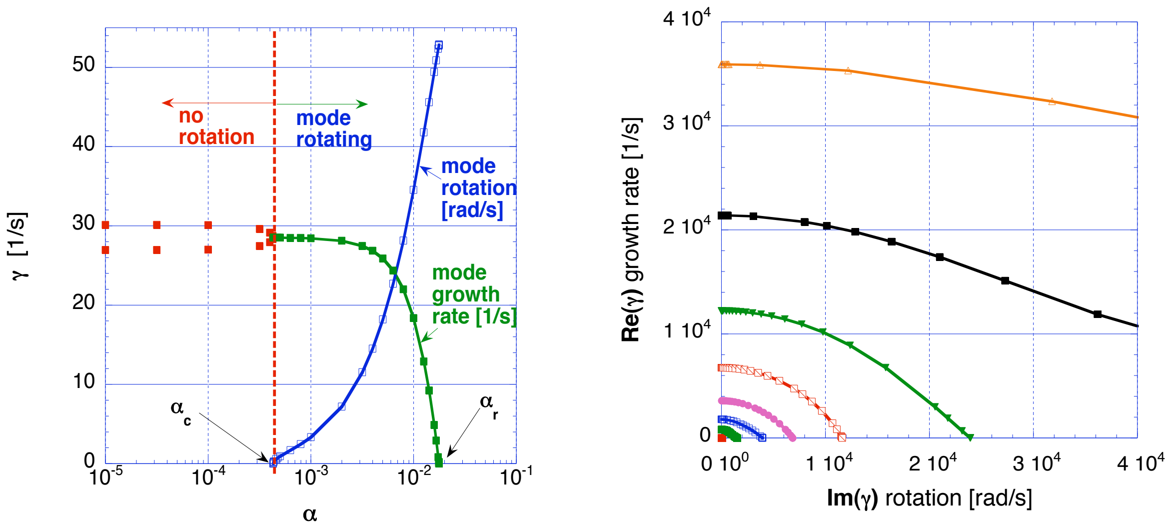

Figure 5. Left: VALEN rotating eigenvalues calculated for the HBT-EP segmented wall shown in fig. 1 showing onset of RWM rotation at α_c and rotational stabilization at α_r. Right: Rotation frequency versus growth rate for a series of instability drives between the no wall and ideal wall limits of operation.

by Boozer [19].

Recent work has also concentrated on the development of quantitative single eigenmode approximations of the full VALEN mode spectrum. These models contract the full VALEN inductance and resistance matrices into dimensionless coupling numbers that characterize a given eigenmode. They may be used for data interpretation, feedback loop design, and the assessment of RWM controllability and observability conditions.

VALEN has also implemented sensor transfer function analysis of the unstable plasma wall feedback coil system and uses conventional Nyquist analysis techniques to estimate closed loop feedback performance. A VALEN frequency response calculation solves the set of circuit equations given by,

$$(\vec{L}(j\omega) + \vec{R})\vec{I}_o e^{j\omega t} = \vec{V}_o e^{j\omega t}. \qquad (1)$$

neglecting the homogeneous response and calculates sensor transfer functions based upon the following normalized definition,

$$P(j\omega) = \Phi_s(j\omega) / M_{sf} I_f(j\omega). \qquad (2)$$

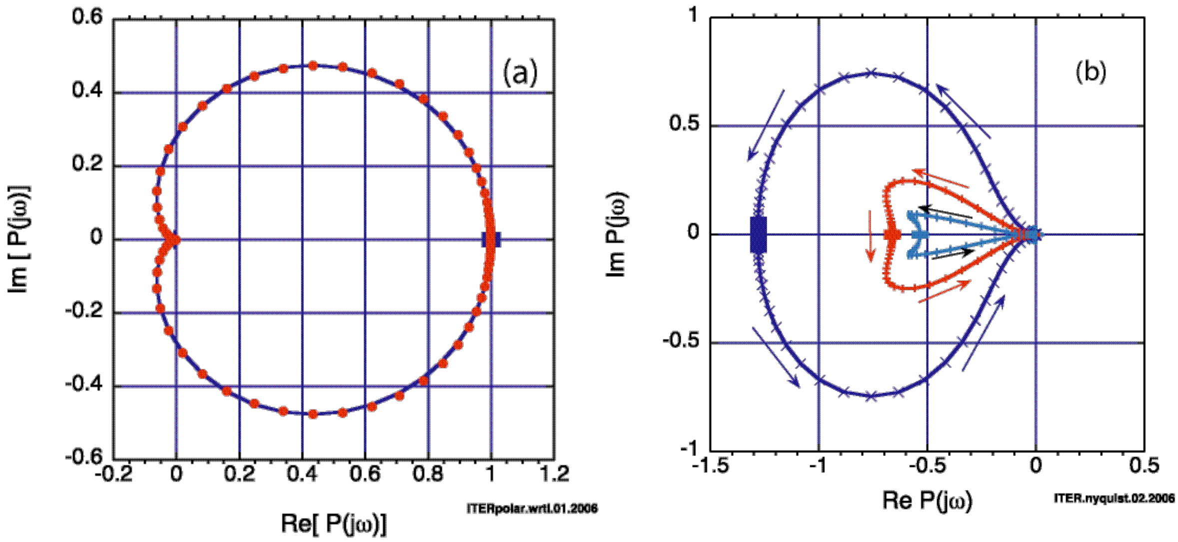

Figure 6. Left: Nyquist plot of the vacuum, no plasma sensor transfer function for a symmetric double wall model of ITER. Right: Nyquist plots for three increasing values of the plasma beta showing feedback system ability to suppress the mode up to ~60% of the ideal wall limit.

Fig. 6 shows the resulting Nyquist plots for a frequency response set of calculations performed for a simple symmetric model of the ITER tokamak showing the vacuum, no-plasma response of the system as well as the Nyquist diagrams for three increasing values of the plasma beta.

4. SUMMARY

We report on the first experimental demonstration of feedback suppression of rotating external kink modes near the ideal wall limit in a tokamak [1]. This was achieved using an optimized control system employing a low latency digital controller and directly coupled modular feedback coils. The magnitude of plasma dissipation affecting kink mode behavior has also been experimentally quantified for the first time using measurements of the radial eigenmode structure of the poloidal field fluctuations associated with the rotating kink mode. New capabilities of the VALEN code [2] are also reported. These include the ability to simulate multiple plasma modes, mode rotation, and the inclusion of realistic noise and time delays in the model of the feedback control loop.

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