SUPPRESSION OF MAGNETIC ISLANDS THROUGH SYNCHRONOUS AND ASYNCHRONOUS APPLICATION OF RESONANT MAGNETIC FIELDS*

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Abstract

Observations of the suppression of the amplitude of tearing instabilities through the application of synchronous (closed loop) and asynchronous (open loop) resonant magnetic perturbations are reported. These observations extend our previous investigations of large changes of tearing mode rotation induced by oscillating currents in small saddle coils. Although mode suppression is achieved using several techniques, the most significant decrease in the size of a magnetic island occurs when the island is made to rotate faster or slower than its natural frequency. By comparing measurements with time-dependent simulations, we find the observed mode suppression is consistent with a dynamic stabilizing effect proportional to the square of the difference between the island's instantaneous and time-averaged rate of toroidal rotation. Our results suggest that internal modes may be controlled more effectively by inducing rapid modulations of island rotation than by applying phase-controlled active-feedback.

1. INTRODUCTION

Active and passive control of MHD instabilities are critical elements of plans to improve the economic potential of steady-state tokamak power sources [1], to achieve high-beta, steady-state operation of spherical tokamaks [2], and to sustain RFP discharges. Passive wall-stabilization can suppress fast external kink instabilities and plasma rotation control and/or active feedback may stabilize resistive wall modes [3,4] and internal tearing modes [5-9]. Experiments using the High Beta Tokamak-Extended Pulse (HBT-EP) tokamak [10] study the feasibility of a high-beta tokamak stabilized by a combination of an internal conducting wall, plasma rotation control, and active feedback. For control of internal modes, HBT-EP (R = 0.92 m, a = 0.15 m, B = 0.35 T, $I_p \sim$ 15 kA, $\langle T_e \rangle \approx$ 80 eV) uses a number of small (6˚ wide toroidally) saddle coils covering only 3% to 5% of the plasma surface, located between the gaps of a movable and segmented conducting wall, and driven by high-power, linear amplifiers, ($P \leq$ 10 MW, $f \leq$ 50 kHz). When the conducting wall is moved near the plasma's edge, the growth rates of fast-growing instabilities are reduced or eliminated in discharges which would otherwise exceed the stability limit for ideal external kinks when the wall is retracted [10,11]. With the wall inserted, slowly growing m/n = 2/1 tearing modes are excited by adjusting the evolution of the plasma current profile. Previous HBT-EP studies demonstrated control of the toroidal rotation of these slowly growing internal instabilities by energizing a small number of the highly localized saddle-coils [12,13]. Instantaneous measurements of an island's toroidal location were well-modeled using a single-helicity, Rutherford description for driven resistive modes and a phenomenological rotational drag [12]. The application of either oscillating single-phase or rotating two-phase saddle-coil currents was seen to strongly modulate the toroidal rotation frequency of the resonant magnetic islands. The phase-instability associated with active tearing mode control was detected, illustrating the rapid toroidal relocation of island position during closed-loop stabilization and the need for a relatively high system bandwidth to maintain phase-accuracy during active feedback control.

In this paper, we report new observations of the suppression of the amplitude of tearing instabilities through the application of synchronous (closed loop) and asynchronous (open loop) resonant magnetic perturbations [13,14]. These observations of amplitude suppression (1) imply the existence of an additional dynamic damping or stabilizing effect [13,14], (2) provide an explanation for the decrease in tearing mode amplitude detected during observations of the phase

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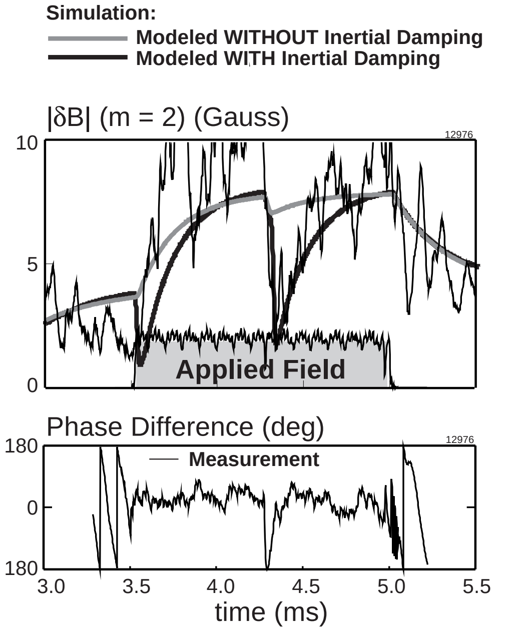

FIG. 1. Modeling of tearing-mode amplitude suppression during phase-instability experiment illustrates role of inertial damping. Bottom shows measured toroidal phase of island with respect to rotating resonant magnetic field.

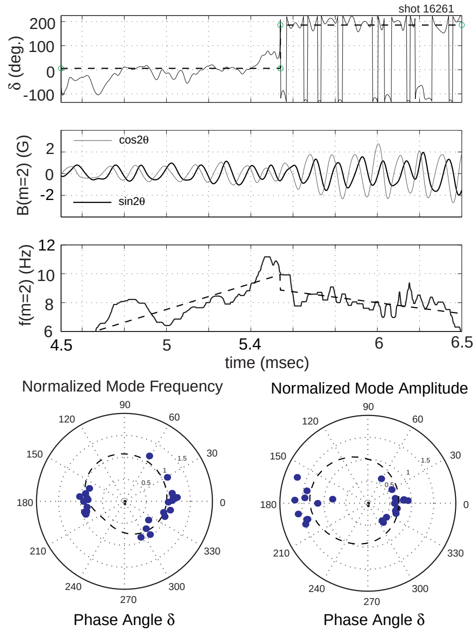

FIG. 2. Synchronous application of 1 ms stabilizing (0˚) followed by 1 ms destabilizing (180˚) active feedback for 1 ms intervals. Bottom shows comparison with the equilibrium solution of the driven island model as a function of feedback angle.

instability, and (3) suggest that internal mode control through (asynchronous) rapid modulation of island rotation may be more effective than (synchronous) active-feedback. Within our ability to estimate plasma profiles, these observations of island suppression are consistent in magnitude and form with theoretical models of magnetic island suppression proportional to the square of the rotation velocity difference between the island and the background plasma resulting from ion inertia and finite Larmor radius (FLR) effects [9]. However, a relatively large difference between the tearing mode rotation rate and the average toroidal ion flow is measured using Mach probes for $r/a \geq 0.6$, and we have not yet established consistency between these flows (nor the local density and temperature perturbations produced by magnetic islands) and theoretical models [9,15].

2. TRANSIENT ISLAND SUPPRESSION DURING PHASE-INSTABILITY

Characteristics of the coupling between the saddle coils and the resonant islands can be measured during the unstable growth of the phase, $\Delta\varphi$, between a rotating external perturbation and an internal resonant mode, referred to as the "phase-instability" [6]. The phase-instability is studied in HBT-EP [12] with a technique previously used in DITE [7]. As shown in Fig. 1, when a rotating resonant external magnetic perturbation is applied having a steady frequency, the island rapidly "locks" to the rotating perturbation and the mode amplitude increases. Measurement of this initial increase of the mode amplitude determines the direct coupling between the coils and the island. When the rotation frequency of the applied field coincides with the plasma's natural rotation frequency, ω_0, the phase-difference, $\Delta\varphi$ approximately vanishes, indicating an absence of externally-applied torque. At a predetermined time, the phase is rapidly advanced by 180˚ such that the "X-point" of the internal mode becomes aligned momentarily with the positive conductor of the saddle coil. This reduces mode amplitude until small deviations in phase produce a torque from the saddle coils which realigns the mode and $\Delta\varphi \to 0$. Measurement of the rate of phase-growth following the rapid phase-flip determines the strength of the torque applied by the saddle coils and the moment of inertia of the island (*i.e.* the fraction of plasma influenced by island rotation.)

For large islands and for strong external resonant fields, the phase instability grows rapidly, $\Delta\varphi/\Delta t \sim \omega$, and this allows direct demonstration of dynamic mode suppression induced by a rapid change of island rotation. When the island moves relative to the plasma, the perturbed inertial

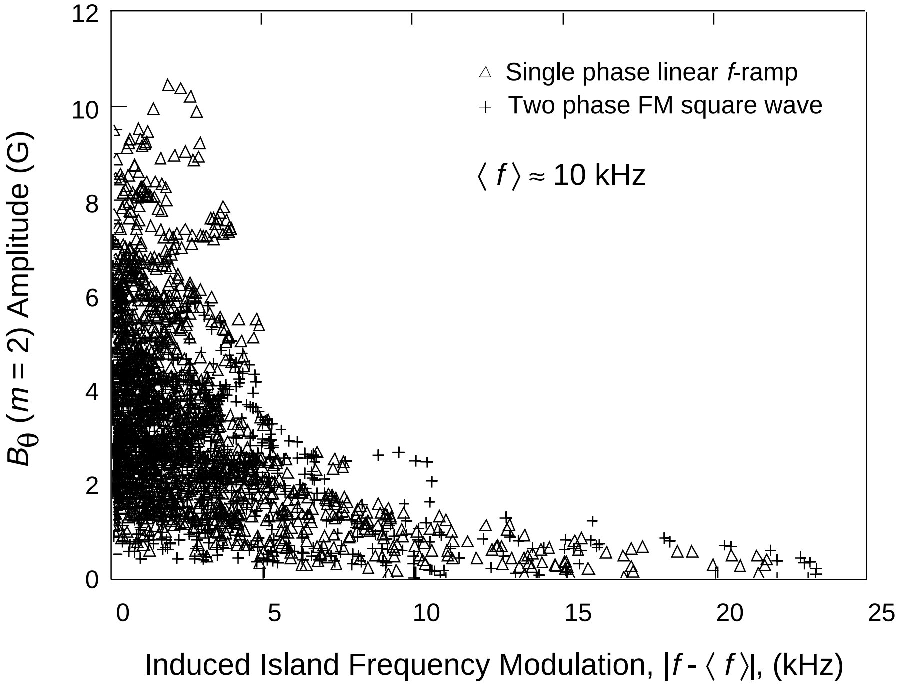

FIG. 3. Suppression of tearing mode amplitude as a result of frequency modulation induced by non-rotating, single phase coil oscillations and by square-wave modulation of the frequency of rotating 2/1 magnetic field perturbations.

force [6] (and, possibly, the perturbed viscous [8,15] force) may become comparable to the perturbed **J** × **B** force and contribute to strong mode suppression through the longitudinal current induced by the ion polarization drift. In the phase-instability experiments, we model this effect as a stabilizing resonant current proportional to $(\omega - \omega_0)^2/\delta^3$, where δ is the island half-width and ω_0 is constant in time. When the magnitude of this inertial damping corresponds to that estimated in Ref. 9, the measured rotational and amplitude dynamics seen during the HBT-EP phase-instability experiments can be reproduced with a single-helicity simulation of nonlinear island dynamics when using reasonable estimates of the plasma profiles [13]. As also shown in Fig. 1, without the effects of inertial damping, the mode amplitude is reduced only slightly by the direct interaction of the external field normally associated with magnetic feedback of tearing modes [5].

3. SYNCHRONOUS (CLOSED-LOOP) CONTROL

Active feedback is used to maintain $\Delta\varphi \approx 180^\circ$ and to apply a resonant magnetic field which appears in the island's rotating frame of reference to be constant and opposite to the self-fields of the tearing mode [5-8]. In HBT-EP, quadrature detection of the toroidal phase and amplitude of magnetic islands is derived from fluctuations of either magnetic or soft x-ray detector arrays [13]. The detector signals are acquired by a high-speed digital signal processor (DSP) after which they are phase-shifted and gain-adjusted to drive the input stages of the high-current linear amplifiers connected to the saddle coils. Groups of localized saddle-coils, connected in series, generate two toroidal phases which excite predominantly a $(m, n) = (2, 1)$ perturbation [13].

As shown in Fig. 2, the closed loop response of active feedback control at moderate gain agrees with the single-helicity theory as the phase angle of the applied field varies relative to the 2/1 island location. However, both predicted and observed suppression levels are modest, and small phase-errors are seen to produce gradual changes in the island rotation. As the feedback gain was increased to achieve greater mode suppression, we are unable to maintain accurate phase synchronism. This is expected, in part, since higher gains produce larger torques and faster phase-instability growth rates. We recently attempted to improve synchronous mode suppression in two ways. The DSP input sample rate was increased to 500 kHz from 100 kHz, and mode amplitude, and phase detection was improved with more accurate and better-shielded magnetic diagnostics. In all cases, a further reduction in mode amplitude was not achieved, and active feedback showed no effect on disruption timing or severity.

4. ASYNCHRONOUS CONTROL OF ISLANDS

Actively modulating island rotation about its natural toroidal propagation rate produces a significant decrease of island size. Significant mode suppression results either from low-frequency oscillation of a single-phase saddle-coil system or from applying rotating two-phase external 2/1 control fields alternately above and below the natural mode frequency, ω_0. The use of this second technique was originally suggested by Kurita and co-workers [8]. In both cases, dynamic suppression only occurs when the frequency modulation drive prevents the island from co-rotating (*i.e.* mode-locking) with the external perturbation. Apparently, the toroidal rotation rate must change at a rate near the inverse of an island's momentum relaxation time. In HBT-EP, the island relaxation time is measured after the saddle-coil currents have been switched off, and its value is approximately 200 μs. Fig. 3 summarizes the mode suppression of naturally-occurring 2/1 tearing modes observed in a large number of discharges. When the saddle-coils are used to modulate the island frequency by more than a few kHz from its time-average, $\langle\omega\rangle \equiv \omega_0$, significant island suppression always results. Simulations similar to those which reproduce island dynamics during the phase-instability, also reproduce island suppression due to induced frequency modulation. Furthermore, these asynchronous control techniques delay disruptions, usually triggered by large sawtooth crashes in the plasma core, by preserving the confinement of the outer flux surfaces.

5. SUMMARY

Rotating and oscillating resonant magnetic perturbations significantly alter tearing mode dynamics and can produce sustained reductions in mode amplitude when the perturbations are applied either synchronous (closed loop) or asynchronous (open loop) [13]. The most significant mode suppression is produced when actively modulating the island rotation about its natural propagation frequency. We have demonstrated several techniques which produced rapid changes in island rotation, and, in all cases, the effect on mode amplitude implies the existence of an additional damping or stabilizing effect proportional to the square of the island's perturbed rotation velocity, $(\omega - \omega_0)^2$ [13,14]. These observations of island suppression are consistent with models of magnetic island suppression resulting from inertial effects [9], and they suggest that internal mode control through asynchronous modulation of island rotation may be more effective than synchronous active-feedback. Experiments planned in the near future include active feedback of slowly-growing resistive wall instabilities [4], the application of multiple-helicity and multiple-frequency perturbations to generate and sustain sheared plasma rotation, and the use of ICRF heating for beta enhancement.

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