Feedback Stabilization of Disruption Precursors in a Tokamak

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Magnetic feedback control has been used in the DITE tokamak to substantially reduce saturated $m=2$, $n=1$ instabilities in both Ohmic discharges and discharges with lower-hybrid current drive (LHCD). Feedback has been used for the first time to significantly increase the disruptive density limit in a tokamak. LHCD on DITE stabilizes the sawtooth instability but generates a large $m=1,2$, $n=1$ instability. Both components of this mode have been controlled for the first time with feedback. Open loop experiments with LHCD show that mode locking occurs and allow detailed study of this phenomenon.

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The feasibility and economics of a tokamak as a fusion reactor are strongly influenced by the occurrence of disruptions—rapid loss of all or a large fraction of the magnetic and thermal energy of the plasma column. It is observed that the vast majority of disruptions are preceded by a period of oscillatory magnetohydrodynamic (MHD) activity with low poloidal and toroidal mode numbers (usually $m=2$, $n=1$). Experiments have been performed in the past to attempt to control these instabilities[1,2] by means of active feedback. Those seminal experiments demonstrated the principle of feedback, and some influence on soft disruptions was indicated.[3] Concern about disruptions in JET (and in the longer term in ITER and NET) has led the JET team to propose a magnetic feedback disruption experiment.[4] The experiment on DITE ($R_p=1.19$ m, $a_{\text{limiter}}=0.23$ m) described in this Letter was conceived as a preliminary to the JET feedback experiments and to allow, in particular, a study of the influence of feedback on disruptions in greater depth than had been done previously.

The feedback loop[5] consists of 32 large-area pickup coils measuring B_θ inside the vessel, electronics to control the gain and phase in the loop, and a set of eight saddle coils inside the DITE vacuum vessel driven by two 250-kW transistor amplifiers $[B_r^{(2,1)}(r=15\text{ cm})\simeq 1\text{ G}]$. The sets of saddles and detectors are each connected to form two independent $m=\pm 2$, $n=1$ combinations. The gain and phase control is then performed by combining the two $dB_\theta(m=2, n=1)/dt$ detector signals with adjustable multipliers. These multipliers can be changed each half period of the oscillation, and are set from a random-access memory look-up table. The address in the look-up table is determined by the mode amplitude, the frequency, and the time into the discharge. This allows compensation for resistive wall effects and power amplifier characteristics, for example, and it is possible to sweep the phase and gain within a single discharge. The most important bandwidth limitation is imposed by the power amplifier (15 kHz) and its necessarily inductive load. The experiment on JET will use eight three-turn coils (9 kAt/coil), and amplifiers with 10 kHz bandwidth and 18 MVA total; scaling to future devices depends critically on f_{mode} and whether it can be controlled.

Table I shows typical discharge parameters for the target plasmas. Under these conditions DITE exhibits sawteeth and quasisteady coherent $m=2$, $n=1$ activity at a level that depends on $\bar{n}_e$ and I_p. Thus mode control experiments can be performed in the flat-top period of the discharge.

The procedure adopted is (i) to minimize direct coupling between the field produced by the saddle coils and the detectors; (ii) to optimize the feedback loop phase; and (iii) to increase the gain and study the effect on the instability. Object (i) is achieved by performing nonper-

TABLE I. Typical parameters of Ohmic discharges used for feedback experiments.

Parameter	$q_a \lesssim 2.2$	$q_a=2.2-3$	$q_a=3-4$	$q_a=4-5$
I_p (kA)	120	90–120	70–125	70–105
B_ϕ (T)	1.1	1.0–1.25	1.0–2.0	1.5–2.0
$\bar{n}_e$ (10^{19}m^{-3})	1.8	1.3–3.7	0.8–5.0	1.0–4.8
$f_{m=2,n=1}$ (kHz)	8–9	8–10	9–11	10–13
$\tilde{B}_\theta^{\text{wall}}$ (G)	1–3	~ 2	0.3–1	0.1–0.3

turbing open loop experiments with plasma and $f_{\text{applied}} \neq f_{\text{mode}}$,[5,6] and mixing out any coupling. The feedback loop is then closed, and the phase scanned at low gain in a single shot to find the optimum. The optimum corresponds to negative feedback: it is the same as the phase of the current induced in the windings by the mode without feedback. Variations of ~25° about the optimum do not seem to be significant.

When the gain is raised the mode amplitude can be reduced by a factor of 3-5 (Fig. 1), the structure remaining primarily $m=2$, $n=1$. There is a limit to the degree of stabilization that can be achieved, due to a combination of the following: sawteeth-driven bursts (Fig. 1 —these play a critical role before disruption; see below); plasma noise; residual direct coupling; limited power; and bandwidth of the amplifiers—when $|\tilde{B}_\theta|$ is reduced $f_{m=2}$ increases (to $\lesssim 15$ kHz), its spectrum broadens and I_{saddle} does not follow dB_θ/dt precisely. As a result $|\tilde{B}_\theta|_{\min}$ appears to be limited by the amplifier power, showing a steady reduction until the power limit is reached. It has been predicted[7] that the interaction between the mode and the applied helical field may lead to a "phase instability" whereby $f_{m=2}$ changes to increase any phase shift away from negative feedback. This effect is found experimentally to be weak in Ohmic discharges on DITE, and seems not to influence the effectiveness of the feedback. Application of static fields at a similar level has no effect on the $m=2$ behavior, but the perturbation is smaller than used on other experiments.[8]

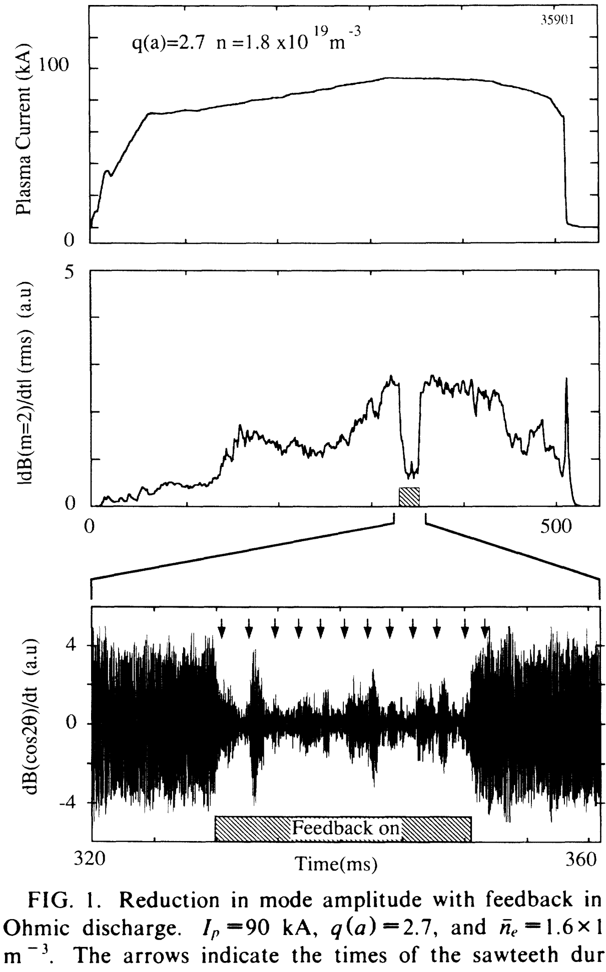

FIG. 1. Reduction in mode amplitude with feedback in an Ohmic discharge. $I_p = 90$ kA, $q(a) = 2.7$, and $\bar{n}_e = 1.6\times10^{19}$ m^{-3}. The arrows indicate the times of the sawteeth during feedback.

Once the optimum phase has been found, $\bar{n}_e$ is raised until disruptions occur and discharges with and without feedback are compared. It is found that the density limit with feedback ($\bar{n}_f$) is higher than without ($\bar{n}_0$), and that $\bar{n}_e$ may be maintained above $\bar{n}_0$ for many energy-confinement times without disruption (Fig. 2, $\tau_E \sim 10$ ms) and occasionally for the whole shot (36690 in Table II). The improvement in $\bar{n}_{\max}$ with feedback is most marked at low $q(a)$, where a 20% increase is achievable. At higher $q(a)$ the effect is present but smaller: 5%-8% at $q(a) = 3.4$ with no significant change for $q(a) \gtrsim 4.0$ (but with less feedback power). Much of this q dependence lies with the reduction in the effective loop gain due to the increased distance between the $q=2$ surface and the feedback windings and detectors. Table II lists a sequence of shots with and without feedback and the density attained. It is seen that there is some variation, possibly due to limiter conditions varying, but an average improvement of 12% is achieved, with a maximum of more than 20%.

The disruption itself apparently always follows a rapid

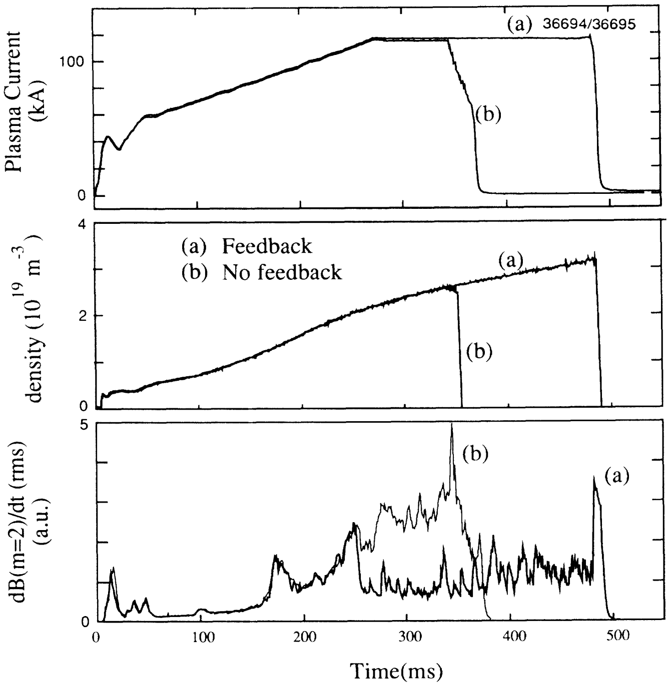

FIG. 2. Extension of the disruptive density limit on DITE by means of $m=2$, $n=1$, magnetic feedback control. $q(a) = 2.4$.

TABLE II. A sequence of discharges with and without feedback at the density limit: $I_p = 115$ kA, $q(a) = 3.4$.

Shot	Feedback?	$t_{\text{disruption}}$ (ms)	$\bar{n}_e$ (10^{19} m^{-3})
36690	Yes	No disruption	3.29
36691	No	340	2.68
36692	Yes	400	2.90
36693	Yes	385	2.84
36694	Yes	480	3.24
36695	No	340	2.68
36696	Yes	405	2.90
36697	Yes	395	2.84
36698	Yes	455	3.07
36699	Yes	435	2.97

growth of $m=2$ activity triggered by a sawtooth in the following way: The 3-5-kHz internal $m=1$, $n=1$ precursor is toroidally coupled to the plasma edge and is visible at a low level on the $m=2$ detector. At the crash, when the (1,1) component normally disappears, the activity at ~10 kHz suddenly increases in amplitude (dominantly $m=2$, $n=1$) and then decays. This happens on a time scale comparable to or less than the characteristic time for the feedback to reduce the mode amplitude, which explains the large size of the burst. As $\bar{n}_e$ is raised towards $\bar{n}_f$ the sawteeth become stronger, with a corresponding increase in the size of the $m=2$ bursts, and probably an increase in the $m=2$ driving force. Eventually one sawtooth leads to disruption in a few ms. Other helicities (e.g., $n=2$) only appear after control has been lost.

In a noise-free infinite-power system a simple model[6,7] predicts that the steady-state island size (W) is dictated by the loop gain ($g \propto I_{\text{saddle}}/\tilde{B}$) and the instability driving force ($\propto \Delta'$). For a finite frequency response there will also be a limit to the value of Δ' that can be controlled. If I_{saddle} is limited by the amplifier and if Δ' is too large, there will be a maximum value of W that can be controlled ($W_{\max}$), for given g. If the gain is too low and if W is rapidly increased beyond $W_{\max}$ by some agent (e.g., noise, sawteeth), then control will be lost. This is qualitatively consistent with the observation of sawtooth-driven bursts leading to disruption on DITE.

Attempts have also been made to control $q(a)=2$ disruptions, but with less success: A ~3% reduction in $q(a)_{\min}$ is achieved, corresponding to the disruption being delayed by 10-30 ms.

Turning now to experiments with lower-hybrid current drive (LHCD): a four-waveguide 1.3-GHz, 300-kW LHCD system has been installed on DITE. The target discharge has $I_p = 100$ kA, $B_\phi = 1.9$ T, and $\bar{n}_e \simeq 7\times10^{18}$ m^{-3}. With current driven in the same direction as the Ohmic current and $P_{\text{LH}} \gtrsim 100$ kW as on other experiments[9,10] the sawtooth is replaced by a continuous large $m=1$, $n=1$ oscillation (5 kHz), at approximately the sawtooth inversion radius. This has a large (~1 G) $m=2$, $n=1$ component that is detected magnetically.

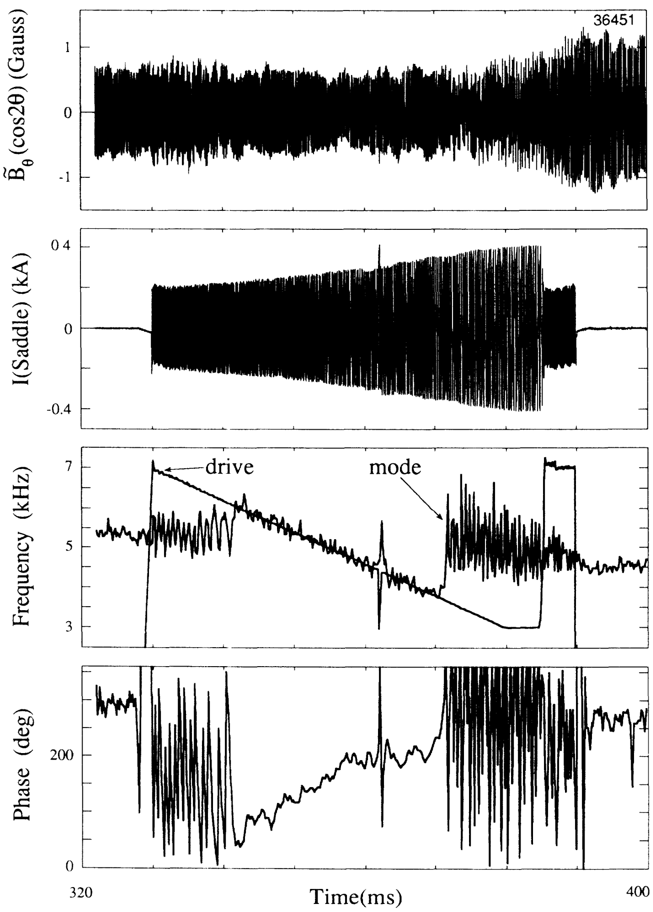

FIG. 3. Mode locking of LHCD-driven $m=1$ mode with the drive frequency swept. There is a phase flip of π at 362 ms.

LHCD discharges allow a direct study of the phase instability: If the saddle coils are driven with a signal generator and phased to give a wave traveling with the mode, then mode locking (movement of f_{mode} to f_{applied}) is observed, provided f_{applied} is close (± ~1 kHz) to f_{mode} (natural). Thus f_{mode} can be changed. It is also found that the phase between the drive signal and the mode depends on $f_{\text{applied}} - f_{\text{mode}}$, varying by $\sim\pi$ across the range of locking frequencies (Δf) (Fig. 3). This phase variation, together with the dependence of Δf on $|\tilde{B}_\theta|$, I_{saddle} places constraints on the theory of the force balance of a rotating magnetic perturbation including any viscosity and resistive wall effects. The phase instability has been investigated by rapidly changing the phase of the external field by π and measuring how long the mode takes to lock again. This time scale is 0.3-3 ms, depending on conditions (typically $\tau_{\text{lock}} \sim \tilde{B}_\theta, I_{\text{saddle}}^{-1}$), and is not a problem given the frequency response of the DITE system. Mode locking is not observed if the wave is traveling in the opposite direction to the mode. Reconfiguring the saddle coils to produce a comparable $m=1$, $n=1$ field also has little effect.

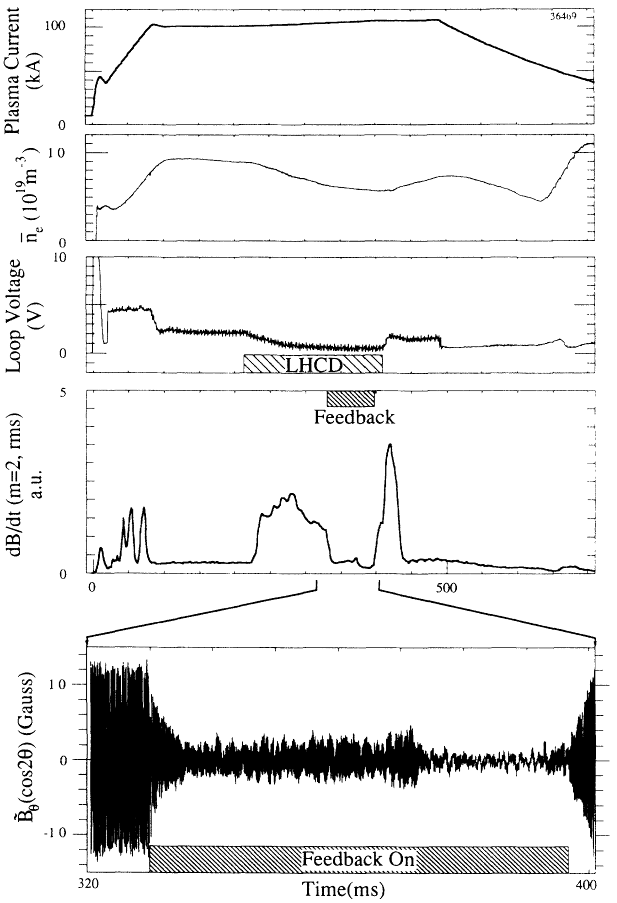

FIG. 4. Control of LHCD-driven $m=1$ mode with $m=2$, $n=1$ magnetic feedback. The loop gain and phase are changed at 370 ms.

If the feedback loop is now closed, then, at low gain, the primary effect of varying the phase is to vary f_{mode}. If the gain is increased, however, than a large reduction in amplitude of the $m=2$ component is possible (Fig. 4). The location of the internal $m=1$ mode remains approximately constant and its amplitude is similarly reduced. The sawtooth remains absent, and the soft-x-ray profile peaks, indicating an improvement in central confinement. The reduction in mode amplitude seems to have little effect on the current drive efficiency, but in cases where the $m=1$ mode has strong particle losses associated with it,[11] then feedback control might be a powerful tool. It should be noted that as on other machines, increasing P_{LH} leads to stabilization of the $m=1$ mode even without feedback, but this requires $P_{\text{LH}} \gtrsim P_{\text{OH}}$.

In summary, the use of a linear feedback system on DITE has allowed the amplitude of saturated $m=2$, $n=1$ modes to be substantially reduced, and disruptions to be avoided or postponed, with an associated improvement in attainable plasma density. When disruptions occur the immediate cause on DITE seems to be mode coupling associated with the sawtooth instability. In the absence of the sawtooth, feedback control would be limited by the combination of plasma noise (of whatever source) and the finite power and bandwidth of the amplifier. Feedback on the $m=2$ mode has also been used to control the internal $m=1$ mode that appears with LHCD, and direct measurements of the phase instability have been made.

An enlargement of the tokamak operating regime is not of itself necessarily advantageous if disruptions still occur, but with feedback a tokamak can be operated with greater safety near the normal limits: For example, the feedback could be used when there is a positive signature of an imminent disruption as a tool to delay the disruption until the plasma parameters can be reduced to safe values.

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