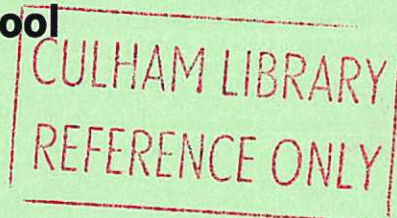
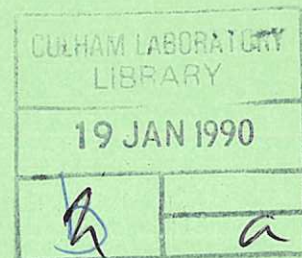

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FEEDBACK STABILISATION OF DISRUPTION

PRECURSORS IN A TOKAMAK

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ABSTRACT

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. Feedback has been used for the first time to significantly increase the disruptive density limit in a tokamak. LHCD on DITE stabilises 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.

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 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 ($R_p = 1.19\text{m}$, $a_{limiter} = 0.23\text{m}$) 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 8 saddle coils inside the DITE vacuum vessel driven by two 250kW transistor amplifiers. 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 $m = 2, n = 1$ detector signals with adjustable multipliers. These multipliers can be changed each half period of the oscillation, and are set from a RAM 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 and its necessarily inductive load.

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

The procedure adopted is (i) to minimise direct coupling between the field produced by the saddle coils and the detectors; (ii) to optimise the feedback loop phase and (iii) to increase the gain and study the effect on the instability. Object (i) is achieved by performing non-perturbing open loop experiments with plasma present at a frequency different from the natural mode frequency [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 $\sim 25^\circ$ 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 (Figure 1), the structure remaining primarily $m = 2, n = 1$. There is a limit to the degree of stabilisation that can be achieved, due to a combination of the following: sawteeth-driven bursts (Figure 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, 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 inter-

action 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 $m = 2$ behaviour, but the perturbation is smaller than used on other experiments [8].

Once the optimum phase for the feedback has been found, the plasma density is raised until disruptions are caused and discharges with and without feedback are compared. It is found that the density limit with feedback (\bar{n}_f) is higher than that without (\bar{n}_0), and that \bar{n}_e may be maintained above \bar{n}_0 for many energy-confinement-times (Figure 2, $\tau_E \sim 10\text{ms}$). 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 $q(a) \gtrsim 4.0$, although this last regime has not been investigated with the full 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 2 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 growth of $m = 2$ activity triggered by a sawtooth in the following way: the 3–5kHz 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 frequency

of the (2,1) component suddenly increases to $\sim 10\text{kHz}$ (the frequency of the background (2,1) activity), the amplitude continues to grow and a large pure $m = 2, n = 1$ mode appears. This happens on a timescale 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 ($g \propto I_{saddle}/\tilde{B}$) and the instability driving force ($\propto \Delta'$). For 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 disruptions at low $q(a)$, but with less success: a $\sim 3\%$ reduction in $q(a)_{min}$ is achieved, corresponding to the disruption being delayed by 10–30ms.

Turning now to experiments with Lower Hybrid Current Drive: a 4-waveguide 1.3GHz, 300kW LHCD system has been installed on DITE. The target discharge has $I_p = 100\text{kA}$, $B_\phi = 1.9\text{T}$, $\bar{n}_e \simeq 7 \times 10^{18}\text{m}^{-3}$. With current driven in the same direction as the ohmic current and $P_{LH} \gtrsim 100\text{kW}$ as on other experiments [9,10] the sawtooth is replaced by

a continuous large $m = 1, n = 1$ oscillation (5kHz), at approximately the sawtooth inversion radius. This has a large (~ 1 Gauss) $m = 2, n = 1$ component that is detected magnetically.

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 travelling with the mode, then mode locking (movement of f_{mode} to $f_{applied}$) is observed, provided $f_{applied}$ is close ($\pm \sim 1$ kHz) to $f_{mode}(\text{natural})$. Thus f_{mode} can be changed. It is also found that the phase between the drive signal and the mode depends on $f_{applied} - f_{mode}$, varying by $\sim \pi$ across the range of locking frequencies (Δf) (Figure 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 [11]. 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 timescale is 0.3–3ms, depending on conditions [11], which is not a problem given the frequency response of the DITE system. Mode-locking is not observed if the wave is travelling in the opposite direction to the mode. Reconfiguring the saddle coils to produce a comparable $m = 1, n = 1$ field also has little effect.

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, then a large reduction in amplitude of both the $m = 2$ and $m = 1$ components is possible (Figure 4). The location of the internal $m = 1$ mode remains approximately constant as its amplitude is 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 [12], then feedback control might be a powerful tool. It should be noted that as on other machines, increasing P_{LH} leads to stabilisation of the $m = 1$ mode even without feedback, but this requires $P_{LH} \gtrsim P_{OH}$.

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. Disruptions still ultimately occur, however, and 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 Lower Hybrid Current Drive, and open loop measurements in such discharges have allowed direct measurements of the phase instability.

An enlargement of the tokamak operating regime is not of itself necessarily advantageous if disruptions still occur, since higher energy plasmas can cause more damage. However, 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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<i>Parameter</i>	$q_a \lesssim 2.2$	$q_a = 2.2 \sim 3$	$q_a = 3 \sim 4$	$q_a = 4 \sim 5$
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}_θ^{wall} (Gauss)	1 ~ 3	~ 2	0.3 ~ 1	0.1 ~ 0.3

Table 1: *Typical parameters of ohmic discharges used for feedback experiments*

Shot	Feedback?	$t_{disruption}$ (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

Table 2: *A sequence of discharges with and without feedback at the density limit.*

$I_p = 115\text{kA}$, $q(a) = 3.4$.

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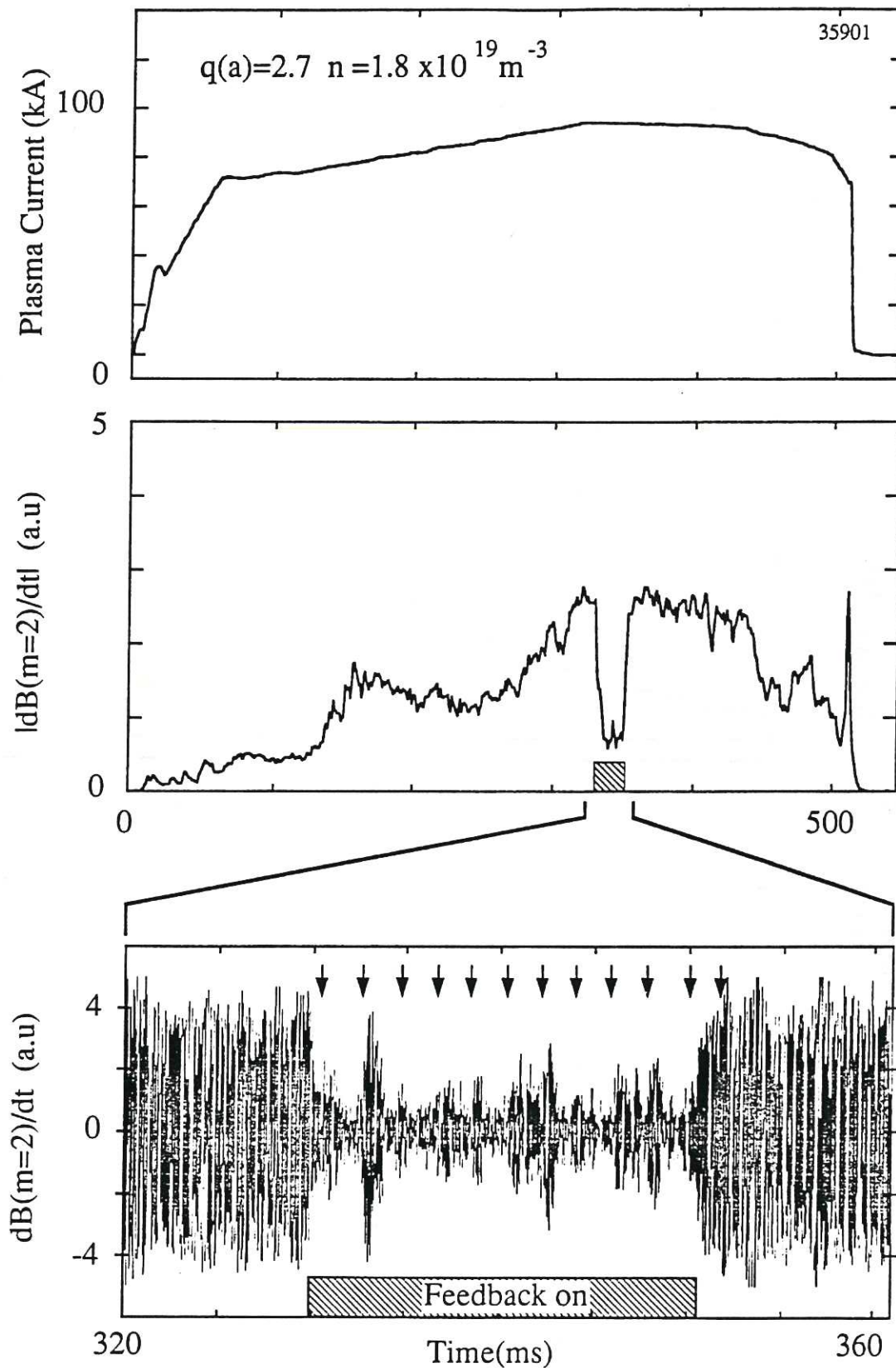


Figure 1: *Reduction in mode amplitude with feedback in an ohmic discharge.*
 $I_p = 90 \text{ kA}, q(a) = 2.7, \bar{n}_e = 1.6 \times 10^{19} \text{ m}^{-3}$ The arrows indicate the times of the sawteeth during feedback.

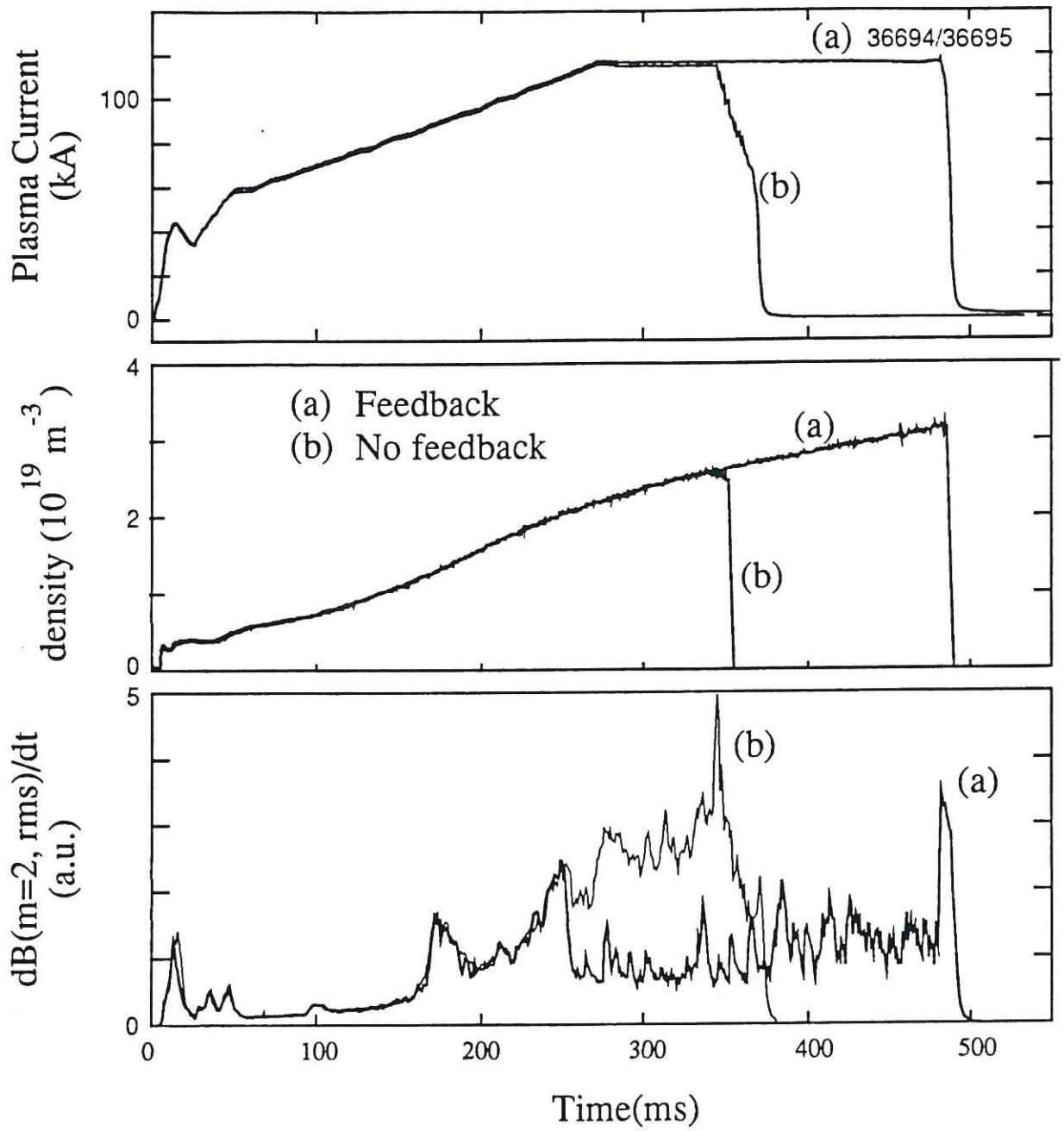


Figure 2: Extension of the disruptive density limit on DITE by means of $m = 2, n = 1$ magnetic feedback control. $q(a) \simeq 2.4$.

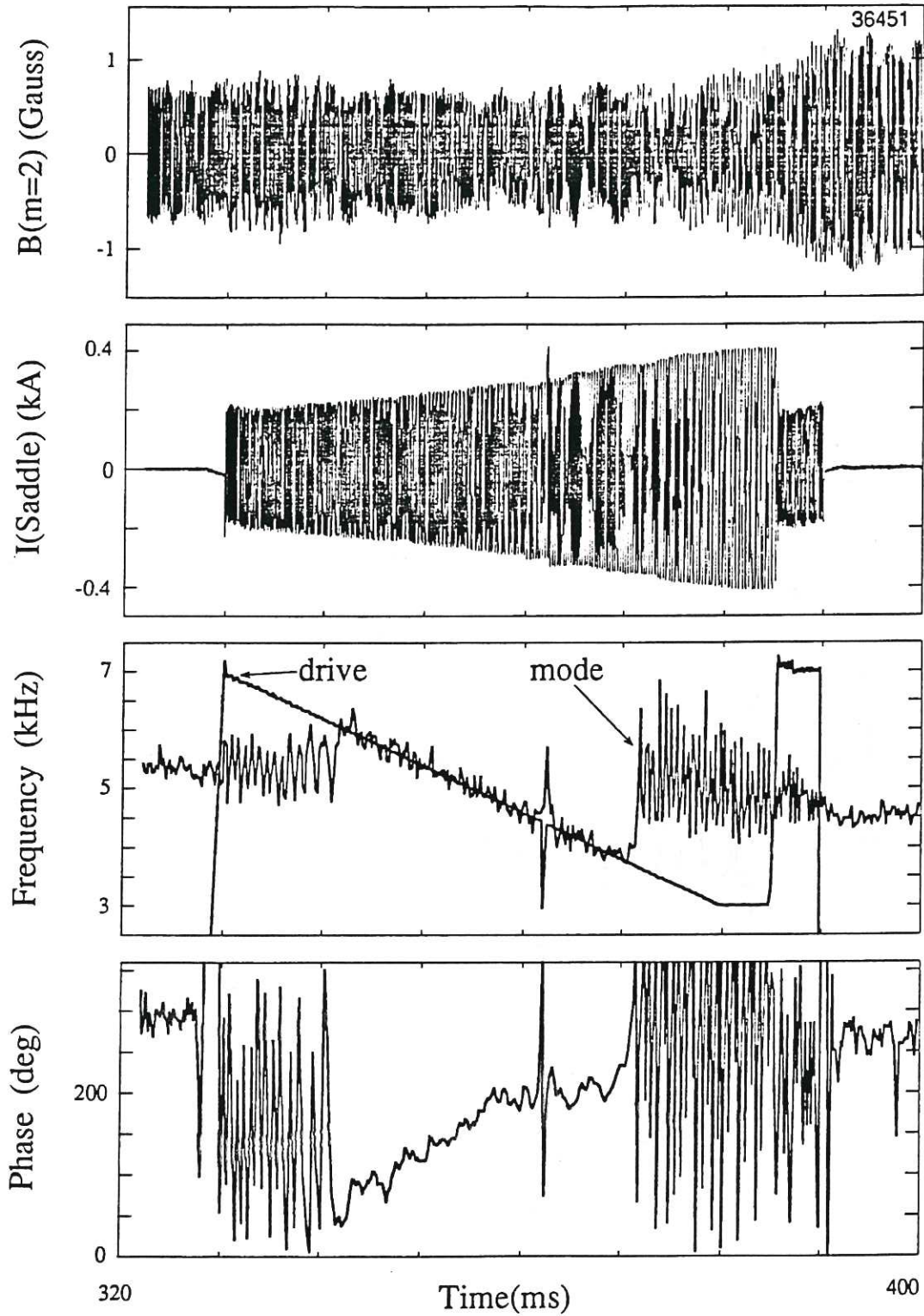


Figure 3: Mode locking of LHCD-driven $m = 1$ mode with the drive frequency swept.

There is a phase flip of π at 362ms.

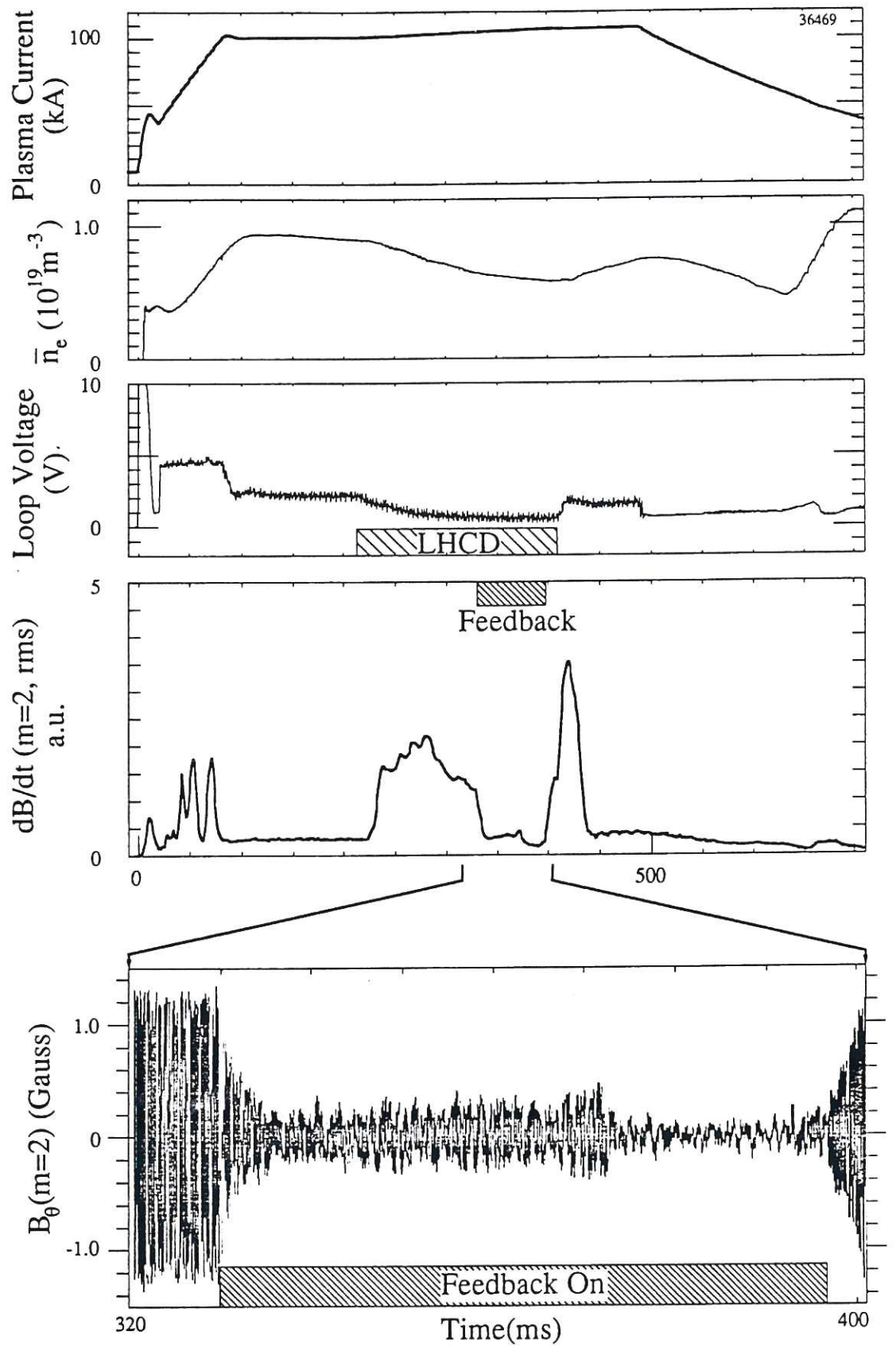


Figure 4: Control of LHCD-driven $m = 1$ mode with $m = 2, n = 1$ magnetic feedback.

The loop gain and phase are changed at 370ms.

