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E. Fredrickson, J. Bialek, A.M. Garofalo, L.C. Johnson, R.J. La Haye,
E.A. Lazarus, J. Manickam, G.A. Navratil, M. Okabayashi,
J.T. Scoville, and E.J. Strait

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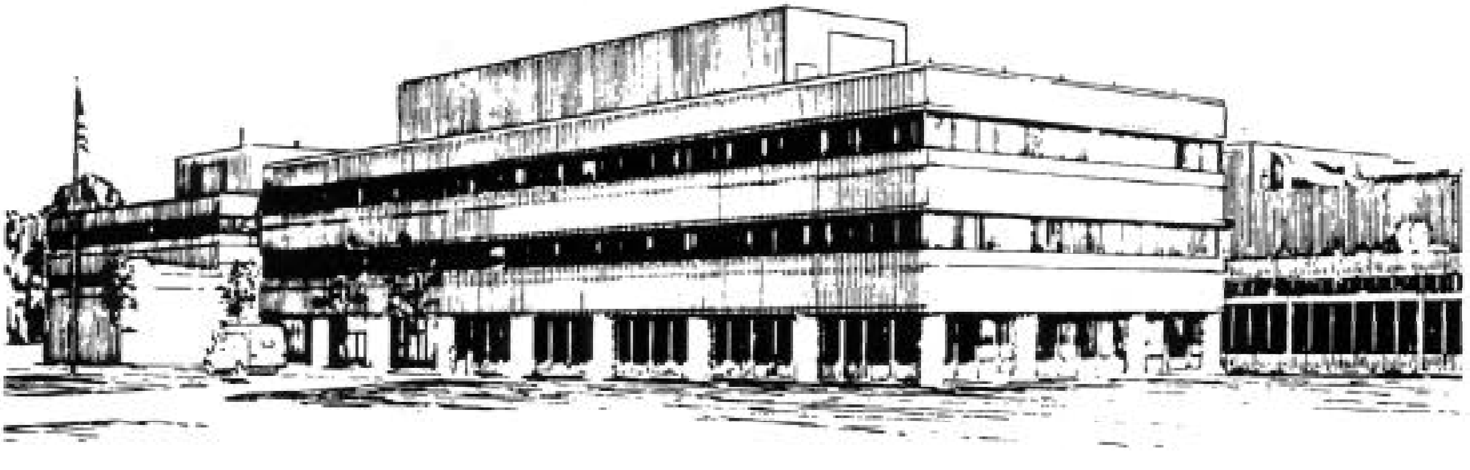

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Closed Loop Feedback of MHD Instabilities on DIII-D

E.D. Fredrickson,[1] J. Bialek,[2] A.M. Garofalo,[2] L.C. Johnson,[1]
R.J. La Haye,[3] E.A. Lazarus,[4] J. Manickam,[1] G.A. Navratil,[2]
M. Okabayashi,[1] J.T. Scoville,[3] E.J. Strait[3]

[1]*Princeton Plasma Physics Laboratory, Princeton, New Jersey*
[2]*Columbia University, New York, New York*
[3]*General Atomics, La Jolla, California*
[4]*Oak Ridge National Laboratory, Oak Ridge, Tennessee*

Abstract

A system of coils, sensors and amplifiers has been installed on the DIII-D tokamak to study the physics of feedback stabilization of low frequency MHD modes such as the Resistive Wall Mode (RWM). Experiments are being performed to assess the effectiveness of this minimal system and benchmark the predictions of theoretical models and codes. In the last campaign the experiments have been extended to a regime where the RWM threshold is lowered by a fast ramp of the plasma current. In these experiments the onset time of the RWM is very reproducible. With this system, the onset of the RWM has been delayed by up to 100 ms without degrading plasma performance. The growth rate of the mode increases proportional to the length of delay, suggesting that the plasma is evolving towards a more unstable configuration. The present results have suggested directions for improving the feedback system including better sensors and improved feedback algorithms.

INTRODUCTION

The external kink can limit the achievable beta, hence performance in many magnetically confined plasma fusion devices including tokamaks [1], reverse field pinches, and spherical tori. The addition of a close fitting perfectly conducting wall can stabilize the mode but, with finite conductivity walls, the growth rate of the mode is only slowed to of order the wall time constant. Methods proposed to extend beta limits closer to the ideal wall limit in future reactor concepts include maintaining the mode rotation, or active feedback to compensate for flux leakage using coils external to the wall [2,3]. In this paper we will discuss an experiment in which a rapid I_p ramp is used to reproducibly excite the RWM. The experiment confirms the initial results of the Resistive Wall Mode (RWM) feedback stabilization experiment reported at the 26th EPS conference [4]. In addition, we will present the details of feedback-stabilized RWM characteristics observed during the rapid I_p ramp.

THE FEEDBACK SYSTEM

The present feedback system on DIII-D is based on an existing "belt" of six midplane picture frame coils (the "C-coils"), each spanning 60º in toroidal angle. A set of six saddle loops installed just outside the vacuum vessel sense the flux leakage. A schematic layout of the sensor coils (saddle loops) and feedback coils (C-coils) is shown in Fig. 1. Both sensor and feedback coils are as close to the vacuum vessel as was reasonably possible.

The C-coils are driven in pairs by the three switching power amplifiers (SPAs). Each C-coil pair consists of two coils separated toroidally by 180º and combined to give only n = odd feedback (where n is the toroidal mode number). The six sensor coil outputs are similarly treated to generate the feedback signal. The maximum voltage available to the SPAs is ≈ 250 V and the maximum current that the C-coils can handle (based on mechanical stress) is 5 kA. With the inductance and resistance of the C-coils the SPAs can drive the maximum feedback current (of 5 kA) at frequencies up to 40 Hz. At frequencies higher than this, the maximum current is limited by the voltage and falls off approximately as the inverse of the frequency.

Experiments last summer showed that the n = 1 flux leakage from the vacuum vessel could be compensated by the feedback system and the amplitude of the MHD mode could be reduced [4]. Code simulations predict that the present feedback system could increase the Resistive Wall Mode beta limit by 10%–15% [5]. We will discuss here experiments where the onset time of the RWM was delayed with the feedback system.

THE RESISTIVE WALL MODE INDUCED BY A RAPID I_P RAMP

In the experiments described here, the RWM beta limit was reduced by ramping the plasma current at rates up to 1.5 MA/s, creating a skin current on the plasma edge. Some representative waveforms from one such plasma shot are shown in Fig. 2. The beta was increased prior to the ramp in plasma current by stepping up the beam power to ≈ 9 MW. The advantage of this experimental approach is that the time of mode onset is very reproducible. The reproducibility of the onset time (without feedback) makes interpretation of the experimental results simpler. The effectiveness of the feedback system is qualitatively indicated by the delay in the RWM onset. Of course, quantitative understanding would still require detailed measurements of plasma parameters and calculations of theoretical mode stability.

In this example the plasma transitions to H-mode at ≈1.1 s as evidenced by the increase in edge rotation during the ELM-free period, and by the drop in H-α light.

Concurrent with the onset of ELMs, the edge rotation begins to slowly decrease. The drop in rotation could be due to several things, including secular changes in the equilibrium plasma parameters or error field amplification due to the high beta. However, it is instructive to note that each ELM event is accompanied by a sharp drop in rotation, suggesting that the ELMs directly affect plasma rotation. Under these conditions, the plasmas reproducibly suffered minor disruptions between 1.35 s and 1.4 s; the timing of RWM mode onset is possibly related to the drop in edge rotation rate below some threshold level.

The sequence of events leading to the minor disruption can be divided into three phases. It begins with a slow collapse of the edge electron temperature and a small, slowly growing mode in Phase I, indicated in Fig. 3. As the thermal collapse progresses and the plasma rotation slows, a threshold is reached where the mode begins to grow rapidly. Concurrent with the rapid growth of the mode, the thermal collapse accelerates. This rapid growth phase is Phase II. In Phase III, the final phase, there is a magnetic reconnection and a disruptive thermal quench.

In Figure 3 it can be seen that the degradation in confinement preceding the disruption begins at 1.375 s with the onset of the edge electron temperature collapse. At the onset of the slow thermal collapse, the resistive wall mode amplitude is <1 Gauss, at the threshold of detectability. Soft x-ray arrays at toroidal angles of 45º and 195º show that most of the displacement of the electron temperature contours in Phase I and II is axi-symmetric, thus the thermal collapse is axi-symmetric rather than a displacement from a mode. Possible explanations for the thermal collapse include an influx of impurities caused by the small amplitude RWM, or the formation of magnetic islands coupled to the RWM. This result suggests that the RWM is just one part of the physics involved in the disruption.

CLOSED LOOP FEEDBACK RESULTS

In Fig. 4 is shown data from a shot in which the fast growth of the resistive wall mode (Phase II) was delayed by 100 ms, similar to what had been previously achieved under different conditions [6]. The feedback circuit apparently keeps the mode amplitude less than ≈ 3 G from ≈ 1.39s to ≈ 1.48s. This amplitude is comparable to the typical amplitude of the mode at the end of Phase I (c.f. Fig. 3). The feedback logic used was “mode control” where the sensor signal is compensated by the feedback coil current so as to leave only a signal from the mode. In the β_N frame, a trace from the discharge of Fig. 2 without feedback is included for comparison.

The SPAs and C-coil also provide time dependent error field compensation according to a predetermined algorithm. For this set of experiments, the SPA control circuitry was not sufficiently sophisticated to simultaneously provide for both feedback control and time dependent error field compensation. In this shot, the feedback was pre-programmed to be enabled at 1.35s, after which the error field compensation was held fixed.

As can be seen in Fig. 4, the H-mode onset and slowing of edge rotation follow a very similar pattern to what was observed in the plasma shown in Fig. 2. The feedback is turned on at 1.35 s. The ELM activity is also much reduced following mode onset (as measured by the amplitude of the H-α bursts). This was also seen in the data shown in Fig. 2. The reduced ELM amplitude could be consistent with an increase in radiated power from the edge plasma, associated with an impurity influx as the RWM is stabilized at a small but non-zero amplitude.

In Fig. 5, the feedback stabilization period is shown in more detail. The radial field amplitude of the RWM inferred from the saddle loop data is $\approx$ 3 G. There is some uncertainty in this estimate due to the uncertainty in compensating for the $n = 1$ component of the intrinsic error fields. The inferred phase of the mode is such as to predict an inward displacement at the location of the ECE radiometer. The amplitude of the RWM remains constant at approximately 3 G until $\approx$1.48 s. At this time, the RWM begins to grow and within 10 ms exceeds an amplitude of about 15 G. A complete thermal quench of the plasma follows (neutrons, ion and electron temperature).

The final growth of the resistive wall mode leading to the thermal quench is likely triggered by the RWM mode drive becoming stronger as the pressure and current density profiles evolve. As shown in Fig. 6, the final growth rate increases from $\approx 300\ s^{-1}$ ($\sim 1/\tau_w$) at early times in shots without feedback, to $\approx 800\ s^{-1}$ in the most strongly stabilized (delayed onset) cases. This result is consistent with an MHD instability drive that increases with time. (The variation in onset time in the figure results from variation of the feedback control algorithm and gain values.) The feedback system tracks the phase and amplitude of the mode up to the thermal quench with a lag of about 0.3 ms. There is no apparent saturation of the feedback amplifiers. This indicates that the present feedback gain is not strong enough to accommodate the rapidly increasing ideal MHD growth rate.

In other experiments in this campaign, it was found that with lower I_p ramp rates the onset of the RWM could be delayed for longer periods. In these experiments the efficacy of derivative, proportional and integral gain terms were investigated which will hopefully lead to improved feedback algorithms. An additional 12 sensor loops above and below the midplane have been installed to measure the poloidal structure of the mode as well as to provide the sensor coils to support the planned extension of the feedback coil array. This information will help to better benchmark the predictions of theoretical codes and models of feedback stabilization.

SUMMARY

Experiments using the RWM feedback system on DIII-D have been extended to a regime where the RWM threshold is lowered by a fast current ramp. In these experiments the RWM onset was very reproducible in time and it was possible to clearly correlate the delay in the mode onset time with feedback control of the mode. The mode growth rate was found to increase proportionally to the length of the delay, suggesting that the plasma was evolving towards a more unstable configuration. Onset of the mode was delayed by up to 100 ms with no significant degradation in plasma performance.

Future plans include improvements in the sensor coils and possible extensions to the feedback coil system (additional coils above and below the midplane and SPAs to drive them). Simulations suggest that reducing the height of the sensor coils will improve the system [7]. Likewise, sensors inside the vacuum vessel, possibly measuring the poloidal rather than the radial field may also improve performance.

ACKNOWLEDGMENT

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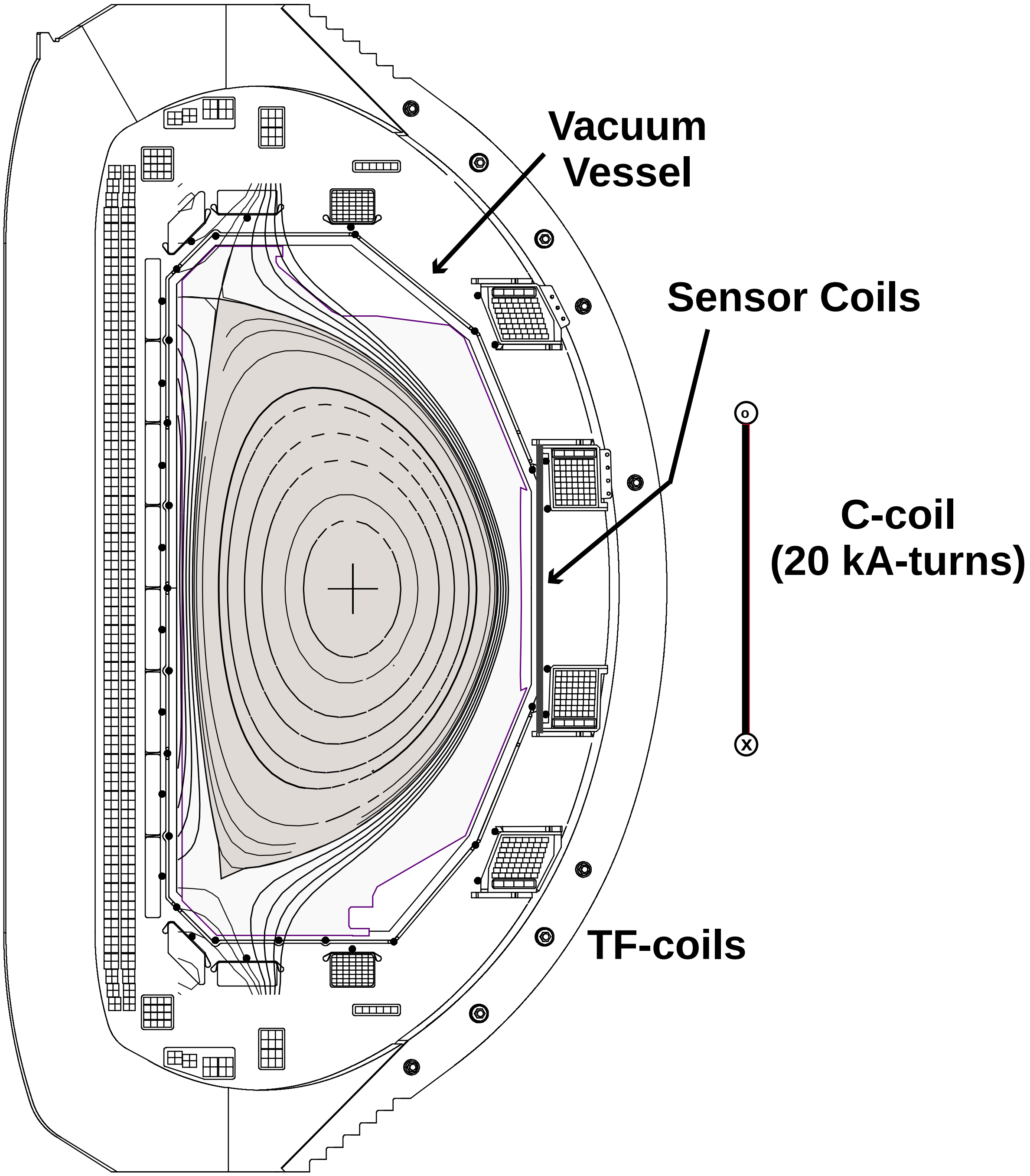

Figure 1. Cross-section of the DIII-D tokamak showing the locations of the toroidal field coils, vacuum vessel, etc. The location of the six sensor coils which measure the radial field is indicated by a heavy vertical line between the vaccuum vessel and the outboard PF coils. The radial location of the six "C-coils" outside the TF coils is also noted.

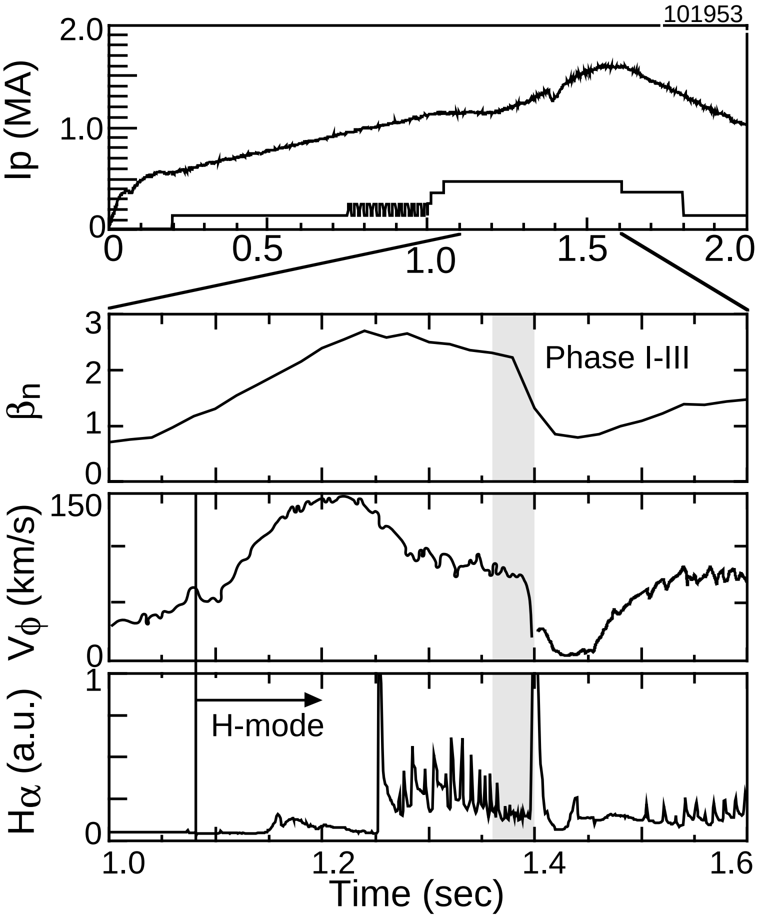

Figure 2. Traces showing the evolution of the plasma current and neutral beam power, β_N, rotation rate at r/a ≈ 0.8 and H-α light as monitored with a photo-diode.

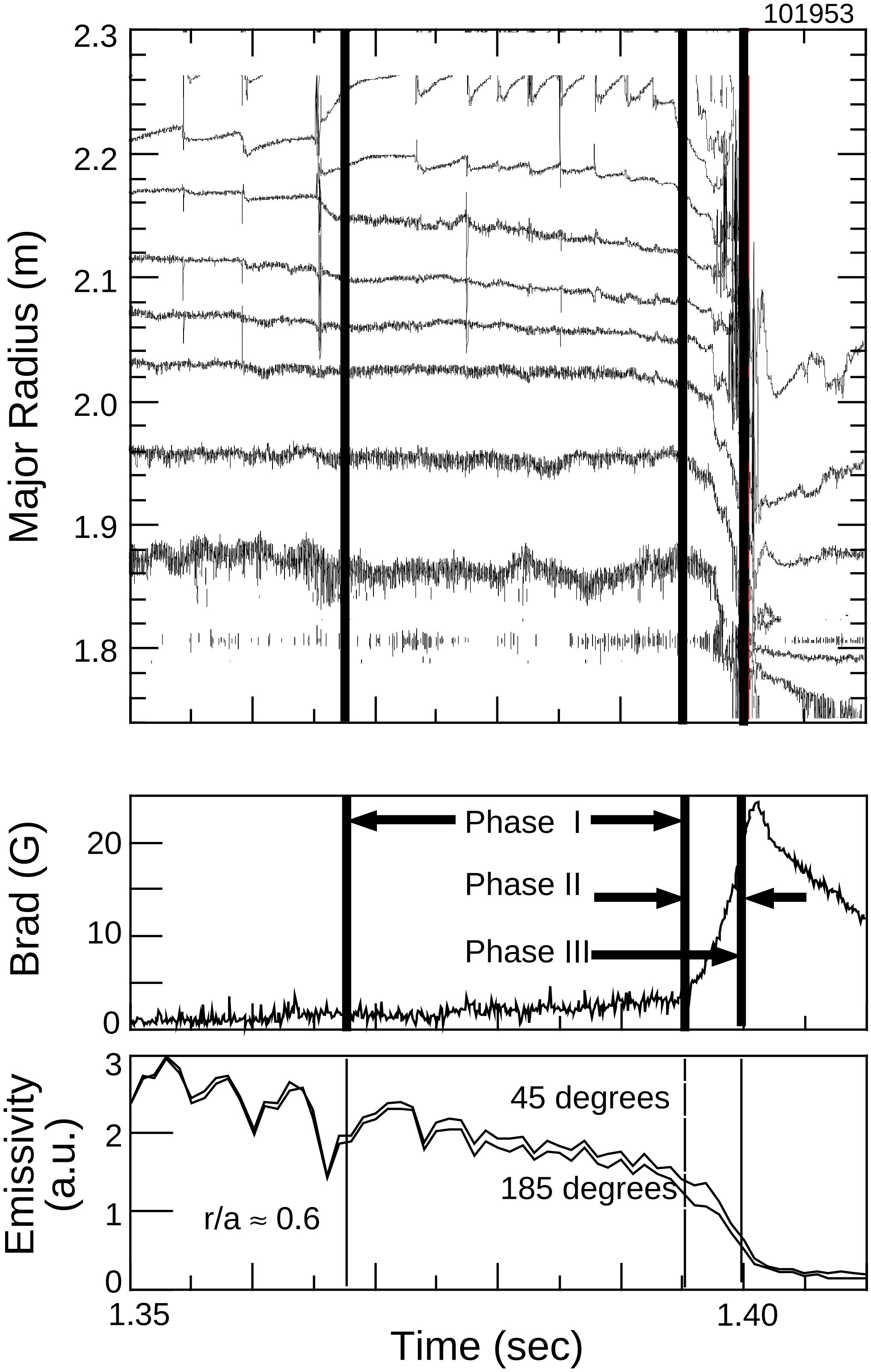

Figure 3. T_e contour plot of the disruption shown in Fig. 2. The lower traces show the amplitude of the RWM and x-ray emissivity from two toroidally separated arrays.

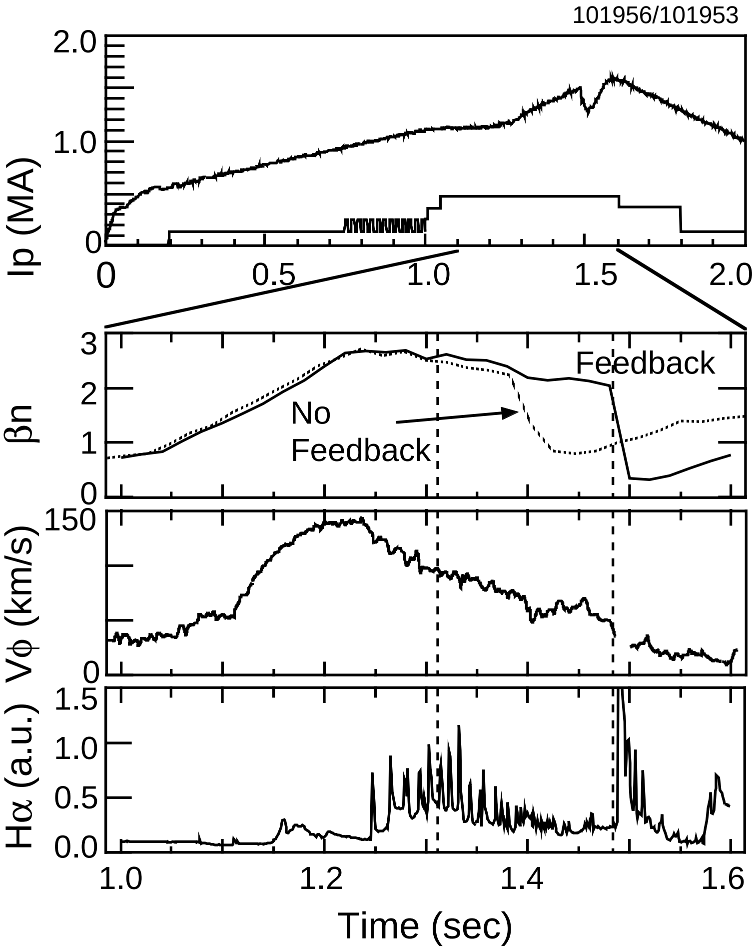

Figure 4. Traces showing the evolution of the plasma current and neutral beam power, β_N (with and without feedback), rotation rate at r/a≈0.8 and H-α light. The dashed lines show the onset time of Phase I and the disruption time marking the end of Phase III.

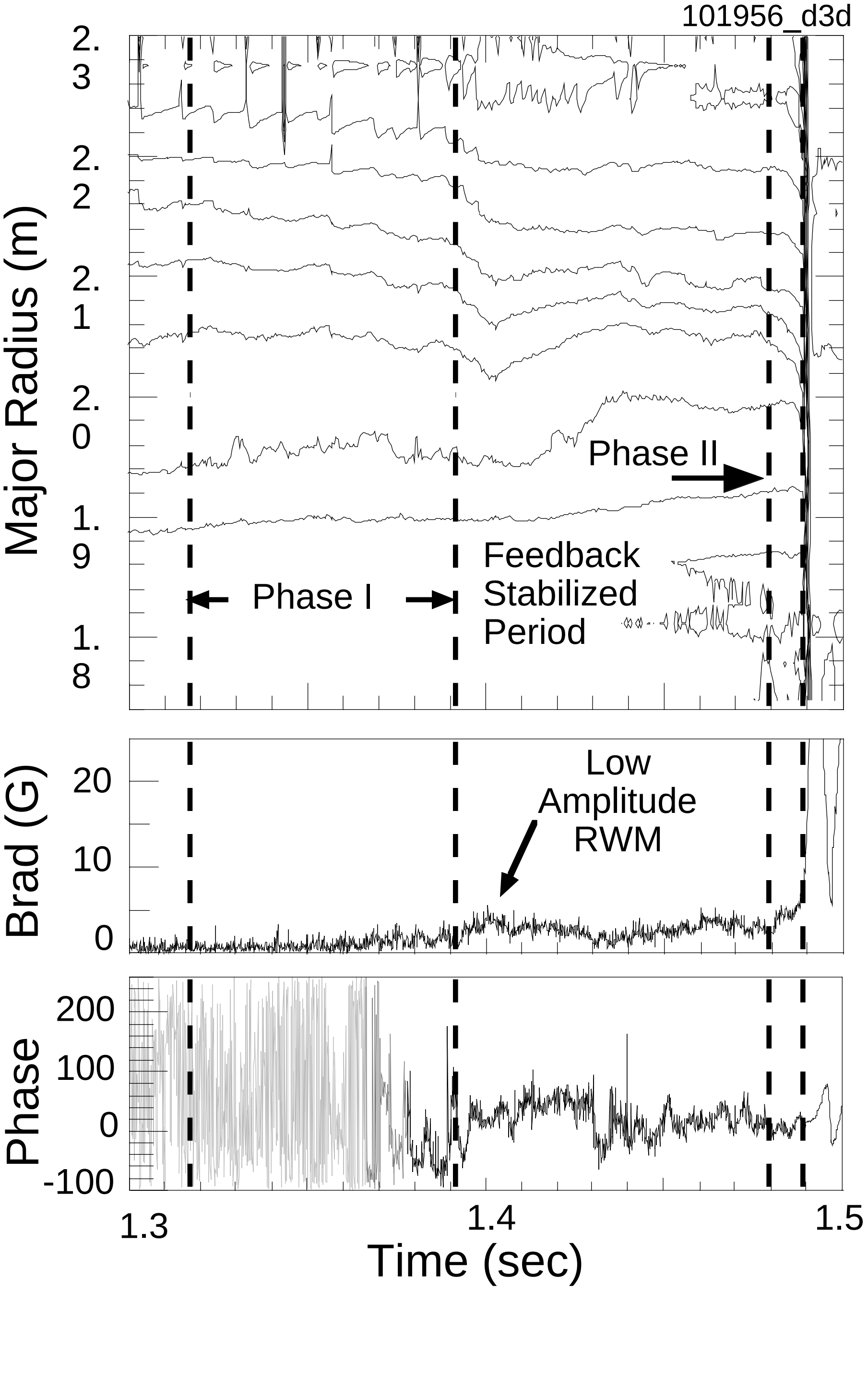

Figure 5. T_e contour plot of the disruption shown in Fig. 4. The lower traces show the amplitude and phase of the RWM.

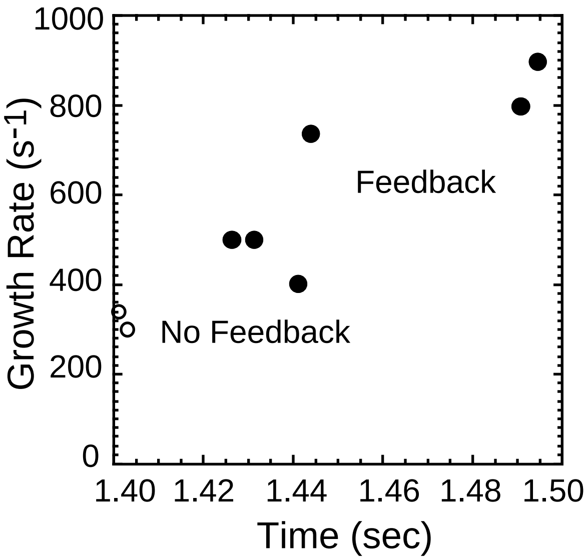

Figure 6. Observed growth rate vs. onset time of the RWM.

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