PPPL-2134

UC20-F, G

DR-0387-5

PPPL-2134

I-16922

OBSERVATION OF FINITE- β MHD PHENOMENA IN TOKAMAKS

By

K.M. McGuire

SEPTEMBER 1984

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

OBSERVATION OF FINITE- β MHD PHENOMENA IN TOKAMAKS

K.M. MCGUIRE

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

PPPL--2134

DE84 017072

ABSTRACT

Stable high-beta plasmas are required for the tokamak to attain an economical fusion reactor. Recently, intense neutral beam heating experiments in tokamaks have shown new effects on plasma stability and confinement associated with high beta plasmas. The observed spectrum of MHD fluctuations at high beta is clearly dominated by the $n = 1$ mode when the $q = 1$ surface is in the plasma. The $m/n = 1/1$ mode drives other $n = 1$ modes through toroidal coupling and $n > 1$ modes through nonlinear coupling. On PDX, with near perpendicular injection, a resonant interaction between the $n = 1$ internal kink and the trapped fast ions results in loss of beam particles and heating power. Key parameters in the theory are the value of q_0 and the injection angle. High frequency broadband magnetic fluctuations have been observed on ISX-B and D-III and a correlation with the deterioration of plasma confinement was reported. During enhanced confinement (H-mode) discharges in divertor plasmas, two new edge instabilities were observed, both localized radially near the separatrix.

By assembling results from the different tokamak experiments, it is found that the simple theoretical ideal MHD beta limit has not been exceeded. Whether this represents an ultimate tokamak limit or if beta optimized configurations (Dee- or bean-shaped plasmas) can exceed this limit and perhaps enter a second regime of stability remains to be clarified.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

1. Introduction

In order to achieve the densities and temperatures required for a successful thermonuclear reactor, the plasma energy must be contained by a magnetic field for a sufficiently long time. In the attempts to achieve this confinement, the issue of macroscopic stability has long been viewed as one of the most important. A plasma confined by a magnetic field is potentially able to break out of the confinement system by a large variety of instabilities, and a number of magnetic field configurations have been proposed which could confine a hot plasma in equilibrium.

When the first toroidal devices /1,2/ for plasma heating and confinement began operation in the early 1950's, the plasma was confined only by the poloidal field due to the plasma current. These discharges were unstable due to "sausage" and "kink" instabilities which led to the destruction of the plasma column on a short time scale /3/. The severity of these instabilities was reduced, but not removed, by the addition of a stabilizing toroidal field ($B_T = B_0$) /4/. Further improvement was found when a strong toroidal field ($B_T \gg B_0$) was applied and this new field configuration was called a tokamak /5/.

In a tokamak the plasma may be unstable against a variety of macroscopic or magnetohydrodynamic (MHD) instabilities with a space dependence $\xi(r) \exp[i(m\theta + n\phi)]$, where $m = 0, 1, 2, \dots$, and $n = 0, 1, 2, \dots$ (m and n are the poloidal and toroidal mode numbers). There are at least three categories of MHD phenomena which are observed in low-beta, ohmically heated tokamak devices.

- a) Sawtooth oscillations are observed as relaxation oscillations in the soft x rays emitted from the central part of the plasma column;

- b) Mirnov oscillations are sinusoidal magnetic field oscillations which can be detected outside the plasma column and correspond to moving helical structures or distortions near the edge of the plasma and;
- c) The disruptive instability is an abrupt expansion of the temperature and current profile accompanied by a large negative voltage spike, and an increase in the plasma current. In addition, a decrease in the plasma internal inductance and an inward major radial motion of the plasma column take place. The disruptive instability can terminate the plasma discharge and cause damage to the device, but it can generally be avoided by carefully selecting the operating parameters.

Under normal ohmic heating tokamak operation very little MHD activity is detected by magnetic loops during the equilibrium phase. When detectable magnetic activity does occur, the mode number is usually an $m/n = 2/1$ which rotates in the electron diamagnetic direction. At plasma start-up, high- m modes are detected on the magnetic loops with helical structures $m/n = 6/1, 5/1, 4/1$, and $3/1$. The most commonly observed MHD phenomena in a tokamak device is the "sawtooth oscillation" /6/ which is observed on the soft X-ray signal as an $m/n = 0/0$ equilibrium change with an $m/n = 1/1$ precursor mode.

The sawtooth instability with its finite-beta manifestations will be the main subject of this paper. In addition, new instabilities observed at high beta and during enhanced confinement discharges will also be discussed. Results of high frequency turbulence as observed by microwave and CO_2 scattering and its relationship to confinement will not be discussed. The

results from these diagnostics are promising and we can hope to see significant contributions to the confinement picture at high beta from these experiments.

2. Sawtooth Oscillations and $m = 1$ Activity

Since their discovery in the ST tokamak /6/, "sawtooth oscillations," which are sometimes referred to as "internal disruptions," have remained one of the intriguing phenomena of tokamak discharges. Von Goeler and others /6,7/ observed that the soft X-ray emission from the plasma exhibited a sawtooth structure, as a function of time, with a superimposed growing $m/n = 1/1$ sinusoidal oscillation. The symmetry of a given sawtooth was found to be $m/n = 0/0$. For present day tokamak devices, sawtooth periods between 0.1 to 50 ms are observed.

Many models have been developed to explain the sawtooth behavior of the soft X-ray signals /8-13/. A scenario (due to Kadomtsev and Monticello) which explains the main features is as follows: The plasma current tends to concentrate at the magnetic axis because the center of the plasma generally heats up more than the edge. This heating on axis causes the q -value ($q = rB_T/RB_0$) to drop below unity at the magnetic axis which destabilizes the $m/n = 1/1$ tearing mode, then nonlinear reconnection of this $m/n = 1/1$ mode causes the temperatures and current profiles to flatten over the center of the plasma. Outside the $q = 1$ surface the temperature increases at the internal disruption giving an inverted sawtooth structure on the soft X-ray signal. The excess temperature outside the $q = 1$ surface diffuses away and the center of the plasma heats up again leading to another sawtooth oscillation.

The above description of the sawtooth oscillation and the $m, n = 1/1$ precursor mode refers to low β_p and ohmically heated plasmas only. As β_p is

increased, the $m/n = 1/1$ mode couples or drives many other higher- m modes, through toroidal and nonlinear coupling. This mode coupling will be discussed in the next section.

3. Finite- β Modifications of MHD Activity

3.1 With Ohmic Heating

High-beta plasmas have been obtained in many ohmically heated tokamaks /14-16/. On the TOSCA tokamak /14/ total β values on axis were $\approx 5\%$ and the main limit to increasing the beta was major disruption activity. On the Torus II tokamak /16/ peak betas of 40% have been obtained. Using a dual beam CO_2 laser interferometer system, the plasmas at these high-beta values were found to be unstable to $n = 10-16$ modes with a frequency of 250 kHz rotating in the ion diamagnetic direction. The amplitude of this instability was largest on the large major radius side of the pressure profile, indicating the presence of a high- n ballooning mode.

3.2 With Neutral Beam Heating

In this section a summary of experimental observation of MHD activity during neutral beam injection will be presented. The results will be limited to the sawtooth oscillation and its coupled modes. The normal $m/n = 2/1$ mode and the disruptive instability will not be discussed, as it is generally considered that the $m/n = 2/1$ mode without sawteeth leads to inferior plasma conditions. So the basic discharges discussed will be those which normally have sawteeth present in the ohmic heating phase.

With the use of high power neutral beams, many tokamaks (ATC /7/, ORMAK /11/, PLT /17/, T-11 /18/, DITE /19/) found that the sawtooth period

increased and that the $\Delta T_e/T_e$ also increased during the neutral beam heating phase of the discharge. With high power neutral beam heating, the plasma beta can be raised to higher values than were possible with ohmic heating alone. The study of the MHD stability of these high-beta plasmas has been undertaken by many experimental groups [20-23].

3.2.1 The JFT-2 Tokamak

The first group to report on the effects of high beta on tokamak plasma stability during neutral beam injection was the JFT-2 team [20]. They found that the sawtooth repetition time and the amplitude of the enhanced sawtooth oscillations during the NBI heating phase, as was observed even in low- β experiments, were greater than the corresponding values of typical sawtooth oscillations with ohmic heating alone. The magnetic fluctuation level was low, except during the sawtooth disruption itself. As the sawtooth disruption phase was approached, an $m/n = 2/1$ poloidal fluctuation with the same frequency as the $m/n = 1/1$ grew and abruptly increased during the internal disruption phase, as is shown in Fig. 1.

For the JFT-2 device, four types of internal oscillations were observed in their beam heated discharges. They were i) enhanced sawtooth oscillations with long repetition time and large sawtooth amplitude, ii) rounded sawteeth and/or reduced sawtooth oscillations with short repetition time and small amplitude, iii) high frequency oscillations without sawtooth oscillations, and iv) high frequency oscillations with sawtooth oscillations. A summary figure of the MHD activity observed as a function of q_a is shown in Fig. 2. In the regions indicated by solid lines the corresponding modes were observed predominantly and these modes were observed occasionally in the regions marked by the dotted lines. Round sawtooth

oscillations (RS) or high frequency oscillations without sawteeth (H) tended to appear in discharges with higher q_a -values if the NBI power was fixed. In low- q_a discharges of $q_a \sim 2$ with a high injection power of 1-2 MW, only enhanced sawtooth oscillations (ES) were detected.

The JFT-2 group found that the enhanced sawtooth oscillations (ES) could be explained by Kadomtsev's theory /8/. The round sawtooth oscillations (RS) may be associated with higher radiation loss. The high frequency oscillations without sawtooth oscillation might be due to a resistive internal mode. The high frequency oscillations with sawtooth oscillations tended to appear in discharges with high injection powers. The JFT-2 team did not make any definite statement about the effects of these MHD modes on plasma transport.

3.2.2 The ISX-B Tokamak

High-beta plasmas have also been obtained on the ISX-B tokamak /24/. Neutral beam heating with up to 2.5 MW from two co-injected beams produced volume-averaged total β of $\sim 2.5\%$. An extensive study of the effects of high beta on the plasma stability has been reported by the ISX-B team /21,25,26/. The observed spectrum of MHD fluctuations was clearly dominated by the $n = 1$ mode when the $q = 1$ surface was inside the plasma, with the $m/n = 1/1$ mode being the dominant instability. It drives $n = 1$ modes through toroidal coupling and $n > 1$ modes through nonlinear couplings. Their present results indicate that the high-beta ISX-B equilibria are marginally stable to finite- n ideal MHD modes.

For the $n = 1$ dominated discharges, the instability signals were altered whenever the injected beam power exceeded the ohmic power. The changes were first marked by the lengthening of the interval of $m = 1$ activity

before the internal disruption and the simultaneous appearance of a strong poloidal magnetic field fluctuations $\tilde{B}_\theta$ at the same frequency as the $m = 1$ oscillation on the X-ray signal. Thereafter, the visual appearance of the instability patterns (i.e., of the envelopes of the oscillatory components of X-rays and B_θ) varied with plasma parameters. These signal patterns are illustrated by the X-ray traces shown in Fig. 3, which gives samples for plasmas with dominant $m/n = 1/1$ mode activity ($q_a < 4.5$). The $\tilde{B}_\theta$ envelopes look like these as well, since the $\tilde{B}_\theta$ and X-ray signals were locked in frequency and in amplitude once the $P_B/P_{OH} \gtrsim 1$ threshold was exceeded. The rapid modulation pattern shown as the final example in Fig. 3(c) looks quite similar to signals from "fishbone" activity subsequently observed in the PDX /22/. Signals like these were rare in ISX-B and no particular confinement deterioration was associated with them.

The $\tilde{B}_\theta$ signal amplitude for ISX-B at the magnetic coils often exceed $\tilde{B}_\theta/B_\theta = 1\% / 21/$ at major radius $R \approx R_0 + 0.3$ m near the outside equator, where the $m/n = 2/1$ mode symmetry was found to be dominant. The results from ISX-B are somewhat similar to those just described on JFT-2. The machines are comparable both in size and beta value and it appears that the same basic instability was present in both machines.

The ISX-B group has shown that there is no clear experimental correlation between the observed mode activity ($m/n = 1/1$) and the degradation of confinement with increasing P_D . They have studied toroidal field (B_T) scans at fixed plasma current and density, which use the fact that raising the edge q reduces the intensity of the $m = 1$ and driven modes and, presumably, any associated losses. Scans at $P_D \approx 2$ MW yielded essentially constant β_p despite marked changes in MHD intensity. With P_D reduced to 0.6 MW, the amplitude of the instability signals again decreased markedly as B_T was

raised. However, β_p did not increase; neither did the stored energy ($\propto \beta_p I_p^2$) or the gross confinement time ($\propto \beta_p I_p^2 / P_{IN}$).

The ISX-B group then turned their attention to high frequency oscillations in order to understand the degradation in confinement with β_p . A few special high-frequency magnetic loops were installed at the larger major radius side of the torus at one toroidal location. The spectrum observed by the magnetic loops could be characterized as follows: (1) A clean peak at frequencies between 5 and 25 kHz (depending on the parameters of the discharge) with higher harmonics was often present (Fig. 4a). The peak corresponded to the $n = 1$ mode and dominated the spectrum when there was a significant plasma volume within the $q = 1$ surface, as was usually the case. (2) A high-frequency tail, resolvable out to 250 kHz, was present independent of the $n = 1$ mode (Fig. 4b). The amplitude increased with beam injection power and the poloidal correlation lengths were typically on the order of 5 cm. (3) At times, highly coherent structures in the tail, generally between 100 and 200 kHz, were observed. For at least some of these there was evidence that they were present for only brief intervals during the discharge.

Studies of the magnetic fluctuations near the plasma edge were conducted for different neutral beam powers (Fig. 4). The $\tilde{B}_\theta$ spectra extend far beyond the range of the $m/n = 1/1$ mode (typically 5 to 25 kHz). The high frequency tail was present independent of the $m = 1, n = 1$; its amplitude level increased with neutral beam heating, and the increases developed after beam turn on in a fashion similar to the development of β_p . Details of the spectra were complex, and the ISX-B group has identified some features that do correlate with plasma confinement. In addition, the experimental results agree well with theoretical calculations on resistive ballooning modes [25]; thus the modes may be responsible for the deterioration in confinement at high values of β_p in ISX-B.

3.2.3 The PDX Tokamak

Experimental investigations of high-beta plasmas produced in PDX with near-perpendicular neutral beam injection have been reported /22,27,28/. Systematic power scans were performed over a wide range of toroidal fields ($0.7 \text{ T} < B_T < 2.2 \text{ T}$) and plasma currents ($200 \text{ kA} < I_p < 500 \text{ kA}$). A summary plot of PDX data is shown in Fig. 5 which shows a boundary above which all the discharges were characterized by "fishbone" activity (the name "fishbone" derived from the appearance of repetitive short bursts of oscillation on the Mirnov traces, which formed an overall pattern reminiscent of the skeletal structure of a fish). Also shown as a dotted line is the region where the "fishbone type activity" causes significant fast ion loss. At its highest levels the MHD fluctuation was so pronounced that it was observed on nearly all diagnostics with sufficient time response.

The evolution of the MHD activity with increasing $\beta_T q_{\text{cyl}}$ is shown in Fig. 6. The X ray and $\tilde{B}_\theta$ signal before and during a sawtooth are displayed along with an expanded time scale for the magnetic oscillations. It is clear that the coupling of the $m = 1$ sawtooth precursor increases with $\beta_T q$. In addition, with $\beta_T q \sim 0.027$ it is clear that the high frequency (10-20 kHz) $m = 1$ mode associated with the "fishbone" activity and the $m/n = 1/1$ mode (1-10 kHz) associated with the fall of the sawtooth oscillation are interspersed, indicating that they are distinct modes.

The soft X-ray emissivity and the $\tilde{B}_\theta$ measurement from the Mirnov coils were used to characterize the evolution of MHD activity as the beam power was increased. Here again the PDX results were similar to those observed on JFT-2 and ISX-B as described in the previous sections. At low beam power and low toroidal field ($\beta_T q < 0.025$) the $m = 1$ sawtooth precursor

oscillation observed near the $q = 1$ surface on the soft X-ray system coupled to higher- m modes detected on the magnetic loops. At higher injected power or high values of $\beta_{Tq} \sim 0.045$, many large envelopes of $m = 1$ activity were seen on the soft X-ray signals throughout the normal sawtooth period. These bursts of $m = 1$ oscillations were very clearly observed on the magnetic coils (Fig. 7). Spikes of greatly increased charge-exchange neutral efflux were observed to be phase and frequency correlated with the magnetic loop. At moderate instability levels, the spikes were observed in the charge-exchange neutral energy range from $E_{INJ}/2$ to E_{INJ} . At high fishbone levels, however, the spikes were observed at energies as low as a few T_i , and as high as $2 \times E_{INJ}$. In addition, there is a marked depletion in the fast ion distribution between $E_{INJ}/2$ and just below E_{INJ} (Fig. 8). In the angular scan range available, from counter near-perpendicular to counter parallel, the charge-exchange spikes and depletion are seen to occur primarily at the near-perpendicular angles.

Also shown in Fig. 7 is the rapid drop observed in the neutron emissivity. The peak-to-peak modulation was as high as 40% of the average emissivity (i.e., $\Delta I_n/I_n = 0.4$). Neutron emission in these conditions ($D^0 + H^+$) is almost completely due to beam-target and beam-beam reactions; the thermonuclear production rate being much smaller.

Calculations in the transport analysis code using a fishbone loss model calibrated to the neutron modulation and charge-exchange measurements indicated that fishbone losses of fast ions could serve to explain some of the observed strong saturation of heating, although an additional loss of thermal confinement may also be present.

The experimental results from PDX were again similar to those observed on JFT-2 /20/ and ISX-B /21/ except that in the PDX case a large loss

of fast ions were observed at β_{Tq} values of ~ 0.055 . The ISX-B and PDX experimental results led to simulations of the internal kink modes which correctly predicted the mode structure as observed in the experiment, namely $m = 1$ from X-rays and $m = 2+4$, $n = 1$ from Mirnov coils /21,29/. Monte Carlo calculations of beam ion orbits in these fields revealed a wave-particle resonance when the mode was rotated at speeds near the precession frequency of the deeply trapped beam ions /30/. The resonance led to secular motion of the beam ions across flux surfaces and their expulsion from the plasma. This result was in agreement with evidence from the experiment where large drops in the neutron emission and bursts in the high energy charge-exchange flux were correlated with Mirnov coil oscillations.

Three additional diagnostics were added to PDX to study this phenomena; a D^+ detector to measure the flux of escaping ions, a set of RF probes to investigate the possibility that RF instabilities were involved in the acceleration of beam ions above the injection energy, and a pair of vertically viewing charge-exchange detectors to determine the major radial location of lost ions /31,32/. From high-beta PDX discharges, bursts in the D^+ detector signal and the RF emission level (at certain frequencies) were found to coincide with Mirnov coil oscillations. An expansion of one fishbone type oscillation on a fast time scale (Fig. 9) shows the modulation of a D^+ detector and the RF probe. It is not yet clear what part if any the RF waves play in the acceleration of beam ion above the injection energy. From the vertically viewing charge-exchange analyzer, it was confirmed that the fishbone instability has an $n = 1$ mode number and that it ejects beam ions in a toroidally rotating beacon directed outward along a major radius. Observations of ejected ions with up to twice the beam energy on the low field side of the torus indicate the presence of a non- μ -conserving acceleration mechanism.

Recent analysis of the PDX data revealed large differences in fishbone activity at similar values of $\beta_T q$, between injection of $D^0 \rightarrow D^+$ or $D^0 \rightarrow H^+$ and $H^0 \rightarrow D^+$. In addition, it was also observed that for H-mode discharges with $D^0 \rightarrow H^+$ or $D^0 \rightarrow D^+$, that the fishbone amplitude can decrease dramatically after the transition from L-mode to H-mode confinement. These results indicate the possible importance of the q-profile and q_0 (q at the axis) in determining the stability of a certain discharge. This profile dependence is clearly observed for H-mode discharges, because after the transition from L- to H-mode, the sawtooth amplitude sometimes decreases and the period lengthens, in some cases the sawteeth disappear, and the fishbone amplitude is observed to decrease dramatically.

3.2.4 The D-III Tokamak

Neutral beam heating experiments on the Doublet-III tokamak have addressed the problem of obtaining high-beta values /23,33/. In limiter discharges, β_T values up to 4.6% were obtained. The Doublet-III group observed large differences in MHD activity between divertor and limiter discharges at high beta. Figure 10 shows a summary of MHD activity observed on D-III with a plot of stored energy divided by $I_p \sqrt{k}$ (where k is elongation) versus power input to the discharge. In the limiter discharges no bursting type MHD activity was observed, but instead broadband fluctuations were detected by Mirnov coils. In contrast, for divertor discharges (H-mode discharges) the soft X-ray signal was modulated by bursting type MHD activity, similar to "fishbone oscillations" observed on PDX. In addition, the D-III group has also observed bursts in the charge-exchange flux associated with the bursts on the Mirnov coil. At high $\beta_p (>1.5)$ the fishbones cause measurable fast ion loss on D-III. However, no serious deterioration of confinement was observed in the presence of these bursting fluctuations.

As shown in Fig. 10, the D-III group observed broadband fluctuations in the limited and divertor discharges at high beta. This result is somewhat similar to the ISX-B results: There was modest correlation of the broadband fluctuations and a deterioration in confinement for all types of discharges.

4. New Forms of MHD Activity Observed at High β

4.1 High-Frequency Oscillations

As mentioned in section 3 above, broadband fluctuations were observed on both the ISX-B and the D-III tokamaks. Some correlation of the presence of these broadband fluctuations and a deterioration in plasma confinement was found. In addition, on ISX-B a high frequency 100-200 kHz fluctuation was observed after the fall of the sawteeth; from magnetic loop data it was inferred that $n \approx 10$. This mode appeared not to affect the plasma confinement /34/. On the PDX tokamak, when the fishbone activity did not explain the general decrease in thermal confinement time with increasing beta, and explained only the saturation at the lowest B_T , additional measurements were made to detect other possible types of MHD activity. A high frequency mode (50 - 150 kHz) was detected by the Mirnov coils and on the soft X-ray array /22,35/. The mode was sometimes a precursor to the fishbone and itself caused a significant drop in the neutron emission. The exact mode number was difficult to measure, but estimates were $n \sim 2-6$ and $m \sim 2-6$ and the mode appeared strongest near the $q = 1$ surface. Figure 11 shows the detailed structures of the MHD activity during a high power PDX discharge; of special interest is the last expansion from 382 to 383 ms, showing a clear coherent oscillation of > 91 kHz just before the growth of a fishbone oscillation.

Theoretical calculations /36/ of PDX equilibria at high beta indicate that a localized interchange (or Mercier mode) may be unstable when the shear is low, inside the $q = 1$ surface. What is of more importance is the fact that the mode observed theoretically has a ballooning mode structure. Therefore, this observation on PDX may indeed be the first direct observation of a ballooning type instability in a high-beta tokamak with neutral beam injection.

4.2 MHD Activity During H-mode Discharges

A regime of enhanced energy confinement during neutral beam heating was first observed with divertor plasmas on the ASDEX Tokamak /37/ and has also been observed on PDX /38/ and D-III /39/. Characteristics of the enhanced confinement are broad density profiles, high edge electron temperature (400 eV), and steep density and temperature gradients near the separatrix. The MHD activity during these enhanced confinement discharges (or H-mode plasmas) is of interest because many new edge instabilities have been observed in these tokamaks.

The first type of MHD activity uniquely associated with the H-mode discharge is the quasiscoherent density oscillation which was observed by CO_2 laser scattering and microwave scattering experiments /40/. This mode was in the frequency range 50 - 100 kHz, having small amplitude inside the separatrix. This mode localized at the plasma edge occurred in bursts of $\sim 300 \mu\text{s}$ duration and a clear one-to-one correspondence between the quasiscoherent mode and the H-mode regime indicates that these fluctuations may well play an important role in the dynamics of this new and important regime of tokamak operation.

The edge relaxation phenomena (ERP) which has been observed during H-mode discharges was first reported by the ASDEX group /37/. This instability was characterized by a sharp spike in the edge $H\alpha/D\alpha$ signal. It was also seen on the PDX tokamak on all edge diagnostics, such as $H\alpha/D\alpha$ emissions, soft X-ray emission at large radii, and on divertor density measurements /35,38,41/. These edge oscillations are sawtooth-like relaxations located inside the separatrix with an inversion radius at the plasma edge, as seen in Fig. 12. Similar type relaxations have also been observed on the D-III tokamak during their H-mode discharges /42/. The presence of these bursts was correlated with decreases in $\dot{n}_e$, τ_p , τ_E , and $\langle \beta \rangle$, along with an increase in the parallel power flow outside the separatrix.

An experimental effort was made to identify the fluctuations or precursors to the ERP. However, the CO_2 and microwave scattering diagnostics did not observe a clear precursor and from the Micnov coils a fast growing magnetic oscillation was sometimes detected near the separatrix x-point before the ERP. This mode was identified as an $m/n = 3/1$ or $3/0$, however the mode amplitude was small and only one or two oscillations were detected before the ERP. From analysis of PDX open divertor discharges /41/, it was found that transitions from L- to H-mode and ERP's were present. This interesting result implies that the ERP's are more a separatrix and transition phenomena rather than a pressure or current driven MHD mode, because for the open divertor geometry, the edge temperature and density were not high and thus there was no large gradient present.

A scenario which appears to explain the main features of the ERP's is as follows: An unstable surface mode grows in amplitude near the separatrix; this MHD mode may cause ergodization near the x-point, thus triggering the discharge back into low mode confinement. The higher χ_e causes

the edge temperature to drop dramatically inside the separatrix, producing the characteristic fast drops (100-300 μ s) observed on the soft X-ray signals. From a simple heat diffusion model it is found that 300 μ s of L-mode every 1 ms will approximately half the increase in confinement due to the H-mode. This approximately agrees with the experimental observations for the intense gas puffing experiment described in Ref. 41.

5. Summary of MHD Activity at High Beta

It is interesting to note that from a comparison of JFT-2, ISX-B, PDX, and D-III, the ideal $n = \infty$ ballooning limit has been reached on these tokamaks. Also these tokamaks have observed decreasing confinement times with increasing neutral beam powers and/or β . Possible explanations for the confinement drop vary among the tokamak groups, but several instabilities have been considered. Stability limits on beta in PDX have been studied with the PEST code /43/, using numerically computed equilibria as described in Ref. 27. It was found that the highest β_T cases obtained in PDX approximately reached the calculated threshold for infinite- n ballooning modes.

From a theoretical framework the stability of high-beta tokamak discharges with respect to modes arising from ideal MHD theory (ideal ballooning and ideal kink modes) would constitute a boundary of tokamak operation. The underlying reason is that such gross violations of MHD stability may cause major disruptions. Resistive modes, while having similar eigenstructures to ideal modes, have lower growth rates and are generally considered candidates for "soft" β limits, by which is meant the appearance of a gradual decrease in energy confinement time as the ideal- β limit is approached.

From the discussions in section 3.2 on the different types of MHD activity observed in high- β discharges, similar behavior is detected on all tokamaks. Tables 1, 2, and 3 attempt to summarize the main features of the MHD activity and how these modes affect the plasma during high-beta operation.

In an attempt to compare the confinement of all the tokamaks close to the beta limit, a generalized form of the PDX scaling /27/ would appear most appropriate. A normalization of the axes can be found by using the L-mode and nonfishbone, a and R confinement scaling obtained by Goldston /44/ where he concluded

$$\frac{\tau_E \text{ (sec)}}{I_P \sqrt{K} \text{ (amps)}} \propto \frac{R^{1.75}}{a^{0.37}} (\text{cm}^{1.38}) f(P_T) .$$

In addition, a simple form of the beta limit /45-47/ can be written as

$$\beta_c = \text{const} \frac{I_P}{a B_T} . \quad (1)$$

Using both these equations, a plot of $(a B_T \beta_T / I_P)$ versus $(P_T R^{0.75} / B_T a^{1.37} \sqrt{K})$ should bring all the low-mode data from the different tokamaks together. (P_T is the total input power, neutral beam plus ohmic heating.) Figure 13a shows such a plot for ISX-B, D-III /23,48/, and PDX; what is striking about this plot is the way the curve turns over at high $(a B_T \beta_T / I_P)$, i.e., close to the ideal beta limit. Figure 13b shows a plot of PDX H-mode data with the same axis as in Fig. 13a. The slope of a line through the origin is higher than that in Fig. 13a, indicating an increased confinement in an H-mode discharge.

A crucial issue in defining the role of a beta limit on confinement is the question of what happens as beta limits are challenged in H-mode discharges. At high toroidal field and $q \gtrsim 3$, H-mode discharges show $\tau_E \approx 2 \times \tau_E$ of L-mode plasmas. If this same pattern were to hold at low q and low B_T , in the H-mode the ideal beta limit could be exceeded by as much as a factor of two, despite even an L-mode scaling of $\tau_E \propto P_b^{-1/2}$. Were this to happen, it would certainly call into question the relevance of the theoretical limit. On the other hand, if τ_E were to begin to drop precipitously as the beta limit were approached in the H-mode, the role of the theoretical limit would be greatly clarified. In practice, this is just what occurred in PDX (see Fig. 13b). As beam power was increased, τ_E fell precipitously and β_T saturated. In part, however, this may have been due to the strong gas feed required to avoid disruptions in PDX under these circumstances. This gas feed was shown to destroy the enhanced H-mode confinement. The disruptions themselves may have been the sign of the β -limit; they are avoidable only by reducing τ_E (and thus β) through spoiling the H-mode confinement. More time to optimize this operational regime might have produced some additional insight. Unfortunately, neither D-III nor ASDEX has operated at low B_T , low q , and high power in the H-mode regime.

From Figs. 13a and 13b one could attempt to find the constant defined in Eq. (1); then, using this constant, one could compare it with theoretical models for $n = \infty$ ballooning and kink mode limits. This constant varies from 0.28 for external kink modes to 0.44 for ballooning modes. The experimental value found from Fig. 13 is ≈ 0.35 . So the external kink limit has been exceeded but not the $n = \infty$ ballooning limit. It should be pointed out that Eq. (1) is the first order approximation and that the constant in the equation depend on inverse aspect ratio ϵ , elongation K , and triangularity

5. Nevertheless, Eq. (1) is a useful guide for comparing different devices and making projections to future devices.

To get a better understanding of the ideal beta limit, it is necessary that each specific tokamak experiment compare its achieved beta to stability calculations performed on the particular equilibrium obtained in the experiment. In many cases this has been done and it is found that the $n = \infty$ ideal ballooning mode limit has not been exceeded.

6. Conclusion

In this paper we have reviewed MHD studies performed to date on tokamaks at high beta. This work has focused on a comparison of the results from the many high-beta tokamaks. The main conclusions are: 1) The high-beta equilibria obtained to date have reached but not exceeded the ideal beta limit. 2) The observed spectrum of MHD fluctuations at high beta is clearly dominated by the $n = 1$ mode when the $q = 1$ surface is in the plasma. The $m/n = 1/1$ mode is the dominant instability, and it drives other $n = 1$ modes through toroidal coupling and $n > 1$ modes through nonlinear couplings. 3) In PDX and D-III, in addition, a resonant interaction of the $n = 1$ internal kink and the trapped fast ions results in loss of beam heating power. A key parameter in the theory is the value of q_0 and the injection angle. 4) Results from ISX-B and D-III indicate that the high frequency background spectrum observed on the $\tilde{B}_0$ signal (broadband fluctuations) correlates with confinement and a prime candidate for this high frequency activity is high- n resistive ballooning modes. Other high frequency modes have been observed on PDX which may be $n \approx 2-5$ ballooning modes. 5) An edge relaxation phenomena (ERP) observed during H-mode discharges on ASDEX, PDX, and D-III has a dramatic effect on plasma confinement.

Tokamak operation at high beta has exhibited an ever richer variety of MHD phenomena. The overall features of the activity are common to all machines. MHD activity continues to limit the range of operating parameters, particularly at the ideal beta limit which has not yet been exceeded on any tokamak. Present results indicate that the beta limit may be defined by the onset of a major disruption. Nevertheless, β optimization techniques are being explored at GA with a low aspect ratio Dee-shaped plasma and at PPPL with a high aspect ratio bean-shaped tokamak (PBX).

Acknowledgments

The author would like to acknowledge J. Dunlap, M. Murakami, A. Wootton, and the ISX-B group for use of ISX-B data; R. Stambaugh, J. C. DeBoo, S. Ejima, and the D-III group for use of D-III data; and G. A. Navratil of Columbia University for Torus II data. In addition, the author would like to acknowledge with appreciation the support of his many colleagues at Princeton Plasma Physics Laboratory and in particular M. Bell, D. Buchenauer, R. Goldston, R. Hawryluk, G. Hay, R. Izzo, S. Kaye, D. Monticello, W. Park, N. Sauthoff, J. Strachan, and R. White for many helpful discussions.

This work supported by U.S. Department of Energy Contract No. DE-AC02-76-CO0-3073.

References

- /1/ Cousins, S.W., Ware, A.A., Proc. Phys. Soc. (London), A64 (1951) 159.
- /2/ Kurchatov, I.V., et al., Sov. J. of At. Energy 1 (1956) 359.
- /3/ Anderson, O.A., Baker, W.R., Colgate, S.A., Ise, J., and Pyle, R.V., Phys. Rev. 110 (1958) 1375.
- /4/ Butt, E.P., Cole, H.C., Dellis, A.N., Gibson, A., Rusbridge, M., et al., Proc. 2nd Int. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Culham, 1965, IAEA CN/21/, Vienna, 1966, 2 751.
- /5/ Artsimovich, L.A., Nucl. Fusion, 12 (1975) 215.
- /6/ von Goeler, S., Stodiek, W., and Sauthoff, N., Phys. Rev. Lett., 33 (1974) 1201.
- /7/ Smith, R.R., Nucl. Fusion, 16 (1976) 225.
- /8/ Kadomtsev, B.B., Sov. J. Plasma Physics, 1 (1975) 389.
- /9/ Waddell, B.V., Rosenbluth, M.N., Monticello, D.A., and White, R.B., Nucl. Fusion, 16 (1976) 528.
Handbook of Plasma Physics, Rosenbluth, M.N., Sagdeev, editors, 1, 650.
- /10/ Sykes, A. and Wesson, J.A., Phys. Rev. Lett., 37 (1976) 140.
- /11/ Jahns, G.L., Soler, M., Waddell, B.V., Calien, J.D., and Hicks, H.R., Nucl. Fusion 18 (1978) 609.
- /12/ Dubois, M., Pecquet, A.L., Reverdin, C., Nuclear Fusion, 23 (1983) 147.
- /13/ Ware, A.A., in Current Disruptions in Toroidal Devices, Report IPP-3/51, Max Planck-Institut fur Plasmaphysik, Garching (1979), papers C1 and C2.
- /14/ Birch, R., Gowers, C.W., Haas, F.A., Jones, P.A., McGuire, K., et al., Proc. 9th European Conf. on Controlled Fusion and Plasma Physics, Oxford 2 (1979) 71.
- /15/ Diva Group, Nucl. Fusion 20 (1980) 271.

- /16/ Grossman, A.A., Levinton, F.M., Machida, G.A., Navratil, G.A., Int. Conf. Plasma Physics, Lausanne, Switzerland 1984. paper P6-10, Vol. 1.
- /17/ Bol, K., Arunasalam, V., Bitter, M., Boyd, D., Brau, K., et al., Proc. 7th Int. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, July 1978, IAEA-CN/37/, Vienna, 1979, Vol. 1, 11.
- /18/ Vlasenkov, V.S., Kulygin, V.M., Leonov, V.M., Merezhkin, V.C., Mukhovatov, V.S., et al., Proc. 6th Int. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgatten, Oct. 1976, IAEA-CN/35/, Vienna, 1977, Vol. 1, 85.
- /19/ Axon, K.B., Baxter, G.A., Burt, J., Clark, W.H.M., McCracken, G.M., et al., Proc. 7th Int. Conf. Plasma Physics and Controlled Nuclear Fusion, Innsbruck, July 1978, IAEA-CN/37/, Vienna, 1979, Vol. 1, 51.
- /20/ Yamamoto, S., Maeno, M., Suzuki, N., Azumi, M., and Tokuda, S., et al., Nucl. Fusion 21 (1981) 993.
- /21/ Dunlap, J.L., Carreras, B.A., Paré V.K., Holmes, J.A., Bates, S.C., et al., Phys. Rev. Lett. 48 (1982) 538.
- /22/ McGuire, K., Goldston, R., Bell, M., Bitter, M., Bol., K., et al., Phys. Rev. Lett. 50 (1983) 891.
- /23/ Overskei, D.O., Armentrout, C.J., Baur, J.F., Blau, F.P., Bramson, G., et al., Proc. 4th Varenna/Grenoble International Symposium on Heating in Toroidal Plasmas, Rome, March 1984, to be published.
- /24/ Swain, D.W., and Neilson, G.H., Nucl. Fusion 22 (1982) 1015.
- /25/ Carreras, B.A., Diamond, P.H., Murakami, M., Dunlap, J.L., Bell, J.D., et al., Phys. Rev. Lett. 50 (1983) 503.
- /26/ Carreras, B.A., Dunlap, J.L., Cooper, W.A., Dory, R.A., Hender, T.C., et al., Oak Ridge National Laboratory Report ORNL/TM-8648.

- /27/ Johnson, D., Bell, M., Bol, K., Brau, K., Buchenauer, D., et al., Proc. 9th Int. Conf., Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, Sept. 1982, IAEA-CN/41/Vienna, 1983, Vol. 1, 9.
- /28/ Kaye, S., Goldston, R.J., Bell, M., Bol, K., Bitter, M., et al., Plasma Physics Laboratory Report PPPL-2109 (June 1984).
- /29/ Park, W., Monticello, L.A., White, R.B., McGuire, K., and Reusch, M.F., Proc. of the U.S.-Japan Workshop on 3-D MHD Studies, Oak Ridge, Tennessee, 1981.
- /30/ White, R.B., Goldston, R.J., McGuire, K., Boozer, A.H., Monticello, D.A., et al., Phys. Fluids 26 (1983) 2958.
- /31/ Beiersdorfer, D., Kaita, R., Goldston, R., Nucl. Fusion 24 (1984) 487.
- /32/ Fuchenaue, D., Hwang, D.Q., McGuire, K., Goldston, R.J., Proc. 4th Varenna/Grenoble International Symposium on Heating in Toroidal Plasmas, Rome, March 1984, to be published.
- /33/ Strait, E.J., Bernard, L.C., Lee, J.K., Moore, R.W., and Stambaugh, R.D., in Controlled Fusion and Plasma Physics (Proc. of 11th European Conference, 1983), Part 1, 59.
- /34/ Dunlap, J.L., Paré, V.K., Bell, J.D., and Wootton, A.J., Bull. Am. Phys. Soc., 28 1873 (1112).
- /35/ McGuire, K., Buchenauer, D., Izzo, R., Manickam, J., Monticello, D., et al., Bull. Am. Phys. Soc., 28 (1983) 1173.
- /36/ Manickam, J., McGuire, K., Miller, A.E., Sherwood Meeting, 1984.
- /37/ Wagner, F., Becker, G., Behringer, K., Campbell, D., Eberhagen, A., et al., Phys. Rev. Lett. 49 (1982) 1408.
- /38/ Kaye, S., Bell, M., Bol, K., Boyd, D., Brau, K., et al., Princeton Plasma Physics Laboratory Report PPPL-2056, (November 1983), to be published in J. Nucl. Mater.

- /39/ Ohya, N., Burrell, K.M., DeBoo, J., Ejima, S., Groebner, R., et al., GA-A17108, General Atomic Technologies, San Diego, California, USA (1984).
- /40/ Slusher, R.E., Surko, C.M., Valley, J.F., Crowley, T., Mazzucato, E., et al., Princeton Plasma Physics Laboratory Report PPPL-2110 (May 1984), to be published.
- /41/ Fonck, R. J., Belersdorfer, P., Bell, M., Bol, K., Boyd, D., et al., Proc. 4th Varenna/Trenoble International Symposium on Heating in Toroidal Plasmas, Rome, March 1984 (to be published).
- /42/ Konoshima, S., Abe, M., Hirayama, T., Kameri, A., Kitsunezaki, A., et al., Bull. Amer. Phys. Soc. 28 (1983) 1121.
- /43/ Grimm, R.C., in Methods in Computational Physics, Vol. 16 (Killeen, J., Ed.) Academic Press, New York (1976) 253. Chance, M.S., et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 7th Int. Conf., Innsbruck, 1978) IAEA, Vienna (1979), Vol. 1, 677, Grimm, R.C. et al., Princeton Plasma Physics Laboratory Report PPPL-1865 (1982).
- /44/ Goldston, R.J., Plasma Physics and Controlled Fusion 26 (1984) 87.
- /45/ Bernard, L.C., Helton, F.J., Moore, R.W., and Todd, T.N., Nucl. Fusion 23 (1983) 1475.
Bernard, L.C., On Tokamak Beta Limits; U.S. Physics Contributions to the May INTOR Workshop Report FEDC-M-84-PE-050.
- /46/ Sykes, A., Proc. 11th European Conference on Controlled Fusion and Plasma Physics, Aachen, (1983).
- /47/ Troyon, F., Gruber, F., Saurenmann, H., Semenzato, S., and Succi, S., Plasma Physics and Controlled Fusion 26 (1984) 209.
- /48/ DeBoo, J.C., et al., Report GA-A17613, General Atomic Technologies, San Diego, CA, USA (1984).

Figure Captions

Fig. 1 Oscillograms of PIN diode signals S.X. (S.X. 1 + central chord, S.X. 4 + chord outside $q = 1$ surface) and pick-up loop signals $\tilde{B}_\theta$, for enhanced sawtooth oscillations on the JFT-2 tokamak.

Fig. 2 Observed regions of the typical MHD modes on the JFT-2 tokamak are shown. Enhanced sawtooth oscillations, round sawtooth oscillations and/or reduced sawtooth oscillations and high frequency oscillations without sawtooth oscillations are denoted by ES, RS, and H, respectively.

q_a : safety factor, β_o : peak β ,
 $\langle \beta \rangle$: average β . $\alpha\Delta$: due to thermal component, and
 $\alpha\Delta$: including beam component in experiment;
 IIII: critical peak β -value from the analysis;
 IIII: critical average β -value. Lower lines of each band indicate critical values for $q_o = 1$ and upper lines for $q_o = 0.9$ $P_{inj} = (0.8 - 1.2)MW$.

Fig. 3 The soft X-ray signal patterns observed on the ISX-B tokamak for plasmas with dominant $m/n = 1/1$ mode activity ($q_{MHD} < 4.5$).

Fig. 4 $\tilde{B}_\theta$ power spectra measured 4 cm behind the limiter near the equatorial plane on the outside for a ISX-B discharge (a) with significant plasma volume within the $q = 1$ surface and (b) with no detectable $q = 1$ surface in the plasma.

Fig. 5 Scatter plot of diamagnetic measurements of β_p and β_T , for $B_T < 1.5$ T for the PDX tokamak. The hatched region roughly separates discharges which show distinct "fishbone" MHD activity from those which do not. The dashed lines separate discharges which show appreciable fast ion loss from those which do not.

Fig. 6 Shows the MHD activity observed on PDX, on a soft X-ray channel and a magnetic loop, as a function of $\beta_T q_{cyl}$. A) $\beta_T q_{cyl} = 0.007$
B) $\beta_T q_{cyl} = 0.027$ C) $\beta_T q_{cyl} = 0.042$.

Fig. 7 The time evolution of the soft X-ray emission along a central chord, the $\tilde{B}_0$ signal from a coil near the outer wall of the vacuum vessel, and the fast neutron flux. Expansion of the data near two "fishbones" is also shown.

Fig. 8 Charge-exchange spectra in the counter-near-perpendicular direction of the slowing-down beam ions for (a) two-beam no-fishbone discharge, compared with (b) four-beam severe-fishbone discharge. The depletion of beam ions from just below E_{inj} down to $E_{inj}/2$ is very evident. Note that these spectra were obtained by sweeping the energy analyzer in time, so that fishbone spikes appear to be localized in energy; in fact they are localized in time. The signal integration time is 100 μ sec for both spectra.

Fig. 9 Correlation of oscillations within the fishbone with modulation of the D^+ detector current and the rf emission for a PDX discharge.

Fig. 10 Relationship of MHD activity and confinement regimes on the D-III tokamak.

Fig. 11 Detailed structure of "fishbone" activity on PDX during a high power neutral beam discharge. Note the high frequency precursor mode (91 kHz) before the burst of $m = 1$ activity at 382.5 ms.

Fig. 12 a) Soft X-ray emission as a function of chord height in the plasma during the H-mode phase of a PDX discharge, b) Divertor H_α/D_α signal, c) Magnetic loop signal.

Fig. 13 a) Normalized beta $\beta/\beta_c = \beta_T B_T a / I_p$ versus $P_T R^{0.75} / B_T a^{1.37} \sqrt{K}$, for beam heated discharges on ISX-B, PDX, and D-III. (β_T in %, B_T in tesla, R and a in centimeters, I_p in kiloamps, and P_T in megawatts.) The slope of a line through the origin is a measure of the global confinement. The data sets used were: limiter and expanded boundary (XB) discharges from D-III ($H^0 + D^+$), limiter discharges from PDX ($D^0 + H^+$), and gettered limiter discharges from ISX-B ($H^0 + D^+$). The hatched region roughly corresponds to the experimental beta limits observed to date on these tokamaks.

Fig. 13 b) Same axis as Fig. 13a, showing H-mode PDX divertor data for D^0 beams into D^+ plasma.

TABLE 1

MHD Activity
(L-mode)

Low- n Modes		Coherent High Frequency		Broad Band
<u>$n \approx 1$</u>	JFT-2 ISX-B PDX DIII ASDEX	100-200 kHz	ISX-B	ISX-B
Coupled				Frequency range of magnetic loops 0-250 kHz
$m = 1$ to $m \geq 2$ (observed on X-ray signals)	(detected by magnetic loops)	$n > 10$ observed after Sawtooth		$m = 0$ or "turbulence"
<ul style="list-style-type: none"> o Sawteeth o Continuous $m = 1$ during sawteeth o Bursts 		High m, n	PDX	D-III
		50-150 kHz		Frequency range of magnetic loops 0-50 kHz
		Discrete Bursts		$m = ?$
		$m > 2$ } observed $n > 2$ } near $q = 1$ surface		
Depends strongly on		250 kHz	TORUS-II	
P_B		$n = 10 - 16$	Discrete burst	
β_P				
β_t				
δ				
k				
q_0				

TABLE 2

Losses

Low-n Modes	Coherent High Frequency	Broad Band
<u>Bursts</u> Fishbones cause beam ion loss (20-40%) 14° $\perp$ injection (PDX)	ISX-B 100-200 kHz observed after sawtooth (no effects observed yet)	ISX-B Correlation of $\delta B/B$ with confinement for I_p scan
D-III 27° $\perp$ injection Can detect beam ion loss. However, not a problem yet (only in divertor discharges at high β_p) ISX-B } $\parallel$ injection JFT-2 } no beam ion loss	PDX High m, n Clear neutron drop, probable resonance with beam ions	D-III Possible correlation of $\delta B/B$ with confinement
$n = 1$ No effect on thermal confinement (outside of $q = 1$ surface). Fishbone oscillations only a beam ion source problem as yet. Large "fishbone" oscillations may have some effect on τ_e		

TABLE 3

Mode Classification

Low-n Modes	Coherent High Frequency	Broad Band
<p>$n = 1$</p> <p>Tearing mode → observed on soft X-rays and magnetic loops</p> <p>↓</p> <p>internal kink → faster growth rate linear rate</p> <p>Good agreement between simulations from 3-D resistive MHD calculations and diagnostic signals</p>	<p>ISX-B</p> <p>100-200 kHz observed at sawtooth drop</p> <p>{ Resistive } ?</p> <p>{ Ballooning }</p>	<p>ISX-B</p> <p>Resistive } Amplitude</p> <p>Ballooning } → Scaling</p>
	<p>PDX</p> <p>High m, n</p> <p>Mercier mode</p> <p>Ballooning mode (maybe)</p>	<p>For ISX-B, poloidal correlation</p> <p>length typically = 5cm</p>
	<p>250 kHz</p> <p>$n = 10 - 16$</p> <p>Instability amplitude largest on the large major radius side of pressure profile</p> <p>⇒ Ballooning mode</p>	

2 ms

S.X. 1

S.X. 4

$\tilde{B}_0$

Fig. 1

Fig. 2

(a)

AT LOW POWER

(b)

AT INTERMEDIATE AND HIGH POWER

(c)

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

82x1142

Fig. 8

Fig. 9

RELATIONSHIP OF MHD ACTIVITY AND CONFINEMENT REGIMES

Fig. 10

Fig. 11

Fig. 12a

Fig. 12b

Fig. 12c

Fig. 13a

Fig. 13b

EXTERNAL DISTRIBUTION IN ADDITION TO TIC UC-20

Plasma Res Lab, Austre Nat'l Univ, AUSTRALIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. D. Palumbo, Dg XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.H. Sakanaka, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Teichmann, Univ of Montreal, CANADA
 Dr. H.M. Skersgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor M. Johnston, INRS-Energie, CANADA
 Dr. Hannes Barnard, Univ British Columbia, CANADA
 Dr. M.P. Bachynski, MPE Technologies, Inc., CANADA
 Zhenggu Li, SW inst Physics, CHINA
 Librarian, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, Academia Sinica, CHINA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schetzman, Observatoire de Nice, FRANCE
 J. Rader, CEN-DS6, FRANCE
 AM Dupes Library, AM Dupes Library, FRANCE
 Dr. Tom Muai, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. S.K. Trehan, Panjab University, INDIA
 Dr. Indira, Mohan Lal Das, Banaras Hindu Univ, INDIA
 Dr. L.K. Chavde, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Var Ruchi Marg, INDIA
 P. Kaur, Physical Research Lab, INDIA
 Dr. Philip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Superman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Clelia De Palo, Assoc EURATOM-CNEN, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Prof. M. Yoshikawa, JAERI, Tokai Res Est, JAPAN
 Prof. T. Uchida, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sigeru Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Setoshi Itoh, Kyushu University, JAPAN
 Tech Info Division, Korea Atomic Energy, KOREA
 Dr. R. England, Ciudad Universitaria, MEXICO
 Bibliotheek, Fon-inst voor Plasma, NETHERLANDS
 Prof. B.S. Lilley, University of Waikato, NEW ZEALAND
 Dr. Suresh C. Sharma, Univ of Calabar, NIGERIA
 Prof. J.A.C. Cabral, Inst Superior Tech, PORTUGAL
 Dr. Octavien Petrus, ALI CIZA University, ROMANIA
 Prof. M.A. Heilberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Atomic Energy Bd, SO AFRICA
 Fusion Div. Library, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Dr. Erik T. Karlson, Uppsala Universitet, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. W.L. Weiss, Nat'l Bur Stand, USA
 Dr. W.M. Stacey, Georg Inst Tech, USA
 Dr. S.T. Wu, Univ Alabama, USA
 Prof. Norman L. Olsson, Univ S Florida, USA
 Dr. Benjamin Ma, Iowa State Univ, USA
 Prof. Magne Kristiansen, Texas Tech Univ, USA
 Dr. Raymond Askew, Auburn Univ, USA
 Dr. V.T. Tolok, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Institute Gen. Physics, USSR
 Prof. T.J. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universität, W. GERMANY
 Nuclear Res Estab, Jülich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Dr. H.J. Kaeppeler, University Stuttgart, W. GERMANY
 Bibliothek, Inst Plasmeforschung, W. GERMANY