MHD Instabilities near the β Limit in the Doublet III-D Tokamak

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(Received 15 April 1988)

Saturation or slow collapse of β is observed in DIII-D divertor discharges at high values of normalized β [$\beta/(I/aB) \gtrsim 2.4$]. The sequential appearance of MHD instabilities with poloidal/toroidal mode numbers $m/n = 5/4$, 4/3, 3/2, and 2/1 at progressively larger minor radii leads to the saturation or collapse of β. Only $n=2$ and $n=1$ modes affect global energy confinement. A model is suggested in which the instabilities originate as high-n ballooning modes near the center of the discharge, progressing to lower-n modes by modification of pressure and current profiles.

PACS numbers: 52.35.Py, 52.55.Fa

Various pressure-driven plasma instabilities may limit the maximum achievable ratio β of plasma pressure to confining magnetic field pressure in a tokamak. β limits in large, neutral-beam-heated tokamak experiments[1-6] are in reasonably good agreement with predictions from ideal magnetohydrodynamic theory[7-12] for kink instabilities (large-scale helical deformations of the plasma column) and ballooning instabilities (smaller-scale perturbations localized in the least-stable regions of the plasma). The limiting β is approximated in theory and experiment by the simple scaling law $\beta = C(I/aB)$, where I is the plasma current, a is the minor radius of the plasma, and B is the toroidal magnetic field. There is some variation of the constant C among theories and experiments, but a typical value is 3.5%/(MA/mT) which was observed in Doublet III.[1]

Discharge behavior observed at the β limit in the various experiments ranges from a saturation or slow collapse of β as heating power is increased, to a β collapse followed by a disruption (rapid loss of plasma energy and termination of the discharge), to a sudden major disruption. β saturation and collapse are generally observed at high values of the edge safety factor q ($q > 3$), and immediate disruption at low q ($q \leq 3$), although this pattern seems to be reversed in TFTR.[6] (The tokamak safety factor q is the number of toroidal rotations a magnetic field line makes to complete one poloidal rotation.)

DIII-D H-mode (high-confinement regime) divertor discharges[13] have reached β values above 6% at $I/aB = 2.5$ in near-steady-state operation.[14] However, in similar discharges at smaller $I/aB = 1.7$, saturation or collapse of β has been observed.

In this paper we examine in detail the phenomena leading up to a β collapse and disruption in the DIII-D tokamak. We propose a model which reconciles the expectation that ballooning modes of high toroidal mode number n should play an important role with the fact that low-n MHD activity is often observed as the discharge approaches the β limit.

A typical β collapse in a DIII-D H-mode divertor discharge is shown in Fig. 1. At first β rises as the heating power increases. The transition from the low-confinement regime, L mode, to H mode occurs at $t = 1870$ msec. Beginning at $t = 2550$ msec, β begins to decay slowly despite constant heating power. This is followed about 100 msec later by a more rapid collapse in which most of the plasma energy is lost. Later a disruption terminates the discharge. The saturation and collapse of β are not due to radiation; the measured radiat-

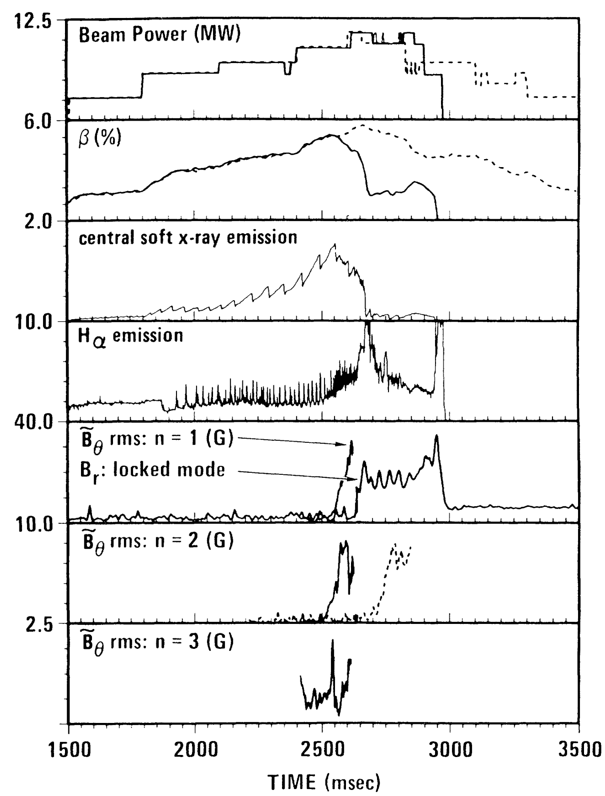

FIG. 1. Time traces for two similar discharges, with $I = 1.0$ MA, $B = 0.9$ T, major radius $R = 1.69$ m, minor radius $a = 0.63$ m, vertical elongation $\kappa = 1.9$, $I/aB = 1.75$ MA/mT, q(95% of poloidal flux) $= 3.1$. At peak β, $T_{e0} \sim 1.4$ keV (scaled from lower-β discharges) and $\bar{n}_e = 7.8 \times 10^{13}$ cm^{-3}. Discharge 55771 (solid line) has a β collapse beginning at about $t = 2550$ msec. Discharge 55773 (dashed line) reaches $\beta = 5.8\%$ in stable operation. Poloidal (B_θ) and radial (B_r) field amplitudes of various MHD modes are shown.

ed power never exceeds half the input power, and there is no increase in carbon or metal line radiation. The repetition rate of the edge localized modes, seen as short bursts on the H_α/D_α emission signal, increases during β saturation decay, and collapse, suggesting an increased rate of heat transport to the plasma edge.

As β increases, bursts of oscillation $\tilde{B}_\theta$ with toroidal mode numbers $n=3$ and 4 appear on the poloidal magnetic field B_θ, as measured at the interior surface of the vacuum vessel (shown in Fig. 1 and in more detail in Fig. 2). At the onset of the decay of β, a larger burst of $n=3$ oscillation occurs, followed by the rise of a large continuous $n=2$ mode, and then a large $n=1$ mode. The rotation of the mode slows, stopping at $t=2640$ msec. At this time the presence of a large, nonrotating ("locked") $n=1$ mode is detected by the saddle loops (large pickup loops on the exterior surface of the vacuum vessel). This is quickly followed by the loss of most of the plasma energy. The amplitudes of the $n=1$, 2, 3, and 4 modes develop differently in time, and their frequencies are not in general harmonically related, so they are evidently separate instabilities. The amplitudes of the $n=3$ and 4 modes are significantly peaked at the outboard midplane.

These instabilities are clearly related to β. Discharges with lower β in the same series run quite stably, and coherent magnetic oscillations with $n>2$ are only seen at large values of $\beta_N=\beta/(I/aB)$. The maximum value of $\beta_N=3.3\%/(\mathrm{MA/m\,T})$ attained so far in DIII-D is very close to the Doublet-III β limit of $\beta_N=3.5$. However, the exact point at which the β collapse occurs depends on the details of preparation of the discharge. In fact, the discharge which reached $\beta_N=3.3$ (also shown in Fig. 1) did so stably, and β began to ramp down with decreasing beam power before the growth of the $n=2$ mode.

To date, the β collapse has been observed in DIII-D only in a restricted range of parameters where the highest β_N has been reached (divertor discharges with $1.7 \le I/aB \le 2.1$), but at least some of the behavior here has been observed in other regimes, as shown in Fig. 3. It should be noted that the envelopes enclosing data points in the figure indicate the general behavior only; exceptions exist within each. In general, as β_N exceeds $1.8\%/(\mathrm{MA/m\,T})$, bursts of $n=3$ and $n=4$ oscillations are first observed. As β_N exceeds 2.1, an $n=2$ mode appears at small amplitude ($\tilde{B}_\theta/B_\theta < 0.2\%$), still with no effect on confinement. As β_N exceeds 2.4, the $n=2$

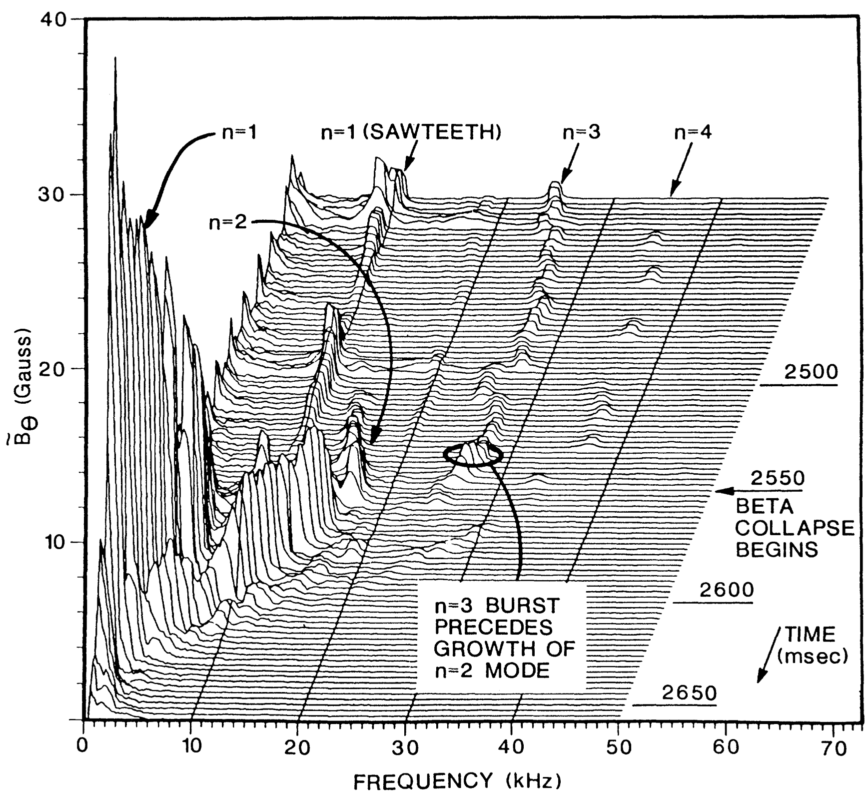

FIG. 2. Time-dependent amplitude spectra of $\tilde{B}$ for discharge 55771, from magnetic probes near the midplane at the outer wall. We define the amplitude spectrum as $\tilde{B}_\theta(\omega) = [\Delta\omega P(\omega)/\omega^2]^{1/2}$, where $P(\omega)$ is the cross-power or auto-power spectrum for dB_θ/dt signals, and $\Delta\omega$ is the frequency-smoothing interval used in calculating $P(\omega)$. (In this plot $\Delta\omega/2\pi = 1$ kHz.) For an unsmoothed spectral peak narrower than $\Delta\omega$, the height of the plotted $\tilde{B}_\theta(\omega)$ peak equals the rms amplitude.

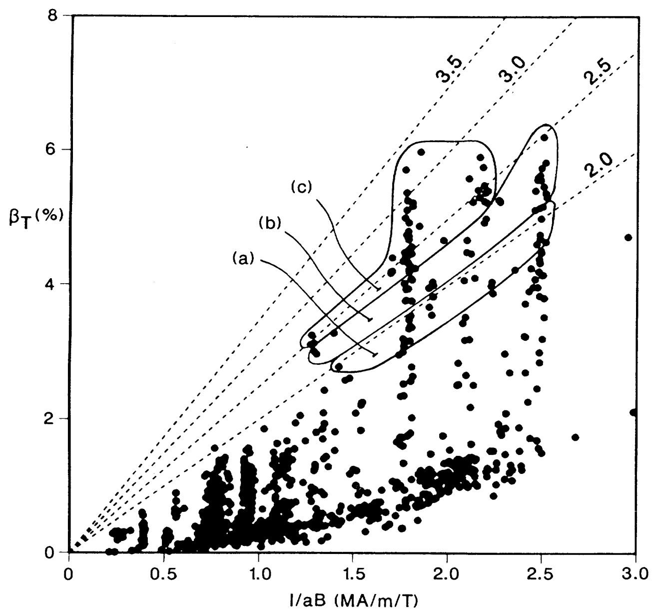

FIG. 3. Regimes of observed β-related instabilities. Dotted lines indicate values of $\beta_N = \beta/(I/aB)$ in %/(MA/mT). (a) Burst of $n=3$ and 4 activity. (b) Small $n=2$ oscillations with bursts of $n=3$ and 4. (c) Large $n=2$ oscillations with $n=3$ and 4. Saturated $n=2$ mode causes energy confinement time to decrease, or growing $n=1$ mode leads to β collapse or disruption.

mode becomes larger, often preceded by a burst of $n=3$ oscillation. The $n=2$ mode may remain with a saturated amplitude ($\tilde{B}_\theta/B_\theta \sim 0.5\%$), accompanied by a small (10% to 20%) decrease in energy confinement time, or an $n=1$ mode may grow, with its rotation stopping as $\tilde{B}_\theta/B_\theta$ reaches about 1.0%. The growth of the $n=1$ mode is always followed by a β collapse or disruption.

Only the $n=2$ and $n=1$ modes have a measurable effect on the global energy confinement time, the $n=2$ mode being associated with the saturation or slow decay of β and the $n=1$ mode with the more catastrophic collapse. When discharges with these instabilities are disregarded, β increases linearly with heating power, up to the maximum normalized value of $\beta_N = 3.3$.

The low-n modes observed in these discharges probably cannot be attributed to ideal kink instabilities. Kink-mode stability was calculated using the GATO code[15] for several discharges in the same series as those of Fig. 1. The MHD equilibria obtained from the EFIT code[16] were fitted using both magnetic data and pressure profile data[17] from Thomson-scattering (electron temperature and density) and charge-exchange-recombination (ion temperature) diagnostics. At the Thomson laser time, β_N was between 2.1 and 2.5, while the observed MHD activity included cases with bursts of $n=3$ and $n=4$ activity, the large $n=2$ mode associated with the β collapse, and the large $n=1$ mode which completes the collapse. Ideal kink modes with $n=1$, 2, and 3 were calculated to be stable for all these cases. Thomson-scattering data were not available for higher β_N in this set of discharges, but calculations on equilibrium fits using only magnetic data predict that all the discharges should have been stable. At the maximum β_N reached in the experiment ($\beta = 5.8\%$, $\beta_N = 3.3$) a conducting wall at 1.5 times the plasma's minor radius was required to stabilize the $n=1$ kink mode. This boundary condition is realistic, because the MHD modes typically rotate with periods much shorter than the vacuum vessel wall's L/R time of about 5 msec.

The observed instabilities show a clear progression to lower toroidal mode number and larger minor radius as time and β increase. The highly noncircular geometry and low aspect ratio of DIII-D make identification of the poloidal mode number m more difficult, and may introduce some mixing of poloidal modes. Nevertheless, phase shifts observed with magnetic probes and soft-x-ray detectors suggest that m/n for these modes progresses through 5/4, 4/3, 3/2, and 2/1. The radial variation of the amplitude of the soft-x-ray oscillations is consistent with resonance at q equal to these values of m/n, falling off rapidly for outer viewing chords which do not intersect the rational surface (as located from MHD equilibrium fits). In some cases, the 3/2 and 2/1 instabilities are also visible as flattened regions near $q = m/n$ in the electron temperature profiles as measured with Thomson scattering. The poloidal structure of each toroidal mode in the kink-mode stability calculations shows m/n for the least stable modes to be 6/4, 4/3, 3/2, and 2/1.

This progression suggests that the chain of events may begin with high-n instabilities deeper in the discharge. The highest β_N reached in these discharges is below the maximum stable value of 4.7 calculated for high-n ideal ballooning modes with optimized profiles, using the MBC code,[18] but the actual profiles may be locally unstable. Stability calculations were carried out using measured pressure profiles for the cases at β_N between 2.1 and 2.5 where data are available. The $q=1$ surface was taken at the sawtooth inversion radius to provide an additional constraint on the central profile shape, since the Thomson-scattering diagnostic measures only the outer 60% of the profile. At $\beta_N = 2.5$, the closest approach of the measured pressure gradient to the marginally stable value occurs at the edge of the plasma (related to the edge localized mode[18]) and near the center of the discharge. If the measured pressure gradient were scaled up with no change in profile shape, then at the maximum β_N reached in these discharges the innermost 40% of the minor radius would be at or beyond marginal stability to high-n ballooning modes. If present, such modes would not be detectable with existing diagnostics due to the short wavelength.

We therefore offer the following hypothesis for the origin of the observed β-related instabilities. Enhanced transport caused by ballooning modes prevents the pressure gradient p' near the axis from increasing beyond the marginally stable value, so further increases in β must require increases in p' at larger radii, causing a broadening of the pressure profile. The current profile is coupled to the pressure profile, and thus also broadens as β increases (such a broadening is seen in the experiment as a decrease in internal inductance l_i with increasing β). As β increases, the central region where p' is held near the marginally stable value grows, and the region where p' is able to increase moves beyond the $q=1$ surface. Up to this point, the experimental evidence is only indirect. Now the intermediate-n modes (5/4, 4/3, and 3/2) are observed, which are probably pressure-driven resistive instabilities. As β increases, each of these instabilities enhances transport in a growing region of the plasma interior, steepening the pressure and current profiles outside that region, and thus destabilizes the next mode resonant at a larger minor radius. This causes the observed progression of MHD modes toward larger $q=m/n$ and smaller n. Eventually the region of instability reaches the $q=2$ surface, and a 2/1 mode causes a major loss of plasma energy. A disruption may occur, particularly if the $q=2$ surface is near the plasma boundary as it is when $q \leq 3$. The 2/1 instability is qualitatively similar to those observed in low-β discharges, and is probably a current-driven mode.

A similar explanation was advanced for the β limit in Doublet-III.[19] In Doublet III, the β limit always appeared as a major disruption with an $m/n=2/1$ structure, sometimes preceded by a very short (10 to 50 msec) decay interval. Modes with $n=3$, 4, and 5 were observed in some Doublet-III discharges near the β limit, although no connection could be established with the β-limiting disruptions. The slow decay and collapse of β observed in DIII-D more nearly resembles phenomena reported in medium- and high-q discharges in ASDEX,[3] PBX,[5] and at lower q in TFTR.[6] However, we believe that the underlying mechanisms are the same in all these experiments.

In summary, a sequence of plasma instabilities has been observed in DIII-D discharges at high β_N which culminates in the saturation or collapse of β. Although the observed instabilities have low to intermediate toroidal mode numbers, calculations and experimental evidence strongly suggest that the β-limiting process begins with high-n ballooning modes near the center of the discharge. However, severe effects on global confinement or stability only appear when the lowest unstable mode number becomes $n=2$ or $n=1$.

The authors would like to thank Dr. A. D. Turnbull and Dr. M. S. Chu for helpful discussions, and W. Howl for assistance with computations. The locked-mode signal developed by Dr. P. Lomas of the JET Joint Undertaking was instrumental in the operation of these discharges. This work was sponsored by the Department of Energy under Contract No. DE-AC03-84ER51044.

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