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by

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BETA-LIMITING INSTABILITIES IN DIII-D DISCHARGES WITH LARGE BOOTSTRAP CURRENT*

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In reactor-relevant discharges with high beta and low collisionality, the beta limit may be reduced by the presence of a large bootstrap current density near the edge of the plasma. The combination of a large current density and a large pressure gradient may destabilize low- n ideal kink modes localized near the plasma edge. This hypothesis is consistent with the behavior of high-performance discharges in DIII-D, in which the ELM-free phase with good energy confinement often ends with a rapidly growing low- n MHD instability.

A large bootstrap current density can occur near the edge of H-mode discharges, even at moderate values of volume-averaged beta, owing to the large pressure gradient associated with the H-mode transport barrier. In discharges with finite aspect ratio and low to moderate collisionality, the bootstrap current density is proportional to the pressure gradient rather than the density gradient¹ and thus becomes large near the edge of high beta and H-mode discharges. A large bootstrap current density is found near the edge of low density H-mode and VH-mode discharges in DIII-D, as predicted by transport simulations and confirmed by equilibrium reconstructions.²

Ideal kink mode stability calculations show that the beta limit is sensitive to the presence of a large current density near the edge. The stability limit decreases for discharges with decreasing internal inductance, as predicted numerically³ and confirmed experimentally.⁴ The calculated beta limit decreases further as the edge current density is increased at constant internal inductance.⁵ These calculations and experimental results suggest that the bootstrap current distribution may lead to rather low beta limits in a steady-state tokamak, unless other forms of non-inductive current drive are used to control the current profile.

The ELM-free phase of VH-mode and low-density H-mode discharges in DIII-D often ends with a sudden, global MHD instability which is consistent with an ideal kink mode destabilized by the large current density near the edge. This event most often occurs at moderately large values of normalized beta, $\beta/\frac{I}{aB} \sim 2.6$ to 3.5. In the example shown in Fig. 1, the stored energy in a double-null divertor discharge increases steadily during ELM-free VH-mode, until a sudden MHD event causes the loss of about 20% of the plasma energy: soft x-ray emission indicates a rapid loss of energy beginning at the edge and extending across the entire profile within 100 to 300 μ s. In contrast, subsequent ELMs primarily affect the edge of the plasma.

The event is typically initiated by an MHD mode with toroidal mode number $n \sim 3$ to 5. In the time-expanded plot of Fig. 1(b), about two cycles of an $n = 5$ oscillation can be seen where the signals from two magnetic probes separated by 36° in toroidal angle are about 180° out of phase. (The mode number identification is supported by the phase shifts of several other probes at different toroidal angles.) The growth of the magnetic precursor within 20 to 50 μ s is consistent with ideal MHD time scales.

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An internal mode with $m = 1$, $n = 1$ is often observed before the rapid growth of the $n \sim 3-5$ mode, as in Fig. 1, and probably contributes to the rapid energy loss from the discharge core. In a second example (Fig. 2), an $m/n = 3/2$ mode is present before the instability but without a $1/1$ mode. There is an immediate loss of energy from the plasma edge, but only a slower loss from the center. The instability grows with almost no rotation, consistent with its being localized near the edge of the plasma according to spectroscopic measurements of plasma rotation. The signals from two probes separated by 45° are about 180° out of phase, indicating a toroidal mode number $n \sim 4$ to 5 .

The instability with $n \sim 3$ to 5 has a ballooning character and is strongly localized in space, despite the relatively low mode number. Figure 3 shows the spatial variation of the mode amplitude at a fixed time, measured by three toroidal arrays of magnetic probes. The perturbation consists of one wave cycle spanning about 90° in toroidal angle, and is also localized in the bad curvature region, with an amplitude about five times larger at the outboard midplane than at the bottom of the cross-section. The overall spatial structure is shown in Fig. 4, where the locations of peak amplitude as in Fig. 3 are plotted versus toroidal and poloidal angles. Although the spatial coverage of the magnetic probes is incomplete, the observed structure is consistent with a perturbation localized along a magnetic field line with $q \sim 5$ and concentrated on the outboard, low-field side of the plasma.

These experimental observations are consistent with ideal kink mode stability calculations. Calculations were made with the GATO code for another VH-mode discharge at the time of a similar MHD event. The equilibrium uses measured temperature and density profiles, giving a large pressure gradient near the edge. The equilibrium reconstruction, including motional Stark effect polarimetry measurements of the field line pitch near the center of the discharge, was most consistent with the presence of a large current density near the edge, as predicted by transport calculations of the bootstrap current. Edge-localized kink modes with $n = 2$ to 4 were found

Fig. 1. Time evolution of the MHD event ending the ELM-free VH-mode phase of discharge 73203 ($B_t = 2.1$ T, $I_p = 1.6$ MA, $q_{95} = 5.1$, $\beta = 4.0\% = 3.2 I/aB$, $\ell_i = 1.0$).

Fig. 2. Time evolution of the MHD event ending the ELM-free VH-mode phase of discharge 72269 ($B_t = 2.1$ T, $I_p = 1.6$ MA, $q_{95} = 5.0$, $\beta = 4.4\% = 3.5 I/aB$, $\ell_i = 1.0$).

to become unstable at the maximum beta reached experimentally, while the $n=1$ mode was marginally unstable, in good agreement with experimental observations.

Both the pressure gradient and the current density at the edge appear to be important for destabilizing these modes. Stability calculations were carried out using equilibria and profiles similar to the experimental VH-mode cases but systematically varying the edge pressure gradient. With similar edge current density profiles (fixed current density at $r/a = 1$ and at $r/a = 0.95$) and fixed volume-averaged beta, increasing the edge pressure gradient caused the character of an $n = 3$ instability to change from an internal quasi-interchange mode to an edge-localized "peeling" mode, as shown in Fig. 5. The many poloidal harmonics of the peeling mode represent a mode localized on the low-field side of the plasma and having a strong ballooning character, in good agreement with experimental observations.

The ELM-free phase of high performance discharges in DIII-D is often terminated by a rapidly-growing MHD instability with toroidal mode number $n \sim 3$ to 5. This mode grows on an ideal time scale and has a spatially localized, ballooning character. The instability is most often observed at high beta ($\beta \gtrsim 2.6 I/aB$), and the associated energy loss may be large, depending on the presence of other low- n MHD activity. Ideal kink mode calculations show that edge-localized kink modes with $n \geq 2$ are unstable in the presence of a large pressure gradient and large current density near the edge. Transport calculations indicate that in hot, collisionless high beta plasmas, the large pressure gradient at the edge gives rise to a large bootstrap current density.

Fig. 3. Toroidal and poloidal dependence of the magnetic perturbation at $t = 3735.0$ ms, discharge 72269.

Fig. 4. Toroidal and poloidal positions of points of peak amplitude at $t = 3735$ ms, from toroidal arrays of magnetic probes at $\theta = 0^\circ$, -36° , and -90° and poloidal array at $\phi = 67^\circ$. Solid circles are measured, open circles are inferred from up-down symmetry of the discharge. The vertical width of the shaded area is proportional to the mode amplitude at the peak locations.

These observations suggest that the combination of the edge pressure gradient and its associated bootstrap current destabilizes an edge-localized ideal kink mode or low- n ballooning mode. Coupling of an internal $m/n = 1/1$ mode (if present) to an edge-localized $n = 1$ kink then contributes to a rapid, global energy loss.

Similar observations have been reported in other experiments. In high β_p discharges in TFTR,⁶ a sudden collapse of the central temperature is associated with a spatially localized mode having $n \sim 3$ to 6. In contrast to the DIII-D observations, this instability is attributed to "infernal"-type ballooning modes occurring in the central low-shear region. In high β_p discharges in JT-60U,⁷ rapid partial collapses are attributed to an $n = 1$ internal kink-ballooning mode, destabilized by the non-monotonic central q profile created by an off-axis bootstrap current. Similar to DIII-D observations, JET high β discharges⁸ display a rapid collapse of stored energy, beginning at the edge of the plasma. This is attributed to ideal ballooning modes destabilized by a large pressure gradient, perhaps in the presence of a large bootstrap current. However, there are no direct observations of the mode which is responsible.

Values of normalized beta ($\beta/\frac{I}{aB}$) as large as 5 to 7 with optimized pressure and current density profiles have been predicted theoretically^{3,9} and confirmed experimentally.¹⁰ In reactor-relevant plasmas with low collisionality, high beta, and long pulse duration, the self-consistent pressure and current density profiles including bootstrap current may not be compatible with these optimized profiles, leading to lower beta limits. However, preliminary calculations indicate that stability can be improved by modifications of the central current density profile, even in the presence of a large edge bootstrap current. The use of non-inductive current drive to control the current density profile may allow the promise of high normalized beta to be realized in reactor-relevant plasmas.

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Fig. 5. Radial mode structure for mode number $n = 3$, calculated by GATO, for model equilibria resembling discharge 73203 with DIII-D wall. (a) low edge pressure gradient. (b) high edge pressure gradient.

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