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RESISTIVE INSTABILITIES IN ADVANCED NEGATIVE CENTRAL SHEAR TOKAMAKS WITH PEAKED PRESSURE PROFILES

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RESISTIVE INSTABILITIES IN ADVANCED NEGATIVE CENTRAL SHEAR TOKAMAKS WITH PEAKED PRESSURE PROFILES*

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Negative central magnetic shear (NCS) is an operating regime[1-3] for advanced tokamaks which could lead to fusion reactors with higher performance and lower cost. In the NCS region, the plasma is in the second stable regime for ideal magnetohydrodynamic (MHD) ballooning modes. In Tokamak Fusion Test Reactor (TFTR) and DIII–D, the plasma also develops an internal transport barrier[4,5] that provides good central confinement, high central ion temperatures, and central peaking of the pressure profile — favorable for a high fusion rate,[5,6] record high neutron yield has been obtained in peaked pressure operations. In L–mode plasmas, *i.e.*, no edge pressure pedestal, these discharges typically terminated with hard disruptions. Despite the favorable ballooning mode stability cited above, localized MHD bursts are observed in plasmas with highly peaked pressure profile in DIII–D. These bursts limit the pressure peakedness $p(0)/\langle p\rangle$ [$p(0)$ is the pressure at the plasma center and $\langle p\rangle$ is the volume averaged pressure], and occur prior to the final disruption. In what follows, the scenario that leads to these bursts and the ensuing disruptions is analyzed through systematic computation of resistive MHD modes in NCS plasmas.

To investigate the parametric dependence of the resistive MHD modes in NCS configurations we generated a set of equilibria by using the TOQ equilibrium code[8] and corresponding to those obtained in DIII–D. The aspect ratio is fixed at 2.7, the elongation from 1.0 to 1.8, and the triangularity from 0.0 to 0.7. The q profile is specified by a spline with eight node points that include the magnetic axis, the minimum q location (at 1/4 of the total poloidal flux), and the location of 95% flux value. The value of q at 95% flux q_{95} is fixed at 5.1 with the value of q_{min} covering a range from 1.1 to 2.5. The value of $q_0 - q_{\mathrm{min}}$ ranges from -0.3 to 1 (a negative value of $q_0 - q_{\mathrm{min}}$ corresponds to normal q profile with the minimum value of q at the magnetic axis). The pressure profile is given by the form $p = p_0(1-\psi)^n$. With increasing value of the exponent n, the pressure profile becomes more peaked. The equilibria studied cover a range of $\beta_{\mathrm{N}} = \beta(I_{\mathrm{p}}/a\,B_0)^{-1}$ (% MA/mT) values between 0.5 and 5.0 (here $\beta = 2\mu_0\langle p\rangle/B_0^2$ is the ratio of plasma pressure to magnetic field pressure, I_{p} is plasma current, a the plasma minor radius, and B_0 the vacuum magnetic field) at the center of the last closed flux surface. Typical q and p profiles and the resultant flux plot is shown in Fig. 1.

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The localized stability criteria of these equilibria evaluated by TOQ are first examined. We found that these equilibria are stable to the ideal interchange even in the absence of magnetic shear ($D_\mathrm{I} < -1/4$) and also stable to the ideal ballooning modes. However, the localized resistive interchange[9] is destabilized ($D_\mathrm{R} > 0$) at sufficiently high β_N at fixed amount of shear reversal or sufficiently large shear reversal at fixed (but moderate) β_N. We note that these trends shown in this numerical evaluation of D_R are in agreement with the large aspect ratio analytic results for tokamaks with circular[10] and noncircular[11] cross-sections.

The stability analysis is performed by using the MARS code with the inclusion of the effect of a toroidal plasma flow.[10,11] The toroidal mode number n has been taken to be $n = 1$. An external ideally conducting wall is placed at 1.3 plasma radius. Two classes of modes have been found. The first is a localized mode, with the characteristics of an resistive interchange (see Fig. 2). They are destabilized beyond a critical β_NC. The growth rates of these localized modes have been found to be independent of the plasma rotation. With increasing plasma rotation, the mode has been found to rotate with the rotation speed of the inner singular surface with no change in its growth rate.

The second class of modes found is the global mode. It has the structure of a double tearing mode coupled to an external kink and an internal localized interchange. A typical mode structure is shown in Fig. 3 for $q_\mathrm{min} = 1.5$ and $\beta_\mathrm{N} = 2.5$. The main poloidal harmonics in this case is given by $m = 2$. Due to the existence of multiple resonance surfaces, there could exist multiple numbers of global modes with different growth rates, depending on different amounts of coupling to the sideband harmonics. In general, the mode with the largest growth rate has the least coupling to the sideband harmonic. The growth rate and coupling to the sidebands increase with increasing β_N. In contrast to the localized mode, the growth rate of this mode is very sensitive to the plasma shape and boundary condition such as the location of the external wall and the resistivity profile of the plasma. This mode is suppressed when the outer 50% of the plasma is assumed to be ideal. I this case, close to the critical β_NC, only the localized mode is found. This indicates that this mode could be stabilized by plasma rotation. Similarly, when the inner half of the plasma is assumed to be ideal, the growth rate of the global mode is reduced significantly. For this set of equilibria, the global mode has been found always less stable than the localized mode. These modes are stabilized by elongation with increasing triangularity and increased shear in edge q profile.

To assess the relevance of these two classes of modes to experimental observations, we compare first the stability boundary (β_NC) of the localized mode with the experimental data base for disruptions. They have been found to agree in their dependences on the value of q_min, and pressure peakness parameter. Since disruption follows the occurrence of MHD bursts, and the localized mode is relatively independent of the boundary conditions; these bursts, which are observed on the inner rational surfaces of these discharges, are identified as the resistive interchanges. Details of this comparison are given in Ref. 13.

Although many characteristics of the global mode, such as beta dependence, and the dependence on the pressure peakness parameter shows similarity to that found for the mode responsible for disruption, we need to compare the details of the predictions of the stability boundary of the global mode with that observed in experiment. For this purpose, evolution of the experimental equilibrium was reconstructed in detail by using EFIT[14] for shot 87009. The reconstructed equilibrium (at 1620 msec)is unstable to the localized mode at the time of MHD burst, but stable to the global mode. The reconstructed equilibrium at the slightly later time (at 1675 msec) prior to disruption is found to be unstable to both the local and the global mode with the global mode having a larger growth rate. The rotation frequency of the global mode is at the computed frequendy. Thus we identify the disruption mode with the computed global mode. We see that the DIII–D experiment is in a parameter space where these two modes are expected to interact strongly with each other. The localized mode regulates the pressure profile whereas the global mode leads to disruption.

We thus propose the following disruption scenario for NCS discharge in L–mode plasmas with peaked pressure profile. In these discharges, the plasma is kept stable to the global mode by plasma shaping and rotation until the resistive interchange stability criterion is violated. In this situation, the localized mode could become unstable. It may interact strongly with the global mode and eventually destabilizes it, leading to disruption. Broader pressure profiles and weaker shear reversal lead to stability at higher beta.

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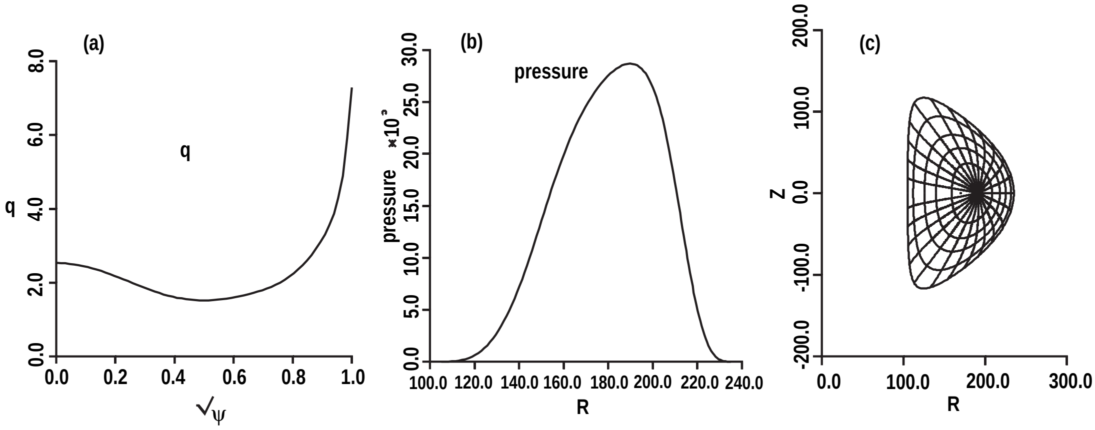

Fig. 1. Typical equilibrium profiles. (a) safety factor q; (b) pressure p; and (c) equilibrium flux plot for elongation = 1.8.

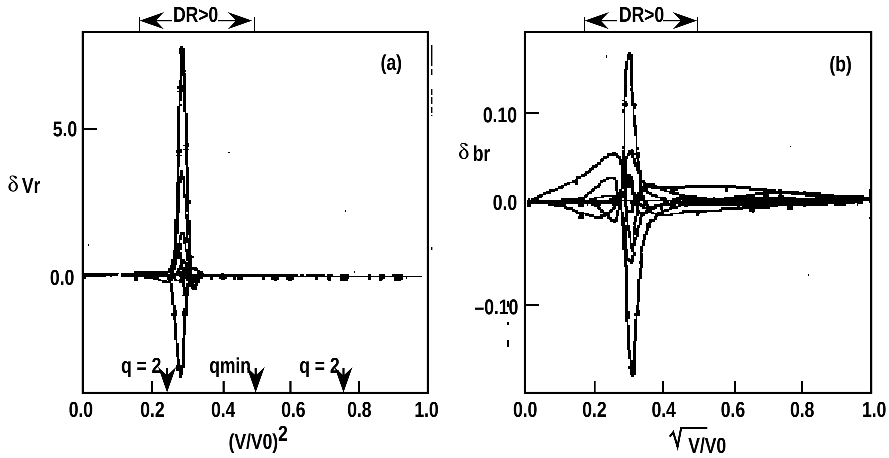

Fig. 2. Eigenfunction of localized mode (a) velocity perturbation, (b) magnetic field perturbation for $q_{\min} = 1.5,\ \beta_{\rm N} = 3.3$.

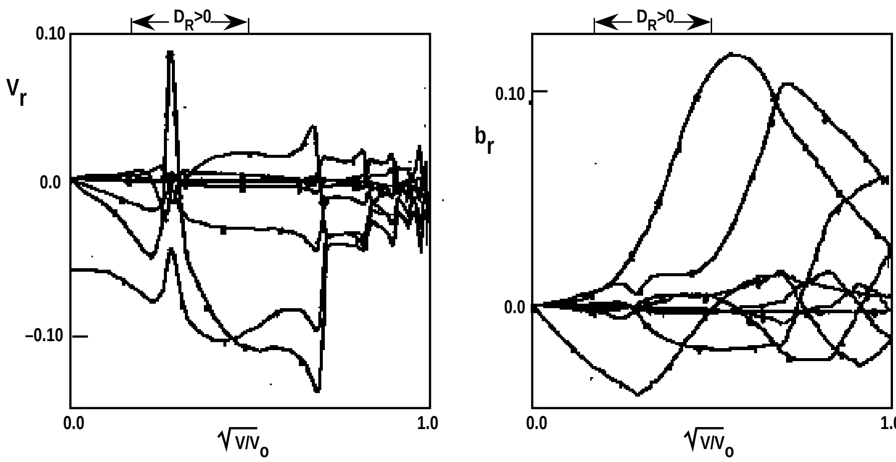

Fig. 3. Eigenfunction of global mode (a) velocity perturbation, (b) magnetic field perturbation for $q_{\min} = 1.5,\ \beta_{\rm N} = 2.5$,