Experimental and Theoretical Stability Limits of Highly Elongated Tokamak Plasmas

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Stability limits of highly elongated, D-shaped plasmas have been measured in the TCV (tokamak à configuration variable) tokamak. It is found that the plasma current is limited by kink-type disruptions, preceded by magnetohydrodynamic (MHD) mode activity. The mode structure has been analyzed using magnetic fluctuation and soft x-ray diagnostics. Mode numbers, growth rates, and experimental stability limits are consistent with ideal and resistive MHD models, based on measured plasma shapes and profiles. These results provide the first experimental confirmation of previously predicted stability limits at high elongation, $\kappa \leq 2.58$. [S0031-9007(98)07294-9]

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The performance of controlled fusion devices can be measured by the triple product $n_i \tau T_i$ where n_i is the volume averaged ion density, τ is the energy confinement time, and T_i is the ion temperature. Over the last 25 years, the maximum value of the triple product achieved in various plasma confinement devices has increased by 4 orders of magnitude, and the values which are presently observed in the largest tokamaks are equivalent to the condition of scientific breakeven, which is defined by the equality of fusion power output and applied heating power. This impressive development in performance is not only due to the fact that tokamaks have grown in size over the years, but is also a result of more subtle improvements of the basic tokamak concept. One of the most important of these concept improvements is the evolution from circular to noncircular plasma cross sections. In particular, vertical elongation of the plasma cross section brings two main advantages. First, the plasma current can be increased since it scales as $I_p \sim (\kappa^2 + 1)/2$, where κ is the elongation, defined as the ratio of the vertical and horizontal minor axes of the plasma cross section. As a consequence, the global energy confinement time also increases since, according to several widely used scaling laws, it is proportional to the plasma current [1]. The second advantage is that vertically elongated and D-shaped cross sections allow much higher β values than circular ones [2–7]. β is defined as the ratio of the volume averaged plasma pressure to the magnetic field pressure in vacuum. The β limit, as determined by ideal magnetohydrodynamic (MHD) stability, has been expressed in a variety of scaling laws [3–6]. Perhaps the most widely used is the Troyon scaling law [3], $\beta(\%) = C_\mathrm{T} I_p(\mathrm{MA})/[a(\mathrm{m})B(\mathrm{T})]$, where I_p is the plasma current, a is the horizontal minor radius, B is the toroidal magnetic field, and C_T is the Troyon factor, which is typically between 2.5 and 4.0, depending on the pressure and current profiles. Both of these advantages have been demonstrated experimentally up to elongations of $\kappa = 2.35$ [8,9] but it is not known whether the favorable trends continue to be valid at $\kappa = 2.5$. Theoretical studies show [10–14] that both the Troyon scaling law and the conventional current limit, $q_s > 2$, are no longer valid at $\kappa = 2.5$. q_s is the safety factor at the plasma boundary, and q is defined as the rate of change of toroidal flux with poloidal flux.

The experimental verification of these predictions is difficult because highly elongated plasmas are unstable with respect to an axisymmetric mode, the vertical displacement instability, and the growth rate of this mode increases rapidly with elongation. The mode can be stabilized by a combination of passive elements and active feedback coils, but very few tokamaks are equipped with feedback systems allowing operation beyond $\kappa = 2$. Consequently, stability limits at high elongation, $\kappa \approx 2.5$, have not been tested experimentally in a systematic way.

The TCV tokamak (tokamak à configuration variable) can operate routinely up to $\kappa = 2.5$ [15]. In recent experiments, we have measured current limits in the range $2.0 < \kappa < 2.5$, and, in this Letter, we present the first experimental evidence for a saturation of the normalized current when $\kappa > 2.3$. We also present tentative evidence for a β limit at high elongation, and we show that the experimental stability limits are consistent with ideal and resistive MHD stability calculations.

Figure 1 summarizes recent experimental results in TCV at high elongation [15]. In this figure, we plot the normalized plasma current $I_N = I_p(\mathrm{MA})/[a(\mathrm{m})B(\mathrm{T})]$ against elongation for D-shaped plasmas with a fixed horizontal minor radius, $a = 0.25$ m. The discharges shown here are all Ohmically heated, and β values are typically between 1.5% and 2.5%. In the course of these experiments, it was noted that, for any given value of κ, there was a maximum value of I_N beyond which it was not possible to obtain stable discharges. The current was limited by kink-type disruptions, not by vertical displacement events (VDE). Kinks and VDE's can be distinguished by mode analysis of magnetic fluctuation measurements, as discussed below. Kinks are characterized by toroidal mode numbers $n \geq 1$, whereas VDE's are purely $n = 0$. The experimental results (Fig. 1) show that the maximum

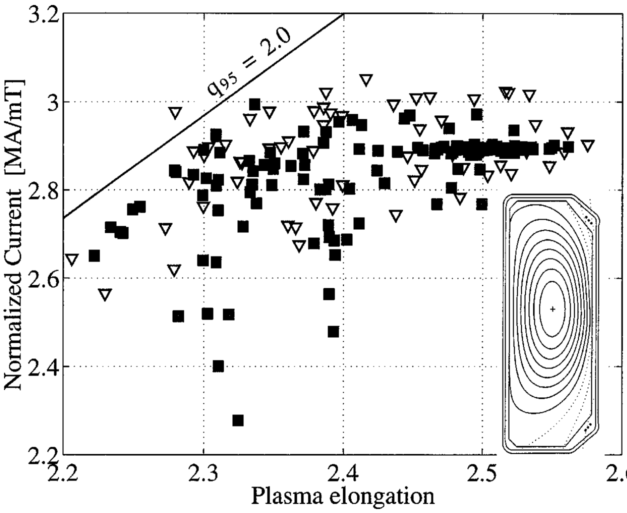

FIG. 1. Normalized current vs elongation for D-shaped plasmas in TCV. Disruptive and nondisruptive discharges are shown as open triangles and solid squares, respectively. The safety factor at the 95% flux surface, q_{95}, is equal to 2.0 along the solid line. Inset: TCV vacuum vessel and plasma shape with elongation $\kappa = 2.55$.

value of I_N increases with κ, as expected, up to $\kappa = 2.3$. This increase is consistent with the ideal MHD stability condition, $q_s > 2$. However, for $\kappa > 2.3$, the maximum normalized current remains roughly constant, $I_N = 3$ MA/mT, all the way up to the highest elongation produced so far, $\kappa = 2.58$.

Ideal MHD theory predicts that, at high elongation, the current limit decreases with increasing β [12,14]. Therefore, it should be possible to reach the stability limit in two ways, either by increasing the current at constant β, as discussed above, or by increasing β at constant current. Evidence for the second path to the stability limit can be obtained from the present experimental results by comparing two consecutive discharges which are identical in every respect, except that one discharge had a slightly higher electron density, and hence a higher β value, than the other. Figure 2 shows two typical pairs of such discharges. In both cases, the high-β discharge disrupted, whereas the one with lower β did not. Since the β limit depends on pressure and current profiles, and since the profiles may be influenced by the gas injection rate, which was used to control the density, we have checked whether there is any difference in the profiles between the low-β and high-β discharges. Electron density and temperature profiles were measured by Thomson scattering, and we find no difference in profile shape, within experimental error, between the low density and high density discharges [16]. Current profiles were not measured directly, but we measure the sawtooth inversion radius, using soft x-ray tomography, and again we find no difference between the low density and high density discharges within experimental error. We conclude that the present experimental results can be interpreted as evidence for a β limit but other interpretations, such as a change in the current limit induced by slight profile variations, cannot be completely excluded. It should be noted that the disruptions seen here are not related to density-limit disruptions since the measured electron densities never exceed 30% of the Greenwald limit [17].

The disruptions which occurred in these experiments were always preceded by mode activity, and even nondisruptive discharges often showed bursts of MHD activity. The MHD activity has been analyzed using magnetic fluctuation and soft x-ray emission diagnostics. Magnetic measurements are obtained from fast pickup coils which measure fluctuations of the poloidal magnetic field inside the vacuum vessel. TCV is equipped with two toroidal arrays in the equatorial plane (8 probes on the high field side and 16 probes on the low field side) and four poloidal arrays (38 probes each). An expansion of the measurements in Fourier components yields toroidal mode numbers up to $n = 8$ and singular value decomposition allows us to identify the poloidal mode number m which corresponds to a toroidal mode number n. The mode activity during two very similar discharges at $\kappa = 2.5$ is shown in Fig. 3. The discharge 12414 exhibits a growing $n = 3$ component, at $t = 0.790$ sec, which can be identified as a $m/n = 4/3$ mode, rotating at 10 kHz. It grows continuously and leads to a minor disruption at $t = 0.794$ sec. The minor disruption is immediately followed by the onset of a $m/n = 3/2$ and a $m/n = 2/1$ mode. The $m/n = 3/2$ mode rotates at 5 kHz and saturates quickly, whereas the $m/n = 2/1$ mode grows locked and causes a major disruption. The discharge 12413 shows similar bursts of $m/n = 4/3$ modes leading to minor disruptions. However, no $m/n = 2/1$ mode appears, and

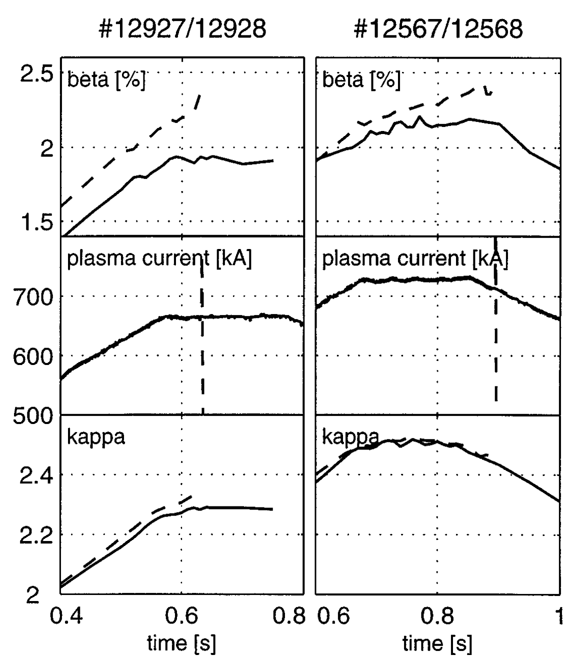

FIG. 2. Evolution of toroidal β, plasma current, and elongation in two pairs of discharges. Disruptive and nondisruptive discharges are shown as dashed and solid lines, respectively.

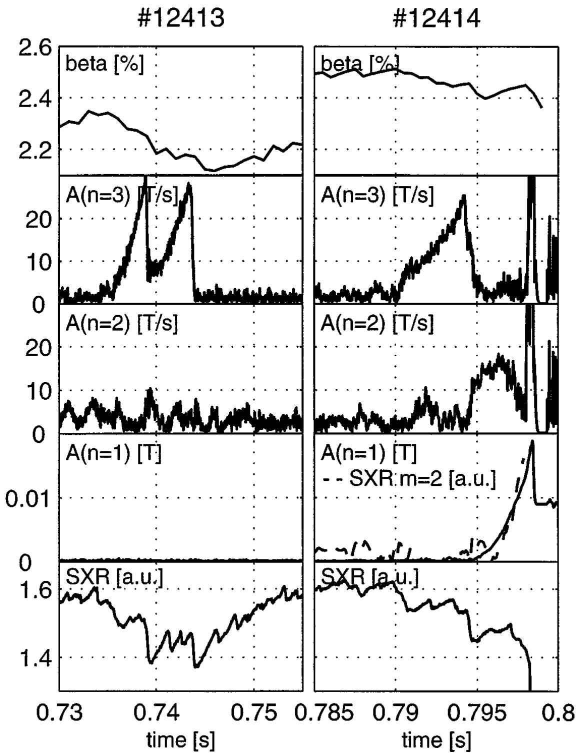

FIG. 3. MHD mode activity in a disruptive (12414) and a nondisruptive (12413) discharge, deduced from magnetic fluctuation measurements. The $m = 2$ amplitude, obtained from soft x-ray tomography is also shown (dashed line).

the discharge survives. Separate analysis of the magnetic fluctuation measurements on the low field side and on the high field side of the plasma shows that the mode amplitudes are similar, typically within a factor of 2, indicating that the modes are likely to be kinks, not ballooning modes. The modes are also seen in soft x-ray measurements. The soft x-ray system on TCV consists of ten cameras viewing the plasma from different angles, all in the same poloidal plane, providing a total of 200 lines of sight and allowing a spatial resolution of about 3 cm. Tomographic reconstructions of the soft x-ray emissivity allow an independent evaluation of the poloidal mode number and the corresponding mode amplitude. As an example, the evolution of the $m = 2$ amplitude is shown as a dashed line in Fig. 3.

Similar disruption precursors have been seen in many tokamaks when operating near MHD stability limits [18–22]. Highly elongated plasmas, up to $\kappa = 2.5$, have also been obtained in the DIII-D tokamak [8,23], but the current limit was not tested at $\kappa = 2.5$.

Theoretical stability limits of elongated tokamak plasmas have been investigated in the past by many authors [10–14]. Turnbull [12] and Eriksson [13] have computed ideal MHD β limits for D-shaped plasmas with $\kappa = 2.5$, as a function of I_N. Their results follow the Troyon scaling up to $I_N = 1.8$ MA/mT, beyond which the β limit drops rapidly. This is consistent with the present experimental results in TCV, although the current and pressure profiles which were used in these early analyses [12,13] are somewhat different from the ones which are now measured in TCV.

In this Letter, we reanalyze MHD stability limits at high elongation, using plasma shapes and profiles of actual TCV discharges. Experimental equilibria are reconstructed with LIUQE [24] and CHEASE [25]. Ideal MHD stability limits are computed with ERATO [26] and KINX [27]. The equilibria considered here all have relatively low values of q_s, which is a necessary condition for axisymmetric stability at high elongation [15]. Consequently, the volume inside the $q = 1$ surface is large, and the reconstructed q profiles usually have $q_0 < 1$. This poses problems for stability analysis since it is difficult to separate the $m/n = 1/1$ internal kink from the $n = 1$ external kink. We avoid this problem by slightly modifying the experimental q profile such that $q > 1.05$ everywhere, while keeping the internal inductance, l_i, equal to the experimental value. The ideal MHD β limit as determined by the $n = 1$ external kink is shown in Fig. 4 for two elongations, $\kappa = 2.2$ and 2.5. Here, plasma shape, pressure, and current profiles are taken from the reconstructed equilibria of the discharges 11835 and 12413. The stability limit is given as a band with finite width to show the effect of small variations in the pressure and current profiles within the experimental uncertainties. The β limits due to ballooning modes and $n = 2$, $n = 3$ ideal kink modes are much higher than the $n = 1$ kink limit and are therefore irrelevant for the present analysis. For $\kappa > 2.2$, ideal MHD theory predicts that the current limit at finite β is reached at progressively higher values of q_s, as the elongation increases, in agreement with the experimental data shown in Fig. 1. The experimental points shown in Figs. 1 and 4 were obtained for D-shaped plasmas with elongations between $\kappa = 2.20$

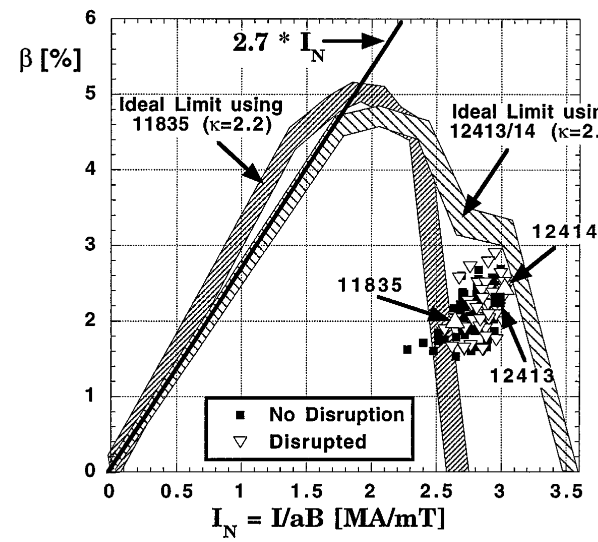

FIG. 4. Ideal MHD β limits vs normalized current. Experimental points with $2.20 < \kappa < 2.58$ are shown as open and solid symbols for disruptive and nondisruptive discharges, respectively.

and 2.58. The shape of the plasma boundary in these experiments can be approximated by the expressions $R = R_0 + a[\cos(\theta + \delta \sin\theta - \lambda \sin 2\theta)]$, $Z = a\kappa \sin\theta$, where R_0 and a are the major and minor radii, respectively ($R_0 = 0.88$ m, $a = 0.25$ m), δ is the triangularity, and λ is the rectangularity. Typical values of the shape parameters, at an elongation of $\kappa = 2.5$, are $\delta = 0.34$ and $\lambda = 0.27$. We note, in Fig. 4, that the theoretical stability limits are entirely consistent with the experiments in TCV. In particular, it is seen that the discharge 12414, as well as all discharges with $I_N > 3$ MA/mT which terminated in a disruption, are very close to the ideal limit, whereas the nondisruptive discharge 12413 is slightly farther away. It should be noted that β limits in TCV are generally lower than in DIII-D [8,9] at the same elongation. This discrepancy is mainly due to the fact that highly elongated plasmas in TCV have lower triangularity, higher rectangularity, and higher aspect ratio than DIII-D plasmas, as has been shown in Ref. [13]. In addition, current and pressure profiles are not the same in the two machines since DIII-D uses high power additional heating, whereas the TCV plasmas considered here are purely Ohmic.

Figure 4 shows that disruptions do not only occur close to the ideal stability limit but also in domains which are ideally stable. These disruptions are triggered by MHD modes, as explained above, and the modes grow on resistive time scales, typically in the ms range. The growth rate of the 2/1 mode shown in Fig. 3 is approximately 1200 s^{-1}. In view of these facts, we have analyzed the experimental equilibria with the resistive MHD code MARS [28], and we also calculate the tearing parameter, Δ', in a cylindrical approximation, using the experimental q profiles. The tearing parameter is defined by the jump in the radial logarithmic derivative of the perturbed poloidal flux across a resonant q surface. We find that the discharges 12413 and 12414 are unstable with respect to $m/n = 4/3$, 3/2, and 2/1 modes. The domain where the resistive modes are unstable lies below the ideal limit and extends down to very low values of β, as resistive stability depends mainly on the current profile. Other modes, such as $m/n = 5/4$, 5/2, 4/2, and 3/1 are stable. This is consistent with experimental observations, since in all discharges analyzed so far, only $m/n = 4/3$, 3/2, and 2/1 modes have been seen. Moreover, the measured growth rates of these modes, typically between 300 and 1000 s^{-1}, agree with theoretical estimates [29] within a factor of 4. This is additional evidence for the identification of the observed MHD activity as resistive tearing modes.

In conclusion, we have shown that the current limit in highly elongated tokamak plasmas follows the conventional scaling, $q_s > 2$, up to an elongation of $\kappa \approx 2.3$, but saturates for $\kappa > 2.3$. The experimental current limit, as defined by the appearance of disruptions, is shown to be very close to the ideal MHD stability limit. We have also shown that the modes which are observed just before major disruptions or which trigger minor disruptions are resistive modes with growth rates in ms range. These results also confirm early theoretical predictions of stability limits at high elongation, $\kappa = 2.5$, made more than ten years ago [12].

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