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COMPARISON OF HIGH CURRENT DISRUPTION LIMIT IN ELONGATED PLASMAS IN TCV WITH IDEAL AND RESISTIVE MHD MODELS†

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Abstract

Elongated plasmas up to κ=2.5 have been obtained in the Lausanne Tokamak TCV[1]. For $\kappa < 2.3$, the normalized current limit, I_N=I[MA]/a[m]B[T], increases with elongation and is limited by the standard ideal limit at q_a=2. However for κ>2.3, a disruption occurs at larger values of $q_a(\kappa)$, such that the current limit stays about constant at $I_N \approx 3$[1]. The modes observed at the disruption are typically m/n=2/1 and 3/2 modes. The observed disruption limit is consistent with the prediction of the n=1 ideal MHD limit presented in Ref.2 for analytical plasma shapes. We have computed the ideal and resistive MHD limit for the actual experimental plasma shapes and profiles. We find that the shots which disrupted are indeed very close to the ideal n=1 external kink β-limit. We also see that, including resistivity, the 4/3, 3/2 and 2/1 modes are unstable even well below this limit, which agrees with the experimental data. For $2.5<\kappa<3$, we have varied the profiles over a wide range and our results confirm the prediction of Refs.2 and 3, which is that only by keeping q_a just above 3 and decreasing the plasma inductance, l_i, one can find stable configurations.

Introduction

The upper β-limit, $\beta=2\langle p\rangle_{vol}/\mu_0 B_0^2$, in an axisymmetric plasma is determined by the ideal MHD limit and is quite well described by the Troyon limit[4]:

$$\beta\ [\%] = c_T\, I_N = c_T\, I\ [MA] \,/\, (a\ [m]\ B\ [T]\ ) \qquad (1)$$

The effective value of the Troyon factor c_T is typically around 2.5 to 4 depending on the pressure and current profiles. The β-limit described by Eq.(1) is not valid for reversed shear profiles, where plasma rotation and wall stabilization effects are necessary to obtain stable high-β plasmas. At very high elongation, which maximizes the plasma current for a given minor radius a, and near the plasma current limit, Eq.(1) is not valid either as has been shown in Ref.2. Therefore, to determine how much we can really increase β when increasing the elongation κ is one of the main objectives of the TCV experiment (Tokamak Configuration Variable)[5]. In the last campaign, highly elongated discharges (κ>2.3) have been obtained, many of which disrupted when approaching a given normalized current $I_N \approx 3.05$[1], close to the prediction of Ref.2. In this work, we compute the ideal and resistive β-limits using the plasma shape and profiles of TCV discharges. As is shown below, we recover the results of Ref.2, and those of Ref.3 for higher κ. Moreover we find that the 4/3, 3/2 and 2/1 modes are the most unstable resistive modes, in agreement with experimental data.

Experimental results and comparison with numerical results

The experimental high elongation discharges are summarized in Figs.1 and 2. For κ=2.3, the theoretical current limit, at zero β, is equal to $I_N \approx 2.85$,

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determined by $q_a \geq 2$. However at higher elongation all discharges disrupt for $I_N \geq 3$. This had already been predicted[2] at the time when TCV was designed, as shown by the solid lines in Fig.1. In that case, two plasma shapes were analyzed in more detail at $\kappa=2.5$, a Racetrack and a D-shaped plasma. We see that the β-limit does follow Eq.(1) at low I_N, however decreases much below the $q_a=2$ limit. As the discharges in Fig.1 are all in ohmic regime, β is not a free parameter and is typically around 2.5% as seen in Fig.1. Therefore the experimental points are near the D-shape limit, even though the actual shape is closer to a Racetrack, with however a non-negligible triangularity.

We have studied in more detail two shots at $\kappa \approx 2.5$, one which did not disrupt, 12413, and one which did disrupt, 12414. The time traces are shown in Fig.3, where one sees that, in the shot 12414, first a 4/3 mode occured, causing a minor disruption, then a 3/2 and finally a 2/1 mode locked and caused the disruption. This sequence is typical with or without the occurence of the 4/3 mode. In the shot 12413, two 4/3 modes occured, causing two minor disruptions, as seen on the SXR measurement, but as no 2/1 mode appeared the discharge survived. One can see that κ, I_N and β were all slightly lower in the shot 12413. These two discharges are quite typical of high elongation ohmic discharges.

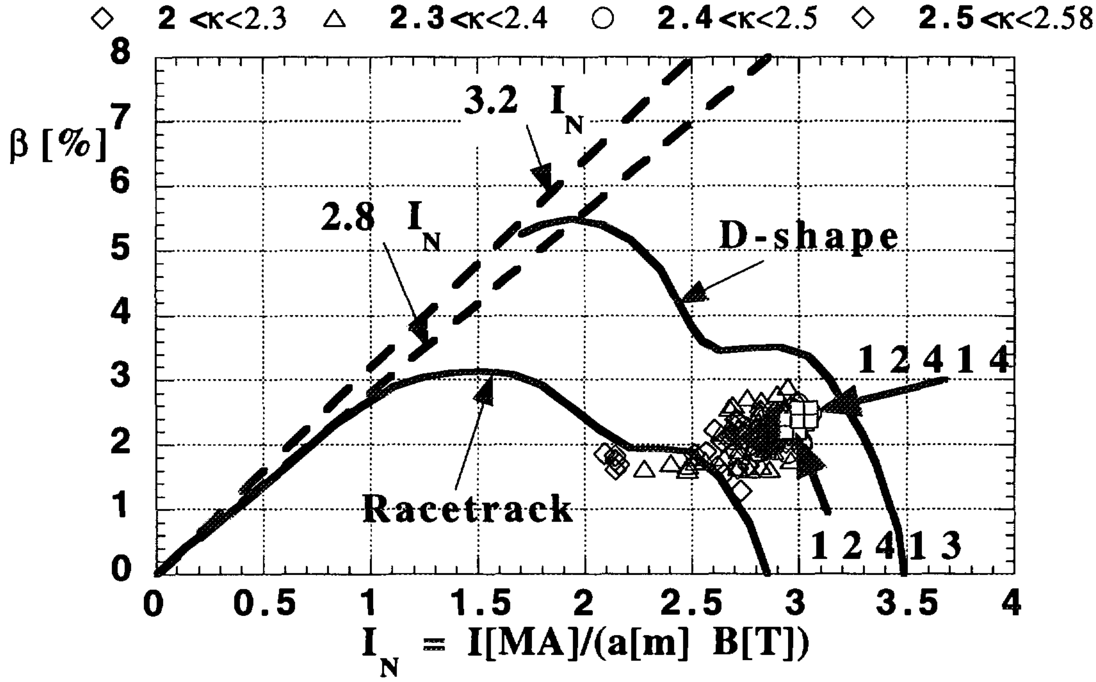

Fig.1: Ideal limit for a D-shaped and a Racetrack plasmas as in Fig.4 of Ref.2. The symbols show TCV results for $\kappa>2$.

The equilibria 12413 at t=0.76s and 12414 at t=0.794s have been reconstructed using LIUQE[6] and coupled to the equilibrium code CHEASE[7]. Then we have used ERATO[8] and KINX[9] to study the ideal limit, and MARS[10] and a cylindrical Δ' calculation to study the resistive MHD modes. All these codes are coupled to CHEASE. As q_a is relatively low, to have stable n=0 plasmas, the inversion radius is relatively large. Therefore it is difficult to separate the stability limit of the internal 1/1 kink mode from the external kink limit. This is why we have flattened the q profile such as to keep $q \geq 1.05$ everywhere, while keeping l_i equal to the experimental value (≈ 0.6-0.65). Note that the central q profile is not accurately measured in TCV. Therefore we have varied the current and pressure profiles, around the experimental profiles, to take into account experimental uncertainties. For both the 12413 and 12414 discharges we find the same ideal β-limit, shown as a hatched region in Fig.2. The marginal β is not a line as it depends slightly on the profiles. We see that the shot 12414, as well as all the shots with $I_N \geq 3$ which disrupted, are very close to the ideal limit, whereas the shot 12413 is further away, consistent with the experiment. However the modes grow on a resistive time-scale and we have checked that the ballooning and n=2, n=3 kink β-limits are much higher.

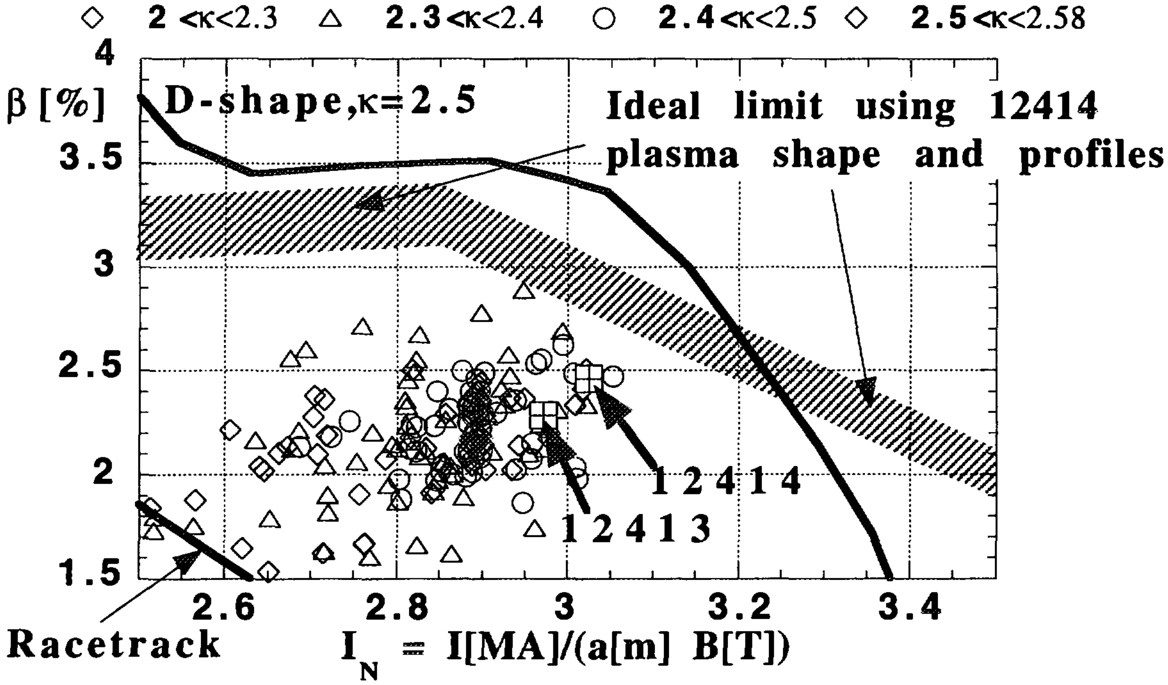

Fig.2: The symbols show TCV results for different elongation. All shots with $I_N \geq 3$ disrupted. The hatched region represents the ideal marginal limit, while the region underneath is unstable to resistive modes.

Therefore we have analyzed these equilibria with the resistive MHD code MARS and found both the 12413 and the 12414 discharges unstable to n=1, 2 and 3, with the largest growth rate for the n=1 mode consistent with the experiment. The resistive unstable region, in Fig.2, is the whole region underneath the ideal limit down to very low β as it depends mainly on the current profile. We have also computed the Δ' values, using the experimental q profiles and a cylindrical approximation. We find the 4/3, 3/2 and 2/1 unstable, whereas the other modes, e.g. 5/4, 5/2, 4/2 and 3/1, are stable. This is consistent with the experiment, as in all the discharges analyzed so far, only 4/3, 3/2 and 2/1 modes have been observed.

In order to increase the operational space, we tried to change the plasma shape and to use different current profiles, reversed shear and low l_i. We find, as first mentioned in Ref.2 and confirmed in Ref.3, that only by keeping $q_a \geq 3$ fixed and reducing I_N as much as possible, one obtains stable configurations for κ up to 3. This reduces l_i and is therefore good for the n=0 stability as well, but reduces the β-limit to a value below 2-3%. The optimal current profiles are very similar to profile (c) in Fig.3a of Ref.2, such that one has finite shear in the center and low shear up to the q=2 surface and l_i is below 0.5. These types of current profiles will probably require the help of the ECRH system, which is now available on TCV, in order to be able to obtain stable κ=3 discharges.

Conclusion

We have shown that the high elongation, κ>2.3, discharges in TCV which disrupt are at or very close to the ideal MHD limit. We have also shown that the modes occuring just before the disruption or causing minor disruptions are conventional resistive modes, even though the modes with large island width can be further destabilized by the neoclassical perturbed bootstrap current. In order to reach elongations larger than 2.5, while remaining vertically stable, one will need to control the current profile to decrease l_i below 0.5.

References

1. F. Hofmann et al, in Proc. of the 24th EPS Conference, Berchtesgaden, Germany, June 1997.
2. A. D. Turnbull et al, Nucl. Fus. 28 (1988) 1379.
3. G. Eriksson et al,Plasma Phys. (Proc. 1992 Int. Conf. Innsbruck) 16C, Part I, EPS(1992) 343.
4. F. Troyon et al, Plasma Phys. Controll. Fus. 26 (1984) 209.
5. F. Hofmann et al, Plasma Phys. Control. Fusion **36** (1994) B 277.
6. F. Hofmann et al, Nucl. Fus. **28** (1988) 1871.
7. H. Lutjens et al, Comput. Phys. Commun. **97** (1996) 219
8. R. Gruber et al., Comput. Phys. Commun. **21** (1981) 323.
9. L. Degtyarev et al, Comput. Phys. Commun. **103** (1997) 10.
10. A. Bondeson et al, Phys. Fluids B **4** (1992) 1889.

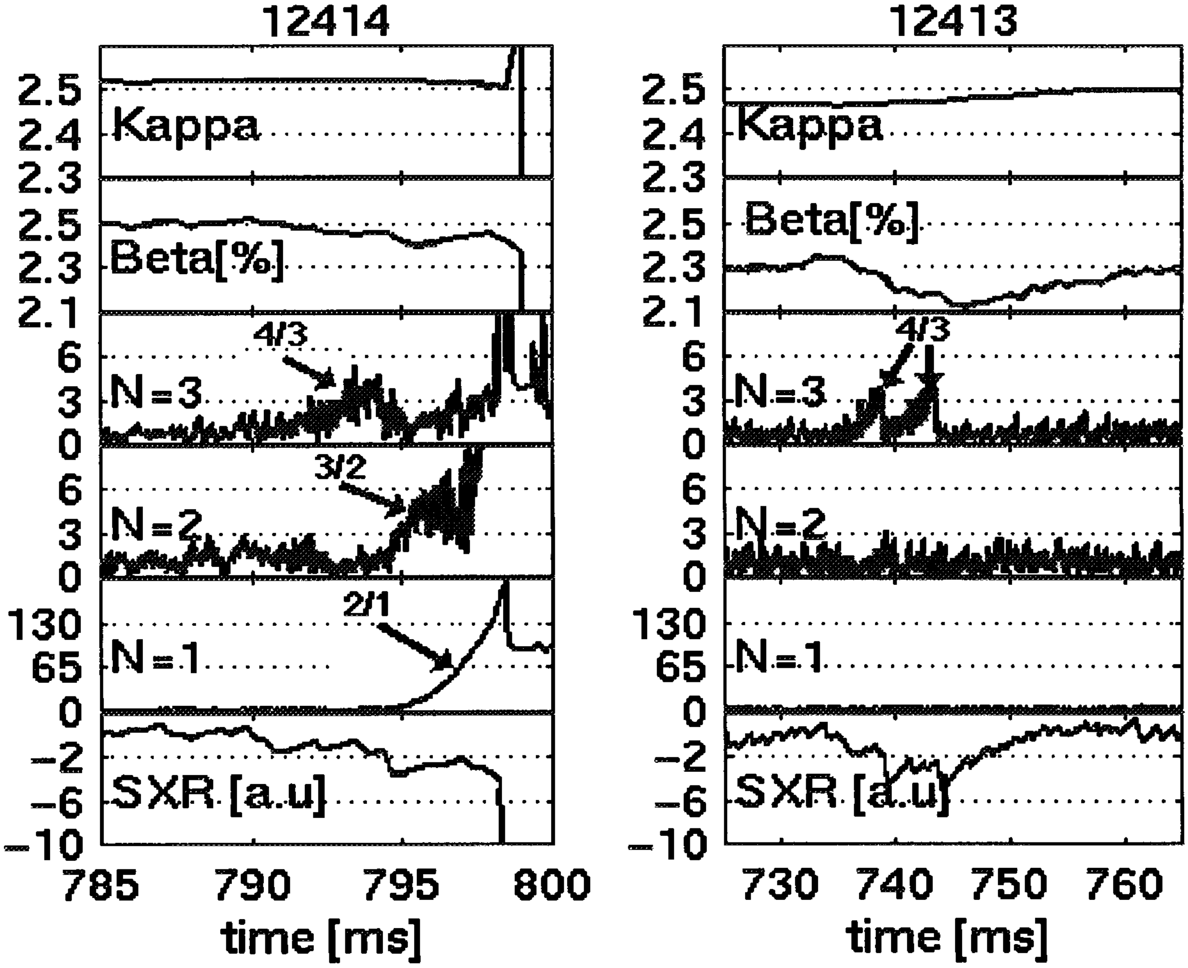

Fig.3: Time traces for shots 12414 and 12413. The 12414 disrupted due to a 2/1 locked mode very near the ideal limit, as shown in Fig.2.