# OBSERVATION OF β-LIMITS IN HIGHLY ELONGATED TOKAMAK PLASMAS

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## 1. Introduction

According to the Troyon scaling law [1], the β-limit is proportional to the plasma current and inversely proportional to the horizontal minor radius and the toroidal magnetic field, $\beta(\%) = C_T I_p(MA)/[a(m)B_t(T)]$, where $C_T$, the Troyon factor, is typically between 2.5 and 4.0, depending on the pressure and current profiles. Ideal MHD theory predicts that the Troyon factor is significantly reduced at high elongation or near the plasma current limit [2,3,4]. Experimentally, the degradation of the Troyon factor at high elongation has not been clearly demonstrated up to now, mainly because very few tokamaks are equipped with feed-back systems allowing operation beyond $\kappa = 2$. The TCV tokamak can operate routinely up to $\kappa = 2.5$, and in this paper, we summarize recent experiments showing evidence for β-limits at high elongation.

## 2. Creation of Highly Elongated Plasmas in TCV

It is well known that the growth rate of the fundamental axisymmetric mode in elongated tokamak plasmas increases rapidly with elongation. In order to stabilize this mode, an active feedback system is required whose response time is of the same order as the inverse open loop growth rate of the unstable mode. TCV has a unique vertical position control system, using slow active coils outside the vacuum vessel and a fast active coil inside the vessel [5]. The response times of the power supplies driving the slow and fast coils are approximately 1.0 and 0.1 ms, respectively. Between 1993 and 1996, TCV was operated with slow coils only. Consequently, the maximum axisymmetric growth rate that could be stabil-ized was of the order of 1000 $s^{-1}$ and the plasma elongation was limited to about $\kappa < 2.1$. In 1997, the fast coil became operational and, after a phase of testing and optimization, the new system allowed us to stabilize plasmas with open loop growth rates up to 4400 $s^{-1}$ and elongations up to 2.58 [5].

## 3. Limits of Operation

Experiments at high elongation have shown that there are basically four conditions that must be satisfied to avoid disruptions. The first of these conditions is the well-known ideal MHD kink limit, $q_a > 2$, where $q_a$ is the safety factor at the plasma boundary. From an experimental point of view, this condition is not quite sufficient for stability, especially when one is working with highly elongated, D-shaped plasmas. In such plasmas, the safety factor rises very steeply as one approaches the plasma boundary. Thus, for $q_a = 2$, we find q-values considerably less than 2 at flux surfaces which are very close to the plasma boundary. Experience has shown that, in this case, stable operation requires that $q_{95}>2$ rather that $q_a>2$. The second obvious condition for stability is that the open loop growth rate of the vertical instability, $\gamma$, must be less than the maximum growth rate that the feedback system can handle. In TCV, this can be expressed as $\gamma<\gamma_{max}\approx 4000\ s^{-1}$. However, $\gamma$ is not a parameter which can be directly controlled by the operator. In low $\beta$, Ohmic plasmas, $\gamma$ depends mainly on elongation, triangularity and internal inductance [6]. The internal inductance at a given elongation is in turn a function of the plasma current. The result is that at each elongation and triangularity, the plasma current must exceed a critical value such that $\gamma<\gamma_{max}$. A third condition for stable operation which has recently emerged form experiments in TCV [7], can be expressed as $I_N<3MA/(mT)$, where $I_N$ is the normalized current, $I_N=I_p/(aB_t)$. This condition replaces the first one, $q_{95}>2$, whenever $\kappa>2.3$. The fourth operational limit finally is the $\beta$-limit. Normally, in Ohmic plasmas, ideal MHD $\beta$-limits cannot be reached because this would require operation at densities exceeding the Greenwald limit by a large factor. In highly elongated plasmas, however, $\beta$-limits can be reached under Ohmic conditions at densites which are less than 30% of the Greenwald limit. Fig. 1 shows experimentally achieved values of $q_{95}$ vs. $\kappa$, in TCV.

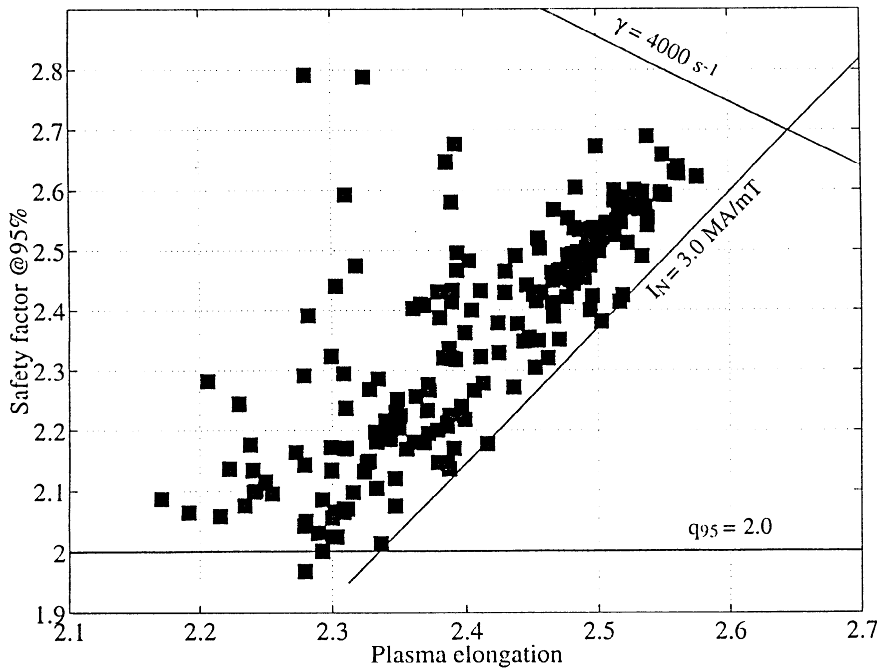


*Fig. 1. Operational limits for D-shaped, Ohmic plasmas in TCV*

### 4. $\beta$-limits at High Elongation in TCV

$\beta$-limits depend on a large number of parameters (plasma shape, q-profile, pressure profile). In Ohmic plasmas, the profiles vary somewhat with machine condition and cannot be controlled. Nevertheless, the existence of a $\beta$-limit can be clearly seen by comparing two consecutive, identical discharges, differing only in their volume averaged pressure. Fig. 2 shows three examples of such discharges. It is seen that the evolution of the plasma current and elongation of the two discharges in each pair are nearly identical, whereas the $\beta$ values are slightly different. In each case, the discharge with higher $\beta$ disrupted, whereas the one with lower $\beta$ did not. These disruptions are usually preceeded by MHD mode activity, leading to a m/n=2/1 locked mode [8].

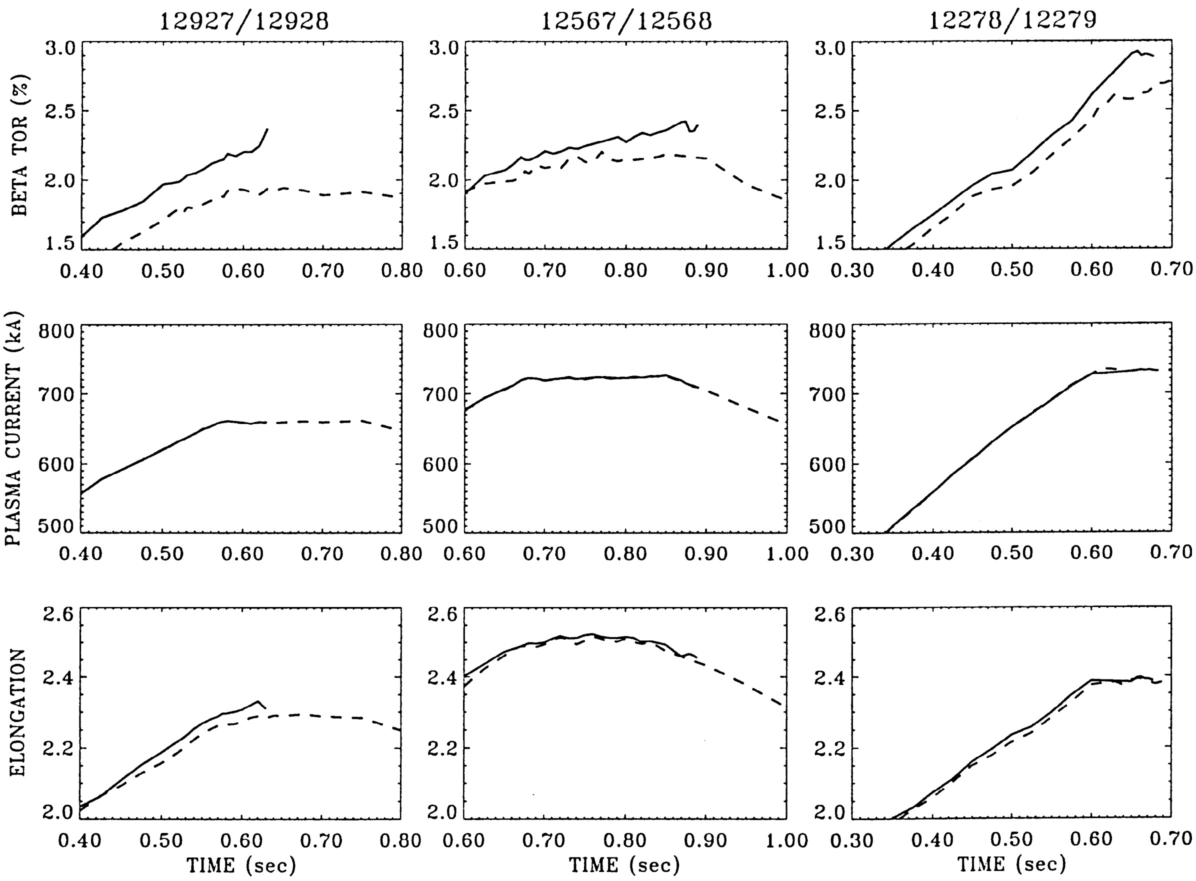


*Fig. 2. Evolution of toroidal β, plasma current and elongation in three pairs of discharges. Disruptive and non-disruptive discharges are identified by solid and dashed lines, respectively.*

## 5. Comparison with Ideal MHD Theory

MHD stability limits at high elongation have recently been calculated, using plasma shapes, pressure and current profiles of actual TCV discharges [4]. TCV experimental equilibria are reconstructed with the LIUQE code [9], then recomputed in flux coordinates with the CHEASE code [10]. Ideal MHD stability limits are computed with ERATO [11] and KINX [12]. The ideal MHD β limit, as determined by the n=1 external kink mode, is shown in Fig. 3 for two elongations, κ=2.2 and κ=2.5. The calculations were performed, using the experimental plasma boundary as well as experimental pressure and current profiles. 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 experimental uncertainties. 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 here. The experimental points shown in Fig. 3 were obtained for D-shaped plasmas with elongations between 2.20 and 2.58. We note 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 $I_N$>3MA/(mT) which terminated in a disruption, are very close to the ideal limit, whereas the non-disruptive discharge 12413 is slightly further away from the limit.

## 6. Conclusions

Highly elongated, D-shaped plasmas have been produced in TCV. Typical shape parameters were $\kappa=2.5$, $\delta=0.35$, $\lambda=0.27$, where $\delta$ and $\lambda$ are the triangularity and squareness, as defined in [3]. Since TCV has a rectangular vacuum vessel, positive squareness is necessary at high elongation in order to reduce the growth rate of the vertical instability. $\beta$-limits were found to be between 2 and 3%, in agreement with ideal MHD stability calculations, based on measured plasma shapes and profiles.

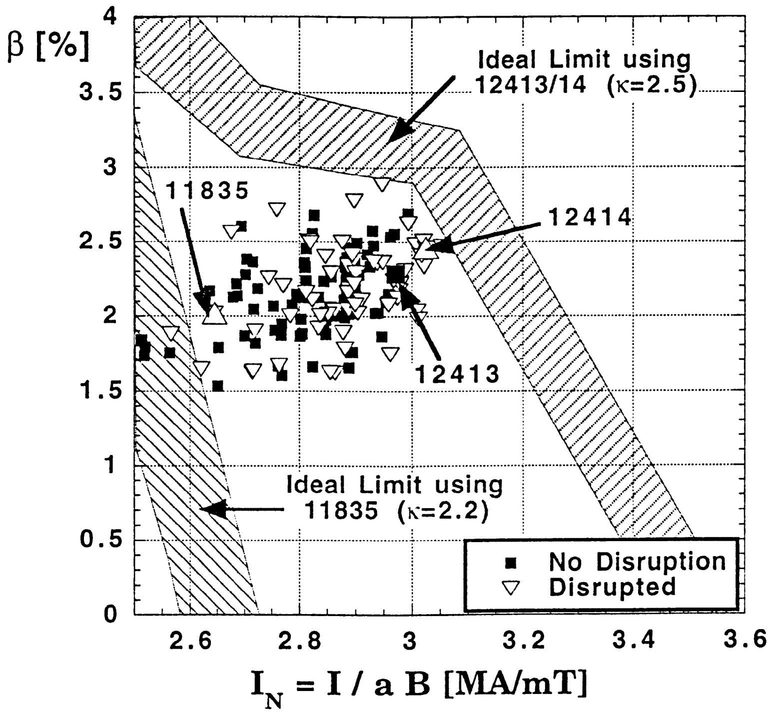


*Fig. 3. Ideal MHD β limits vs. normalized current. Experimental points are shown as open triangles and solid squares for disruptive and non-disruptive discharges, respectively.*

**Acknowledgements**

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