Stability Margins of Elongated Plasmas in TCV and Implications for ITER

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ABSTRACT

During the operation of the TCV tokamak an extremely wide variety of plasma shapes has been controlled with elongations up to $\kappa=2.5$, beyond the present designs for ITER. The operational regime explored by TCV is summarised in this paper using a representative sample of discharges. The growth rates for these discharges were estimated using a rigid current displacement model. The Poloidal Field coil voltages required for plasma control, using the slow external coils and the fast internal coils have also been inspected.

Introduction: The TCV tokamak has an extremely flexible plasma shaping system [1] allowing a wide range of plasma equilibria to be studied. These equilibria are mostly controlled using the MGAMS algorithm [2]. The operational range exceeds that of the RTO/RC ITER designs. The use of internal coils is also a feature which is being explored for some ITER designs. In view of this interest, we have re-visited the TCV operational space to determine which ranges of plasma parameters are accessible.

Data sampling: During TCV operation, a full plasma equilibrium is reconstructed by the LIUQE algorithm [3] every 50 milliseconds. The complete database of TCV reconstructed equilibria comprises 133991 samples. To generate a representative sample with a manageable size and uniform density, avoiding clusters of "popular" standard equilibria, a novelty filter was defined by the Euclidean distance between the PF current vectors constructed from the 16 PF shaping coil currents at each equilibrium, selecting the equilibria by the PF currents which created them, rather than by the resulting geometry. The discharges were sampled backwards in time to retain preferentially the most recent data. A minimum permitted distance was defined, which reduced the sample to 5139 representative points. A reduced database of these equilibria was then created, including all geometrical information on each equilibrium, the PF coil currents and voltages and the parameters of the RZIP rigid current distribution model [4]. These parameters included the current-averaged vertical field, the current-averaged radial field derivative, the instantaneous stabilising restoring force magnitude (Fs) and destabilising quadrupole field force magnitude (Fd), resulting from a unit vertical displacement. The growth rate and the stability margin, defined by $m_s = Fs/Fd-1$ are also derived. No outliers were removed.

Operational space and disruptivity: The TCV operational space is rather highly dimensioned and only selected cuts can be shown. Figure 1 illustrates the ranges of elongation of the last closed flux surface, κ, and the triangularity of the same surface, δ. Different symbols correspond to different ranges of the plasma current. The extreme values are not
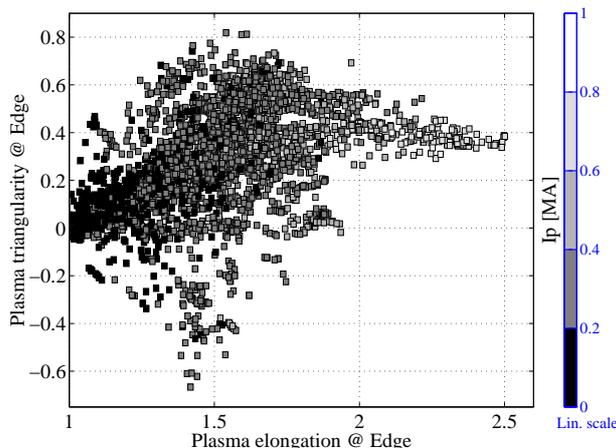
Fig 1 LCFS elongation vs triangularity.

necessarily included by the novelty filter, since they are not explicitly included. The highest elongations have been obtained only for a restricted but rather conventional range of triangularity. Highest currents are obtained for significant elongation. Figure 2 shows the variation of κ with q_{95}, the safety factor at the 95% flux surface, with the plasma current ranges indicated. Higher elongations are only obtained for rather low values of q_{95}, typically 2.5 or below.

Below an elongation of 1.8, all values of q_{95} are explored. Low elongations are normally not indicated, since the value of q_{95} cannot be estimated for almost circular plasmas. The filtering of the equilibria did not consider whether they disrupted later in the discharge or not; 65% of the discharges were non-disruptive and 95.2% of the equilibria were taken at least 30 milliseconds before a disruption, typically many tens of growth times of the vertical instability. These equilibria can therefore
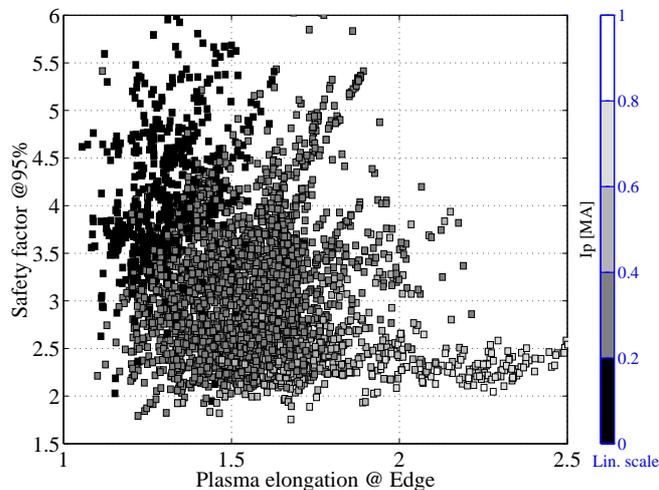

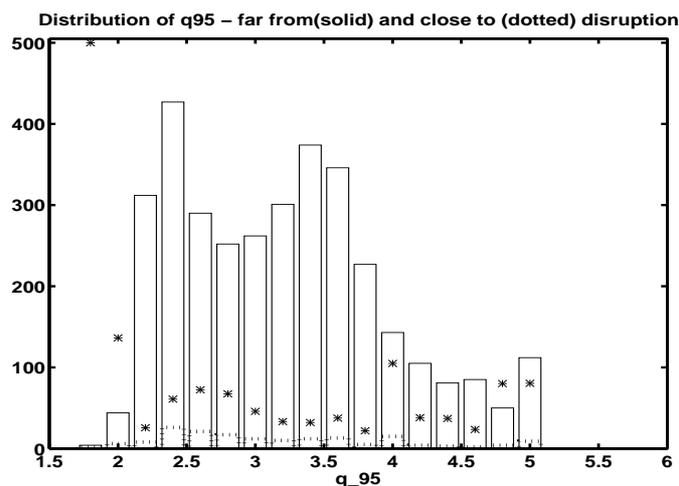Fig 2 κ vs q_{95}. The shading indicates plasma current.

be considered as normally controlled. Figure 3 presents a histogram of q_{95} for the representative equilibria, showing regular operation down to $q_{95}=2$. More samples are shown between $q_{95}=2$-3 than for 3-4, corresponding to a greater range of absolute values of plasma current. A minimum around $q_{95}=3$ is traditional, shown by the lower histogram containing the distribution of the equilibria with a disruption occurring within 30msec of the sample. This latter distribution does not show any pronounced effect close to $q_{95}=3$ and until q_{95} approaches 2.0.
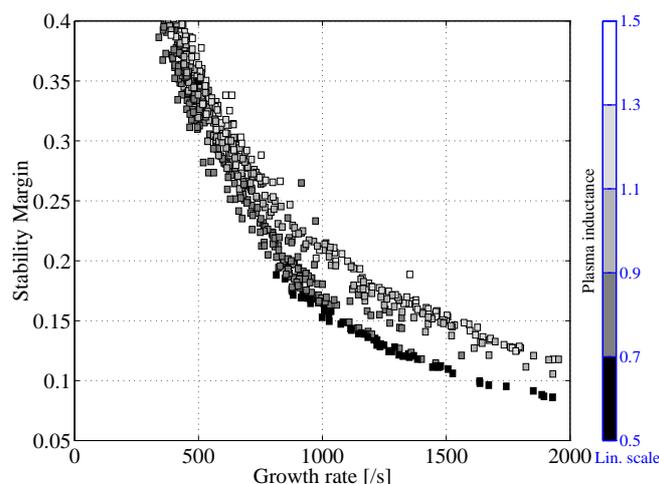

Fig 3 Histogram of q_{95}, showing regular operation down to $q_{95}=2$. The solid line shows equilibria more than 30 milliseconds from a disruption and the dashed line shows those closer to a disruption. The asterisks show the percentage of samples close to a disruption (x10).

Fig 4 Vertical instability growth rate vs stability margin.

Stability margins: Figure 4 illustrates the variation of the vertical instability growth rate with the stability margin. If the time-constant of the passive structures were fixed, then the growth rate would be a simple function of the stability margin. The thickness of the observed distribution is due to the fact that the restoring force is provided by different parts of the passive structure, depending on the position and on the distribution of the plasma current. The dominant effect is the plasma current distribution, indicated by the symbol variation of Fig. 4,

corresponding to different values of the internal inductance, li [5]. The value of the stability margin estimated by the RZIP model drops to around 0.08 at minimum, the estimated restoring force always being calculated as larger than the estimated destabilising force in the model. The fact that m_s does not reach zero can be attributed to the imprecision of the RZIP model, to the finite voltage and bandwidth of the power supplies, or to the controller, or to plasma transients such as sawteeth, provking
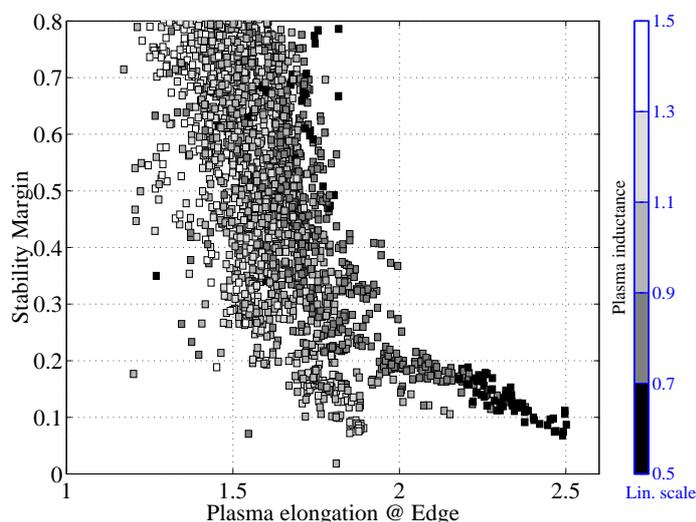

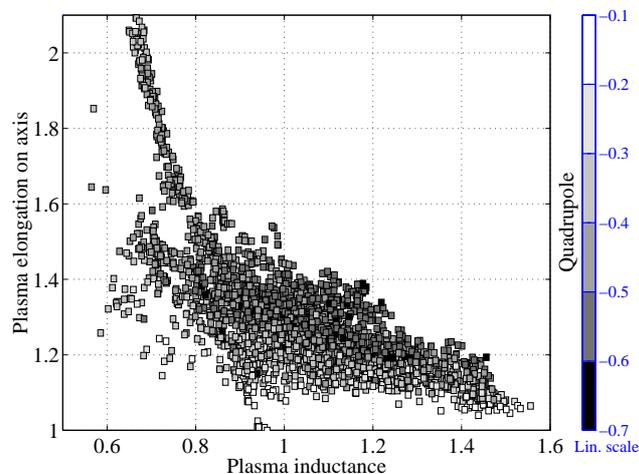*Fig 5 Stability margin vs κ against the internal inductance.*

variations in m_s. Figure 5 illustrates the variation of the same stability margin for different values of κ_{95}. The different symbols correspond to different values of internal inductance. The highest elongations require the lowest internal inductance in order to have reasonable stability margins.

Figure 6 shows the relationship between the elongation on axis, internal inductance and applied quadrupole field averaged over the current distribution and normalised by the plasma current (MA). The tendency is for a drop in inductance to

Fig 6 Elongation on axis vs internal inductance against the quadrupole field.

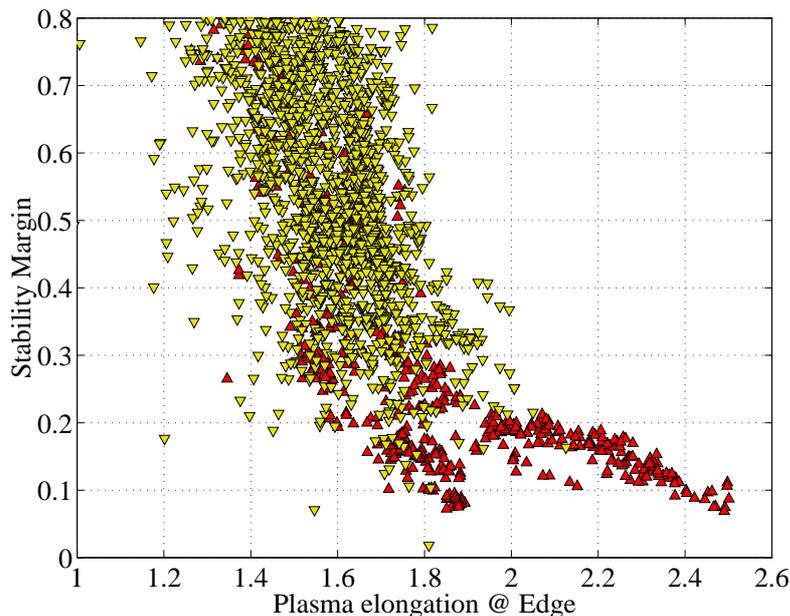lead to an increase in elongation, however the highest elongations actually have a lower

Fig 7 Stability margin vs κ against the RMS voltage on the internal coils. Down grey triangles use only external coils./

averaged quadrupole field. The edge elongation shows a less regular dependence on the two parameters. These effects are probably due to a more important role of higher structural components of the vacuum field and of the precise details of the plasma current distribution as the elongation is increased, under exploration.

The most unstable plasmas in TCV are stabilised using feedback applied to radial field coils placed inside the vacuum vessel [6], to increase the speed of response to vertical movement. Figure 7 shows the same data as Fig. 5, but marking the equilibria according to the root-mean-squared voltage applied to these coils, averaged over the 30 milliseconds preceding the sample. The equilibria with little use of the internal coils (downward triangles) fill the region of lower elongation (κ<2) and higher stability margin (m$_s$>0.2). The equilibria obtained making use of the internal coils extend the elongation and the stability margin towards 2.5 and 0.08 respectively (upward-triangles).

Conclusions: An implication for ITER is that the reduction of the stability margin for the different reduced cost designs, from above m$_S$=1.0 for the FDR design to around m$_S$=0.5 for the current designs, should not correspond to any significant increase in the difficulty of controlling these plasmas, such stability margins being well controlled by the outside coils. There should be no increase in the probability of disruptions due to the problems of control, although disruptions at very low stability margins might become serious. The question of increasing the elongation and the growth rates does not, therefore, only depend on the value of the reduced stability margin.

References:
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