Edge current density limits in conventional and spherical tokamaks.

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The external kink has long been recognized as a critical instability to avoid for stable operation of tokamaks. At low β the kink is driven by the plasma current, at high β there can a pressure driven kink. Avoiding the current driven kink is clearly necessary to get to high β and even at high β minimizing the contribution of the current drive can provide an added margin of stability. When considering the role of the current there are several important issues; the total current, an effect more familiar as the $q = 2$ limit, the current-density near the edge, which may play a role in some class of ELMs and finally the proximity of the nearest rational surface in the vacuum, *i.e.*, $m - q_{\rm edge}$, where m is the first integer larger that $q_{\rm edge}$. On the stabilizing side, in addition to reducing the edge current density, one can invoke shear stabilization, q'. The change in shear can be achieved either through modification of the current profile or through changes in the plasma boundary shape, *eg.* increased triangularity. While many of these effects are recognized implicitly, unraveling their explicit interdependence is a daunting task. We can independently control $q_{\rm edge}$ by scaling the toroidal field, however it is very difficult to independently vary J_{edge} and the shear q' as they are strongly interdependent. The only method for doing this is to hold the current-density fixed and vary the plasma boundary shape. We have adopted all these approaches to study the external kink.

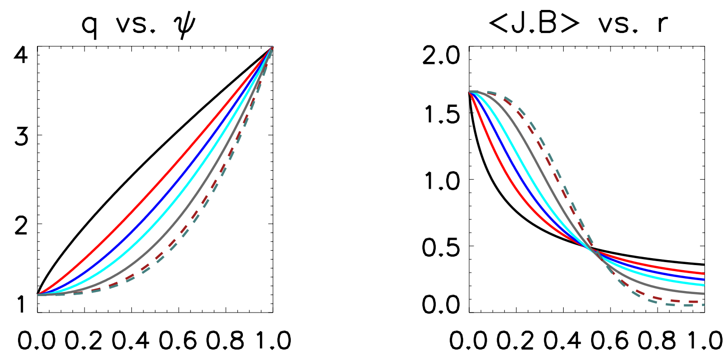

Figure 1: $q = 1.2 + 2.8\psi^{\alpha}$, *with* $0.8 \leq \alpha \leq 2.0$, *the corresponding current-profiles are shown on the right. Note that the edge current density varies inversely with* q'

To illustrate some of the main features of the current-driven kink, we examine the stability of a family of equilibria, where the q-profile is specified, $q = 1.2 + 2.8\psi^{\alpha}$, and α is varied to change J_{edge} and the shear q' , Fig. 1. The pressure is set equal to zero and the plasma has a circular cross-section with aspect-ratio, $R/a = 4$.

The growth-rate for the $n = 1$ kink as a function of $q_{\rm edge}$ is shown in Fig. 2. We note the characteristic stable gaps for $q_{\rm edge}$ slightly greater than 3, which increases as α increases. At sufficiently large values of α, (> 2), the mode is stable for all values of $q_{\rm edge}$. Increasing α has the effect of simultaneously raising q' and reducing $\rm J_{edge}$, however it is possible to change q' without changing $\rm J_{edge}$ by changing the plasma shape,

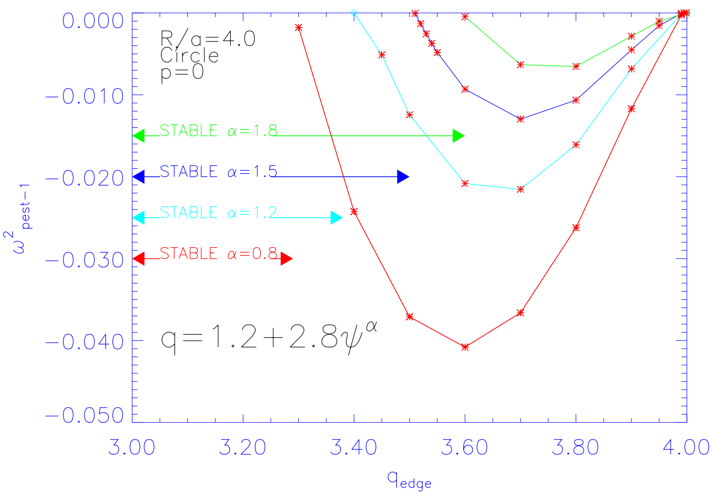

Figure 2: *The stability diagram for the* $n = 1$ *external kink shows the dependence on* $q_{\rm edge}$ *as well as the stabilizing influence of increasing shear.*

for example by increasing the triangularity. An example of such shear stabilization is shown in Fig. 3.

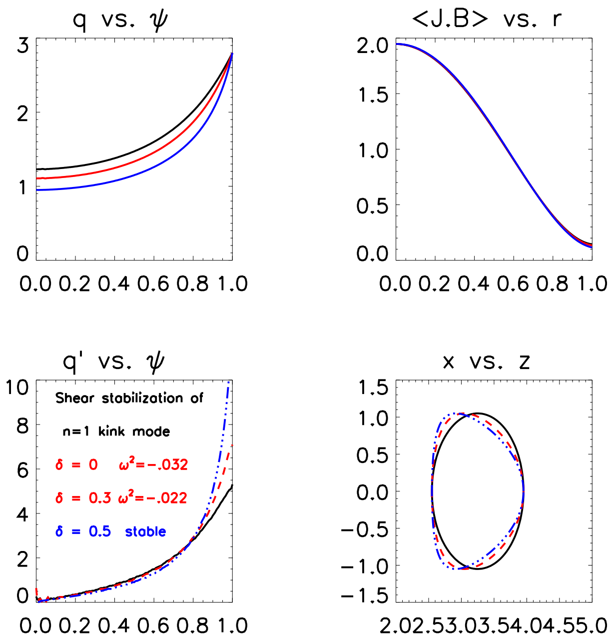

Figure 3: *Changing the shape of the plasma cross-section changes* q' *without significantly affecting* $\mathrm{J_{edge}}$ *. The increased* q' *is shown to stabilize the* $n = 1$ *external kink.*

We can integrate all these effects,*i.e.* role of $\mathrm{J_{edge}}$, q' and plasma shape by introducing a new parameter, $\mathrm{I_{90}}$, given by

$$\mathrm{I_{90}} \equiv \frac{\int_{0.90}^{1} < J \cdot B > d\Psi}{\int_{0}^{1} < J \cdot B > d\Psi}$$

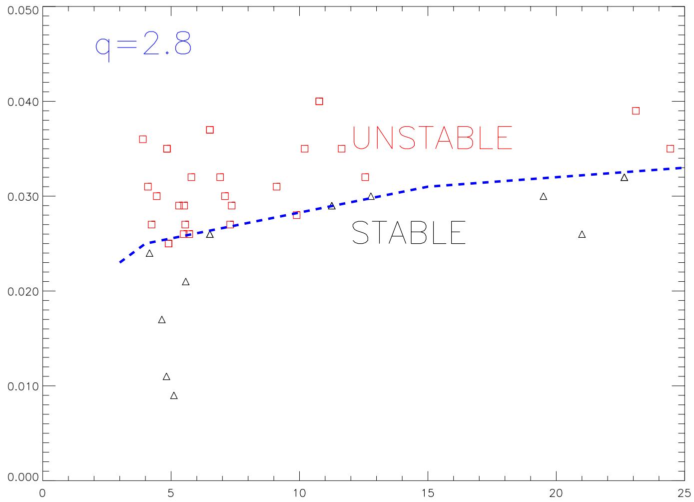

Figure 4: *The result of examining a large number of equilibria in a plane of current density* I_{90} *, ordinate, vs the shear* q' *, abscissa, with different plasma cross-section shapes and* q *and* $< J \cdot B >$*profiles. The toroidal fields are scaled to force* q_{edge} *=2.8. The broken blue curve is an approximate boundary between the stable, below, and unstable region, above.*

We note that a relatively well defined threshold emerges which is consistent over a large variation of the plasma characteristics. The threshold I_{90} has a strong dependence at low shear and a weaker one at high shear. We have repeated this exercise with different values of q_{edge} . The results are shown in Fig. 5.

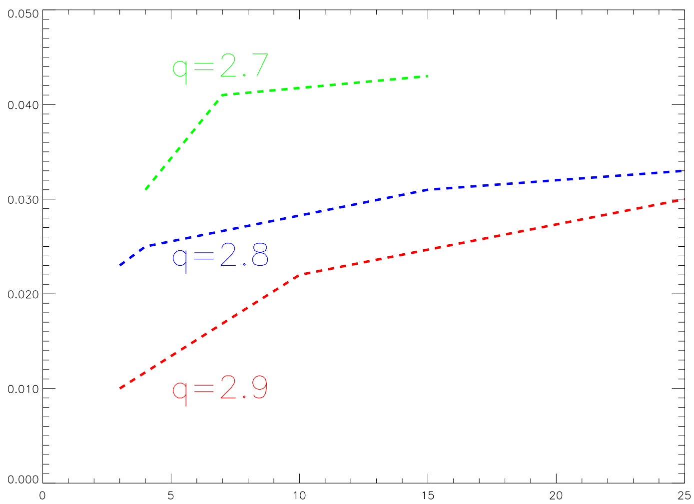

Figure 5: *The threshold edge current density,* I_{90} *, vs.* q' *for different values of* q_{edge} *. The curves represent the approximate boundaries between the stable, below, and unstable regions, above.*

We note that as (3 - q_{edge}) increases the stable region increases and the threshold I_{90} required to drive the kink increases. In this context it is important to note that the external kink is driven by the nearest 'rational surface in the vacuum'. For the $n = 1$ kink this is the first integer greater than $q_{\rm edge}$, in this case the $q = 3$ surface. These results can be transposed from the region, $2 \le q \le 3$ to other regions eg. $3 \le q \le 4$, $4 \le q \le 5$, *etc.* This does not however extend to $q < 2$.

We also note that these results apply directly to the low-β regime and finite pressure brings in other complications. However, even in the case of finite-β the model has approximate validity. In Fig. 6 we compare the stability limits for a spherical tokamak with finite pressure with the marginal stability curves. We note first that the shear in STs is significantly higher than in the conventional aspect ratio regime. As such it is ncessary to repeat the extensive study done at conventional aspect-ratio to establish the appropriate I_{90} threshold for the kink mode at low aspect-ratio. Nevertheless it is encouraging to see that there is approximate correspondence between the two curves, see Fig. 6. We also note that unlike the curves of Fig. 5 which were obtained at zero β , the curves for the ST are obtained with finite pressure. Two pressure profiles, characteristic of L-mode and H-mode were used.

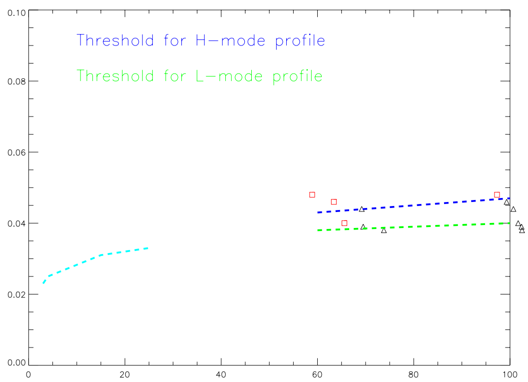

Figure 6: *The threshold edge current density,* I_{90} *, vs.* q' *for* $(m - q_{\rm edge}) = 0.2$*. The curve at low value of* q' *is from the study at aspect-ratio* ~ 4*, the data points on the right at large* q' *are for an ST with aspect-ratio* ~ 1.6*. The model for destabilizing the external kink by increasing* I_{90} *is approximately valid over this wide range in shear.*

This study has largely focused on the current driven external kink, an instability mostly seen during the start-up of an experimental discharge as the plasma current is ramped up. Experimentally in this regime the mode rarely presents a major barrier to further development of the discharge, however understanding this can help in managing the profiles at later times in the discharge when $q_{\rm axis}$ drops below unity and as the plasma β increases. Minimizing the current drive for the kink can mitigate the effects of coupling the external kink to internal, pressure driven modes such as sawteeth, infernal modes and the true pressure driven kink. This could reduce the disruptive capability of the external kink. This study suggests that reducing the current density near the plasma edge to be at or below 5% of the total current is an effective means of achieving this goal.

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