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Ballooning mode stability for self-consistent pressure and current profiles at the H–mode edge

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Abstract. The edge pressure gradient (H–mode pedestal) for computed equilibria in which the current density profile is consistent with the bootstrap current may not be limited by the first regime ballooning limit. The transition to second stability is easier for: higher elongation, intermediate triangularity, larger aspect ratio, pedestal at larger radius, narrower pedestal width, higher q_{95}, and lower collisionality.

The sensitivity of "stiff" transport models to the magnitude of the edge pressure pedestal has recently increased the interest in the limits and explanation of the maximum sustainable pressure gradient near the plasma boundary of tokamaks. Ballooning modes can limit the pressure gradient and this work explores the constraints of ballooning stability upon adding a large pressure gradient localized near the edge of the plasma. The equilibrium and infinite n ballooning stability calculations use TOQ and BALOO [1] and are facilitated by an improved numerical implementation of the ballooning mode equation using an approach of Bishop *et al.* [2]. The added edge pressure gradient produces a pressure pedestal as observed in DIII–D [3] and can also produce a significant bootstrap current that typically raises the stability limit for the pressure gradient by reducing the local shear [4,5]. The local pressure gradient near the boundary in DIII–D ELMing H–mode discharges exceeds the first regime ballooning limit by as much as a factor of two [3]. Bootstrap current may resolve this discrepancy.

In DIII–D, the pedestal pressure profile near the plasma edge is well represented by $p(\tilde\psi_{wid}) = p_0\,(1\text{-}\tanh[(\tilde\psi-\tilde\psi_p)/\tilde\psi_{wid}])/2-p_0(1\text{-}\tanh[(1-\tilde\psi_p)/\tilde\psi_{wid}])/2$ where $\tilde\psi$ is the normalized poloidal flux, $\tilde\psi_p$ and $\tilde\psi_{wid}$ characterize the location and width of the pedestal region, and $p_{edge}=p(1)=0$. The plasma current is specified using: $\langle J\cdot B\rangle = JB_0(1-\tilde\psi^{\mu})^2$ where JB_0 and μ are adjusted to determine q_{axis} and q_{95}. The $\langle J\cdot B\rangle$ from bootstrap current is added to the above. The plasma boundary, $\tilde\psi=1$, is specified by elongation κ and triangularity δ via: $R(\theta) = R_0+a\cos(\theta+\sin^{-1}\delta\sin\theta)$; $Z(\theta)=\kappa a\sin\theta$. The plasma boundary has no X–point.

Parameters to be varied are κ, δ, $A=R_0/a$, $\tilde\psi_p$, $\tilde\psi_{wid}$, and μ. As an aid in assessing stability an artificial parameter, C_{boot}, is introduced which multiplies the bootstrap current. With $C_{boot}=1$ the bootstrap current is the collisionless bootstrap current [6], with $C_{boot}=0$ there is no bootstrap current. The reference equilibrium is $\kappa=1.8$, $\delta=0.3$, $A=170/65$, $\tilde\psi_p=0.98$, $\tilde\psi_{wid}=0.0125$, $q_{95}=3.5$, and $q_{axis}=1.1$. With no bootstrap current the magnitude of the pedestal pressure profile is increased until there is a plasma flux surface marginally unstable to ballooning modes. As the bootstrap current is increased, by increasing C_{boot}, the magnitude of the pressure for marginal stability increases. That the second stable regime is accessed for large enough bootstrap current is illustrated in Fig. 1. $C_{boot}=0.8$ in Fig. 1 is seen to be more than sufficient to obtain second stability.

An abrupt transition to second stability is seen for all of the many cases examined. Accordingly, we can identify the value of C_{boot} required for second stability, bearing in mind that $C_{boot} > 1$ is physically unattainable. The effect of varying $\tilde\psi_p$, the location of the

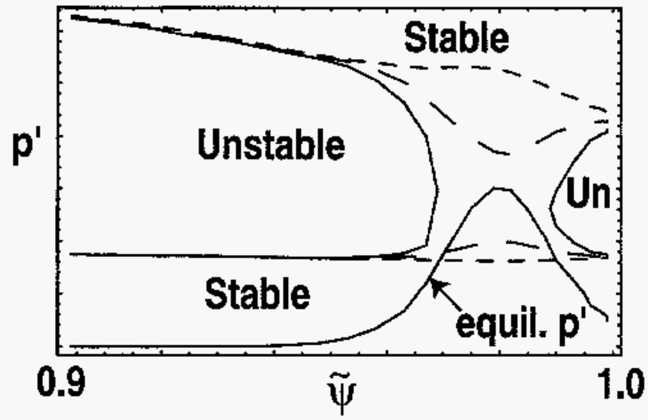

Figure 1. p' versus $\tilde{\psi}$ along with first and second stability boundaries for C_{boot} = 0.0 (short dash), 0.4 (long dash) and 0.8.

maximum pressure gradient, is that it becomes increasingly more difficult to achieve transition to second stability further from the edge of the plasma. A larger width of the pressure profile, $\tilde{\psi}_{wid}$, also makes the transition more difficult, however, the stability dependence upon width does not seem strong enough to determine the width of a pedestal region.

The elongation is at least as important a parameter as triangularity, with higher elongation leading to improved second stable access, at least up to κ=1.8. This is shown in Fig. 2 for q_{95}=3.5. Higher q_{95} improves second stable access. The aspect ratio is another important parameter, with higher A providing easier access. A scan holding the <J·B> profile fixed, instead of q_{95}, produced C_{boot} = 1.7, 1.01 and 0.59 for A = 1.5, 2.5, and 10. q_{95} increases with A in this scan so holding q_{95} fixed would produce an even stronger A dependence.

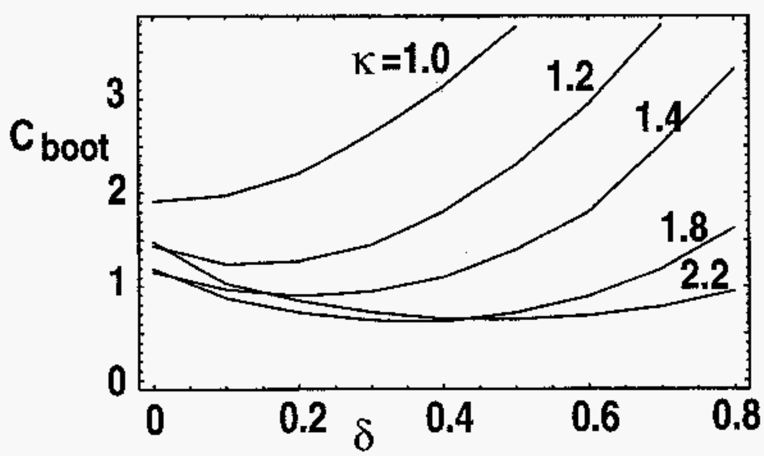

Figure 2. C_{boot} versus δ for κ = 1.0, 1.2, 1.4, 1.8, and 2.2.

The results to this point have used the collisonless bootstrap model of Hirshman [6] but collisional effects can be significant near the plasma edge. Results using the collisional model of Sauter *et al.* [8] are shown in Fig. 3. The collisional effects can be roughly approximated by $J_{boot} \rightarrow J_{boot}/\left(1+\sqrt{\nu_*}\right)$. For the reference equilibrium with $n_{edge} = 2 \times 10^{19}\ m^{-3}$ and $T_{edge} = 500$ eV, $\nu_* \sim 0.15$ suggesting about a 30% reduction in bootstrap current which is what is seen in Fig. 3. Since $\nu_* \propto n/T^2$, results for other collisionalities can easily be estimated from Fig. 3. Ranges of average values for H–mode plasmas in DIII–D are $n_{edge} = 1\text{–}6 \times 10^{19}\ m^{-3}$ and $T_{edge} = 50\text{–}300$ eV [9]. Clearly most of this range is quite collisional suggesting that higher q_{95} may be required for bootstrap access to second stability. Results (not shown) for q_{95}=4.5, $n_{edge} = 2 \times 10^{19}\ m^{-3}$, and $T_{edge} = 250$ eV at κ=1.8 indicate second stable access over a range of δ from 0.2–0.6.

In summary, the transition to second stability is easier for: higher elongation, intermediate triangularity, larger aspect ratio, pedestal at larger radius, narrower barrier width, higher q_{95}, and lower collisionality. A more complete MHD picture of self-consistent bootstrap current at the edge should include stability to low-n modes as well [10].

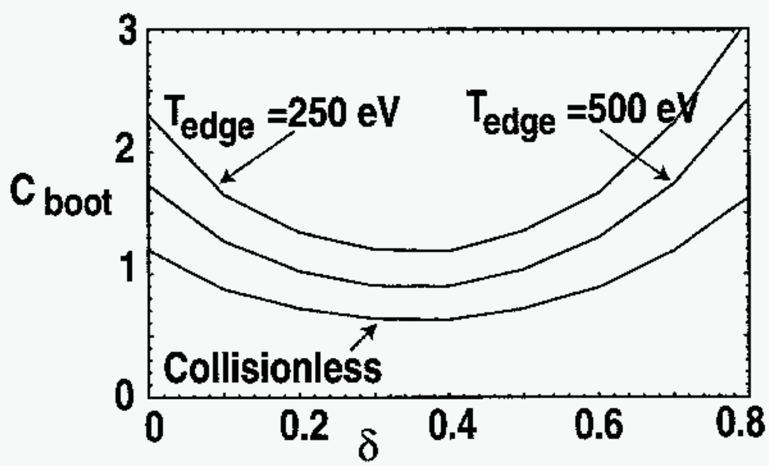

Figure 3. C_{boot} versus δ for collisionless, $n_{edge} = 2 \times 10^{19}\ m^{-3}$, $\kappa = 1.8$.

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