STABLE TOKAMAK ACCESS TO, AND OPERATION IN, THE SECOND STABILITY REGION

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Abstract

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Tokamak operation in the second region of stability to ballooning modes holds promise for economic fusion reactor operation. A second region of stability is confirmed to exist in circular tokamaks with a nearby conducting shell for $\epsilon\beta_\theta > 1$. In addition to ballooning instabilities with high toroidal mode number n, the presence of low n internal pressure driven modes in low shear regions can pose serious problems for access to the second region. These modes can be present even when ballooning modes with infinite n are stable. Stable access to the second region for all ideal modes is demonstrated with current profile programming that raises the safety factor on axis above unity. Present calculations for stable access using this technique indicate that a conducting wall must be located close to the plasma edge (~ 0.1 plasma minor radius) to stabilize external modes. Pressure and shear profile optimization could be used to increase this value. As $\epsilon\beta_\theta$ is raised above unity, the stabilizing wall can be moved to progressively larger major radii. This behavior is attributed to restabilization of the pressure driven component in low n kink modes. Finally, it is shown that poloidally discontinuous conducting structures are effective in stabilizing low n external kink modes.

1. INTRODUCTION

The economic advantage of high $\langle\beta\rangle$ fusion reactor operation has long been recognized. Here, $\langle\beta\rangle = 2\mu_o\langle p\rangle/B_o^2$, where $\langle\rangle$ denotes a volume average and B_o the nominal vacuum toroidal field at R, the major radius of the plasma center. It has traditionally been sought in Tokamak configurations by maximizing the $\langle\beta\rangle$ limit through cross-sectional shaping and minimizing the aspect ratio, A. The widely used criterion for this 'first region' limit, the Troyon limit, is $\langle\beta_T\rangle = 3\times10^{-8}\, I/aB_o$ [1]. It has been shown [2,3] that high toroidal mode number, n, ideal MHD pressure driven instabilities can restabilize at high values of $\epsilon\beta_\theta>1$, giving rise to a 'second stable region' ($\epsilon = a/R$, $\beta_\theta = 8\pi\,\bar{p}/\mu_o I^2$, a is the minor radius, I the toroidal current, $\bar{p}$ the cross-sectional pressure average - all units are SI). In general, a close conducting shell is required to simultaneously stabilize parallel-current-driven low-n kink instabilities in this second stability region.

This paper explores the potential for high $\langle\beta\rangle$ second stability region operation and access in moderate to large aspect ratio circular Tokamaks. Some of the benefits are that, within standard constraints such as wall loading, the higher power density second region reactor operates with significantly reduced toroidal field and current, when compared to first region Tokamak reactor concepts, or alternatively has the potential for advanced fuel operation. Additionally, a large aspect ratio circular configuration may have significant advantages from the important standpoint of accessibility and hence maintainability. The results described here span a parameter space ranging from that of the Compact Ignition Tokamak (CIT) [4] to a conceptual large aspect ratio second region experiment (SRX) [5].

2. SECOND REGION PARAMETER SPACE

Our parameterization of the second region boundary is not yet sufficiently comprehensive to permit the definition of an equivalent to the Troyon criterion. However, a few general remarks can be made. When the safety factor on axis, q_o ~ 1, we find a wall stabilized second stable region when $\epsilon\beta_\theta \sim 1.2$. As q_o is allowed to rise above unity at fixed q_e, the edge safety factor, the first and second region $\epsilon\beta_\theta$ boundaries shift downward in approximate proportion to q_o.

Figure 1 shows the lower bound on unstable toroidal mode numbers, n_c, using the ballooning mode formalism. It also shows the critical conducting wall location, $(b/a)_c$ (expressed in units of the minor radius) for n=1 stability. For clarity, the stability of n=2,3,4 which has been calculated, is not shown. The n=2 and 3 modes onset and begin to restabilize at successively higher $\epsilon\beta_\theta$. The first and second region $\epsilon\beta_\theta$ boundaries for the n=3 internal mode are ~0.7 and ~1.1 respectively. The n=4 mode is stable with a wall at infinity for all $\epsilon\beta_\theta$. A circular A=9 equilibrium sequence with q_o = 1.01, q_e = 4.1 and $q \propto \psi^4$ was used for these calculations. The pressure profile was initially optimized to marginal n = ∞ first region ballooning stability on all flux surfaces and then scaled to generate the $\epsilon\beta_\theta$ variation. The purpose of Figure 1 is to illustrate that conventional ballooning theory is not a sufficient criterion for internal

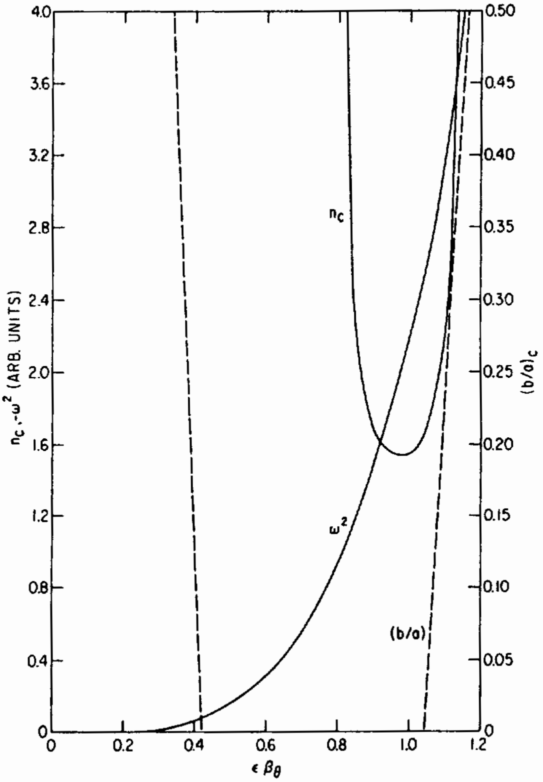

FIG. 1. Critical toroidal mode number, n_c, for ballooning stability ($n \leq n_c$); $n=1$ mode growth rate, ω^2, with a wall at infinity; and $n=1$ mode critical conformal wall location for stability, $(b/a)_c$, expressed as the displacement from the plasma edge in units of the minor radius, as functions of $\epsilon\beta_\theta$.

mode stability, since low n modes onset long before the lower ballooning threshold and restabilize after the upper ballooning threshold. This also violates the ballooning mode picture of decreasing stability with n.

Conventional ballooning mode theory relies on an ordering where the wavelength transverse to the magnetic field is short in relation to other equilibrium variations. However, when the shear is weak, the ballooning mode ordering breaks down and a new higher order theory is required [6]. At the largest values of $n \gg (\psi\ dq/d\psi)^{-2} \gg 1$, the standard theory is recovered, but when $(\psi\ dq/d\psi)^{-2} \gg n \gg 1$, the new theory, which shows an oscillatory dependence of the growth rate ω^2 on $1/n$, is required (here ψ is the poloidal magnetic flux). However, when the shear is further weakened, we observe that even this theory breaks down and there is no longer a simple behavior of the envelope of the oscillation. In particular, it is possible to have bands of instability, as $1/n$ is varied, which do not extend to high n. Consequently, high n modes can be stabilized without stabilizing the low and intermediate n internal ballooning modes, the "infernal" modes. This situation can be remedied by increasing the shear or shifting the peak gradient in the pressure to regions of larger shear. Thus, the explicit form of the shear and pressure profiles is crucial to access and operation in the second stablity region.

3. STABLE SECOND REGION ACCESS

Several mechanisms (see for example [5]) have been proposed for reaching the second region of stability. Here we will only consider current profile programming [7]. As q_o is raised, n_c rises, the first and second region boundaries move to lower values of $\varepsilon\beta_\theta$, and the width of the unstable region, $\Delta(\varepsilon\beta_\theta)$, decreases significantly. Peaking the pressure profile, flattening the safety factor profile or decreasing A will raise n_c. This dependence on A is similar to that observed when stable second region transition is obtained by indenting bean shaped plasmas. As A is increased in beans, the first and second region $\langle\beta\rangle$ boundaries decrease and the width in $\langle\beta\rangle$ of the unstable gap is reduced. However, the indentation required to access the second region in a stable manner increases.

Figure 2 demonstrates that stable second region transition with respect to all ideal MHD modes is possible, in principle, with current programming. A circular, $A_4 = 9$ equilibrium sequence with $q_o = 3.1$, $q_o \sim 4.1$ and $q \sim \psi^4$ was used. The $\varepsilon\beta_\theta$ variation was generated by scaling a pressure profile $\sim\psi^{2.5}$. Optimization of the plasma profiles in the manner suggested above could be used to reduce the high q_o value and relax the constraint on the low n mode stabilizing wall.

We have also performed accessibility studies where the form of the pressure profile is iteratively modified to remain stable to $n = \infty$ modes as $\langle\beta\rangle$ is increased. When the shear near the axis is small and $q_o > 1.0$, central surfaces in the low shear region are observed to have a stable transition to the second region. This leads to a centrally peaked two-region pressure profile, where a second region core is surrounded by a first region mantle, whose transition is inhibited by the peaked pressure. Such cases can be stable at twice the Troyon limit, for high and low n modes with $(b/a)_c \sim 0.1$. Resistive

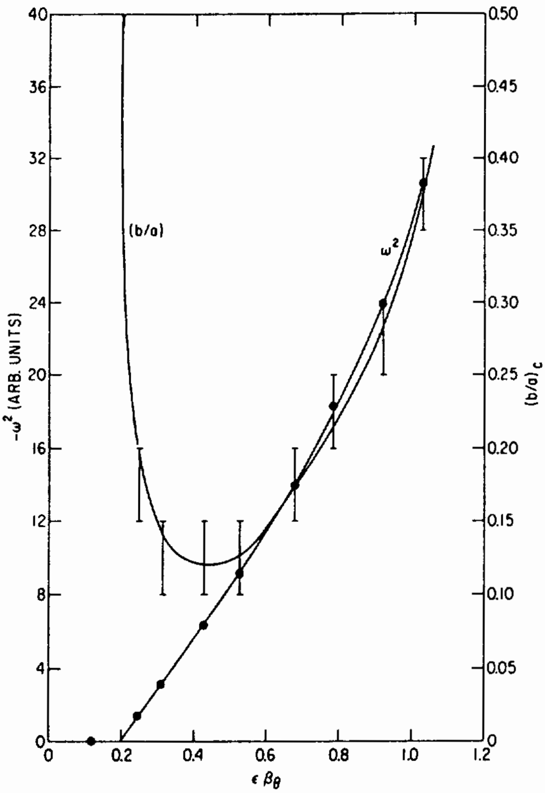

FIG. 2. n=1 mode growth rate, ω^2, and critical wall location, $(b/a)_c$, resolved to within 0.05, as functions of $\epsilon\beta_\theta$. $n=\infty$ ballooning stability exists for all $\epsilon\beta_\theta$.

interchange instability near the first/second region boundary is a potential problem, since, if a resistive interchange stability requirement is included in the optimization procedure, then the central surface transition is inhibited. Alternatively, the shear profile can be adjusted to inhibit central transition and promote edge transition. We find that edge transition is difficult to achieve at high A, and at lower A it tends to be localized to the outermost flux surfaces. The transitioning region of the plasma does not propagate inwards towards the magnetic axis as $\langle\beta\rangle$ is increased. Consequently, the edge pressure gradient grows with $\langle\beta\rangle$ and leads to the development of unphysical profiles, as, for instance, in the case of a large parallel skin current. Similar localized edge transition is observed for $q_0{\sim}1$, and either high q_e (~9) circular equilibria that correspond to Tokamak Fusion Test Reactor (TFTR) supershot like parameters [8] or conventional q_e (~3) highly triangular

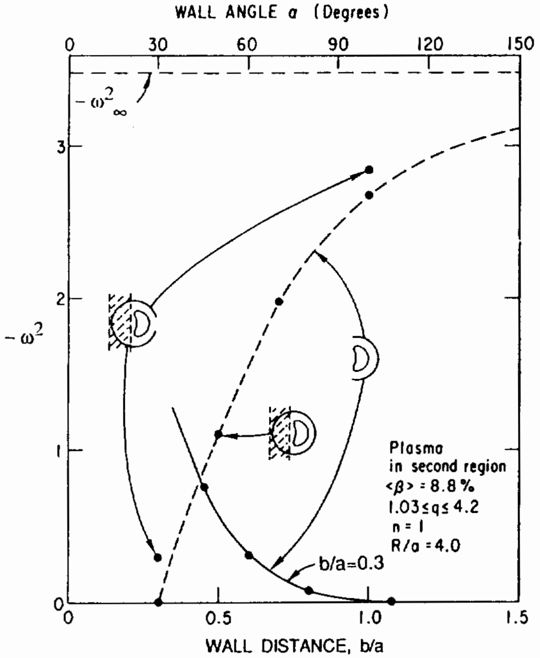

FIG. 3. n=1 mode growth rate, ω^2 (solid curve), as a function of the angle, α, subtended from the outboard midplane by a circular wall. The dotted curve shows the dependence on wall distance (b/a).

and highly elongated CIT equilibria [4]. Since the local form of the shear profile is critical for transition, other transition scenarios will exist in addition to these examples.

4. POLOIDALLY DISCONTINUOUS WALL STABILIZATION OF KINK MODES

Whereas the consequences of internal pressure driven modes can be minimized by tailoring the plasma profiles, low n global kink modes with significant surface perturbations require a conducting shell for stabilization. Since physical access to the plasma precludes a completely closed shell, we have calculated the effect of the presence of an axisymmetric gap in the shell. Typical results for the n=1 mode are shown in Figure 3 for a bean-shaped plasma of elongation 1.38 and indentation 0.3 in the second region of stability. We see that, firstly, a partial wall at (b/a) =0.3 can stabilize the n=1 mode if the angle α sustended by the wall is ~100°. Secondly, the inner major radius side of the shell plays an insignificant role in stabilization, so the hashed portions of the wall may be removed. Finally, a moderate gap on the outer major radius midplane can be tolerated.

5. CONCLUSIONS

Equilibria which are stable to all ideal MHD modes in the second region of stability are observed with $\varepsilon\beta_\theta>1$, provided a nearby conducting shell stabilizes the low n modes. Stable access to this region is not easy, but programming the current so that $q_o>1$, coupled with other access techniques [5], shows promise. Restabilization of low n as well as high n modes is observed as $\varepsilon\beta_\theta$ is increased above unity. The potential benefits of second region fusion reactor operation encourage further study of these issues.

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