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EXPERIMENTAL RESULTS ON TOKAMAK BETA LIMITS FROM ISX-B*

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ABSTRACT. It is observed that the expression $A\langle\beta\rangle/q\psi/\kappa=18\%$ defines one of the operational boundaries for ISX-B and other tokamaks. Although this expression closely coincides with the simplest expressions for ideal MHD instability thresholds, it is not obvious that it constitutes a real tokamak beta limit. Confinement degradation is observed well within this operating boundary, and there is neither experimental evidence nor a satisfactory theoretical model connecting this phenomenon with ideal MHD activity.

1. INTRODUCTION

Since 1978, an objective of the ISX-B experimental program has been the investigation of tokamak beta limits and limiting mechanisms. Early results showed that beta was indeed limited (to $\sim 2.6\%$), not by the sudden onset of instabilities, but by a progressive deterioration in energy confinement as heating power was increased, a phenomenon we termed the "soft beta poloidal limit." In this paper we revisit the issue of beta limits to see whether any new insights can be gained with the benefit of six years' accumulated data from ISX-B and other tokamaks.

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2. OPERATING SPACE

To characterize the operating boundaries in ISX-B, we use a data base of about 700 shots, representing essentially the entire range of experimental conditions studied in ISX-B, and dating back to 1980. For this data base, poloidal magnetic measurements[1] were used as the basic diagnostic of plasma geometry, safety factor, and beta.

Figure 1 shows that the operating range of ISX-B can be conveniently depicted in the space $(A\langle\beta\rangle/\kappa, 1/q\psi)$. One boundary is the low- q limit for ISX-B which occurs at about $q\psi=2.5$, or $1/q\psi=0.4$; the other is a "beta boundary" described by the line $B \equiv A\langle\beta\rangle/q\psi/\kappa = 18\%$, where A is the large aspect ratio R_0/a , κ is elongation b/a , $q\psi$ is true q or safety factor, and $\langle\beta\rangle$ is volume-average toroidal beta. PDX data, plotted in this space (courtesy of M. G. Bell, PPPL), fall within similar boundaries; although

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they reach higher values of $1/q_\psi$ (up to ~ 0.55), the diagonal beta boundary is essentially the same, $B = 18.5\%$.

This diagram is reminiscent of the familiar "Hugill diagram," whose axes are $(\bar{n}_e R_0/B_T, 1/q_\psi)$, and, in fact, the two diagrams combine to describe a three-dimensional operating space for tokamaks. Two of the boundaries of this space are the low- q boundary occurring at $1/q_\psi = 0.40-0.55$, and the density limit at $\bar{n}_e R_0 q_\psi/B_T = 1-2 \times 10^{-18} \text{ m}^{-2} \text{ T}^{-1}$. Although the exact location of these boundaries varies from machine to machine and according to machine cleanliness, wall conditioning, and heating power, it is clear that under any particular set of circumstances they manifest themselves as disruptive limits. The situation relative to the third boundary, the beta "limit" $B \simeq 18\%$, on the other hand, is not so clear. The question is whether this is really a limit at all, and if so, whether it occurs as a soft limit characterized by beta saturation and deteriorating confinement, or as a hard limit imposed by disruption.

At a recent IAEA-sponsored workshop on beta limits held in Lausanne, a universal operating boundary for all tokamaks was recognized, given by $\langle \beta \rangle (\%) < (2.4-2.8) \times \mu_0 I_p / (a B_T) \cdot [2]$ This is equivalent to $A \langle \beta \rangle q_I / \kappa < 15.0-17.5\%$, which is close to the ISX-B boundary, given that the "engineering q " $q_I \simeq 0.8 q_\psi$ as a first approximation in ISX-B. We note that theoretical estimates for ideal ballooning instability thresholds, reduced to simple scaling-law forms by Rutherford[3], Bernard et al.[4], Troyon and Gruber[5], and others, are given by $A \langle \beta \rangle q / \kappa = 19-22\%$ (although with some variation in the definitions of q). Thus, while there is no clear experimental evidence of ideal instabilities limiting beta, the universal operating boundary is remarkably close to theoretical ideal beta limits. Furthermore, case-by-case ERATO stability analyses of ISX-B experimental profiles for cases at or near the boundary indicates marginal stability to both low- and high- n ideal modes.[6]

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3. CONFINEMENT AND TRANSPORT

Global confinement in clean, beam-heated ISX-B discharges is well described, both approaching and well within the operational beta boundary, by the ISX-B empirical scaling $\tau_E^* = 5 \times 10^{-3} I_p^{3/2} P_b^{-2/3} \text{ (ms, kA, MW)} \cdot [7]$ It has been found that the confinement degradation implied by this scaling is mainly attributed to an enhancement of the electron thermal diffusivity χ_e .

and that this enhancement is not caused by the distorted ($m=1; n=1$) MHD activity that dominates the observed signals. More recent experiments have tested beam-specific causes such as toroidal rotation and fast ion losses, and so far there is no indication that such effects are responsible. However, we have found that confinement can be improved by a factor up to 1.8 by the presence of light impurities, either intrinsic or deliberately injected, in what is termed the "Z mode". [8]

If the maximum attainable beta $\langle\beta\rangle_{\max}$ were only limited by the available beam power and confinement ($P_b\tau_E$), then one would expect that increasing either would increase $\langle\beta\rangle_{\max}$. Figure 2 shows that in the Z mode (ungettered or neon-injected plasmas) τ_E is increased, yet the quantity B does not exceed that obtained in clean (gettered) plasmas. This does give some credence to the idea that the beta boundary is a real limit; still one must reserve judgment because Z mode operation tends to reduce the limits on $1/q$ and density. Therefore we cannot yet determine whether $\langle\beta\rangle$ is limited in these cases by usual disruptive limits or by a beta limit.

Nevertheless, consider the hypothesis that confinement is a function of the proximity to the beta boundary, even well within it. In B_T scans in ISX-B, B_T is varied by a factor of 2, yet poloidal beta β_I , and hence τ_E^* , remain constant. Thus τ_E must not be a function of B_T , $\langle\beta\rangle$, or B; it may, however, be a function of β_I , or $\beta_I/A \sim A\langle\beta\rangle q_{\psi}^2/k$. Connor, Taylor, and Turner (CTT) have proposed a model [9] which reproduces the ISX-B scaling over some range by locally imposing an ideal-MHD limit on ∇p . However, ISX-B scaling applies in the experiment even when ∇p is well below the limit everywhere, a result which the CTT model does not predict. Thus, despite the fact that the operational beta boundary coincides with ideal MHD predictions, there is neither experimental evidence nor a satisfactory theoretical model connecting confinement scaling with ideal MHD limits.

On the other hand, resistive ballooning modes are unstable well below the ideal limit and give rise to enhanced χ_e . [10] The theoretical χ_e is consistent with experiment in many respects [11], but not all. Thus, we cannot yet conclude that resistive modes govern confinement in ISX-B, either.

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FIG. 1. ISX-B operational boundaries in $(A\langle\beta\rangle/x, 1/x)$ space. The "beta boundary" $\beta \approx A\langle\beta\rangle/x = 1.8\%$ is close to that seen in other tokamaks and to ideal MHD beta limit.

FIG. 2. Plot of the parameter $A\langle\beta\rangle/x$ vs. beta power, normalized according to ISX-B empirical scaling. In the Z mode, confinement is improved by up to 11.8 relative to ISX-B scaling, but $\beta = 1.8\%$ is not significantly exceeded.