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EXPERIMENTAL VERTICAL STABILITY STUDIES FOR ITER PERFORMANCE AND DESIGN GUIDANCE

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Experimental Vertical Stability Studies for ITER Performance and Design Guidance

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Axisymmetric stability control in ITER is expected to be challenging because the target operational scenarios can approach practical controllability limits, while the consequences of loss of control are potentially severe [1]. ITER scenarios require plasma $\kappa_x = 1.85$ and correspondingly high growth rate, particularly at high values of internal inductance that can result during startup or in ohmic, L-mode, or high-q_{95} operations. Loss of vertical control in ITER could result in local forces on blanket modules which approach their allowable limits [2]. Sufficient control performance with adequate margins is thus critical to the success of ITER. We present results of experiments and analysis of operational experience in Alcator C-Mod, ASDEX-UG, DIII-D, JET, NSTX, and TCV. These results include ITPA joint experiments coupled with ITER modeling and model validation, and suggest that improving the vertical control capability of the ITER baseline design may be important to provide robustness comparable to that of operating devices. Modeling and simulation includes use of the LLNL Caltrans code [3], the GA TokSys environment [4], and the MIT Alcasim environment [5]. The present study focuses on "machine-independent" performance metrics that describe the proximity to practical controllability limits rather than ideal stability boundaries.

The stability margin, m_s, which is approximately the ratio of the unstable growth time to the wall penetration time, $m_s \approx \tau_g/\tau_w$, can be thought of as describing the distance from the ideal stability limit (which occurs at $m_s \approx 0$) [6]. However, because of differences in conducting structures, control coil configurations, and power supply dynamics, attainable stability margins differ from device to device. For example, TCV operates above a minimum stability margin of m_s(min) ~ 0.10, DIII-D above m_s(min) ~ 0.16, and C-Mod above m_s(min) ~ 0.26. The absolute stability margin does not therefore reflect a machine-independent control requirement.

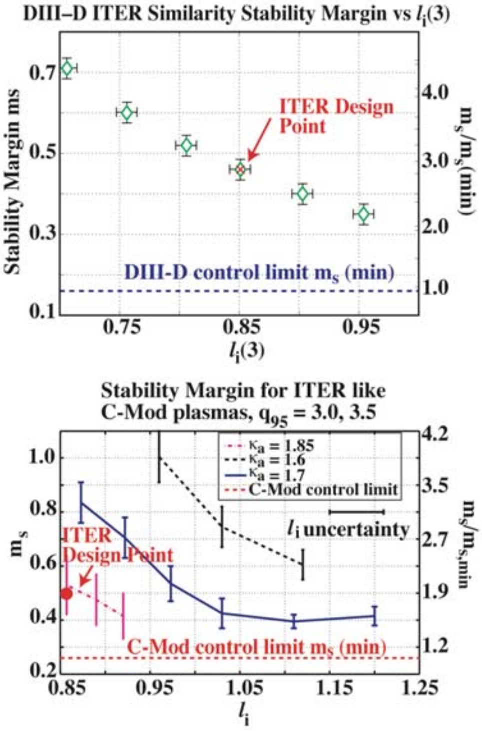

Fig. 1. Experimental stability margins for ITER similarity equilibria in DIII-D and Alcator C-Mod.

More appropriate for inter-machine comparisons is the distance from the minimum controllable stability margin described by the ratio $\tilde{m}_s \equiv m_s/m_s(\mathrm{min})$, where $m_s(\mathrm{min})$ is the practically attainable m_s for a given coil/structure configuration and power supply response. Typical robust operation in both DIII-D and Alcator C-Mod, including the ITER baseline point with $l_i(3)=0.85$, corresponds to $\tilde{m}_s \sim$ 2-3 (Fig. 1). Calculations for ITER itself indicate $m_s \sim 0.70$ and $m_s(\mathrm{min}) \sim 0.37$, corresponding to comparable $\tilde{m}_s$ and robustness level.

Another proposed key metric of control performance is the maximum controllable displacement, which most directly quantifies the nonlinear constraints imposed by power supply limits. To determine this metric, control is disabled, and the plasma is allowed to move vertically by some distance, at which time commands to the power supplies used for vertical control are maximized to oppose the motion. For sufficiently large displacements, the power supply response and voltage available will not be able to reverse the motion, and the instability will continue to grow. The maximum displacement for which this procedure can reverse the motion is defined as the maximum controllable displacement, denoted ΔZ_{max}. Various dimensionless forms of this quantity describe different machine-independent aspects of robustness, including $\Delta\tilde{Z}_a \equiv \Delta Z_{\mathrm{max}}/a$ (normalized by minor radius), or $\Delta\tilde{Z}_n \equiv \Delta Z_{\mathrm{max}}/\langle\Delta Z_{\mathrm{noise}}\rangle_{\mathrm{RMS}}$ (normalized by the RMS amplitude of the variation in measured vertical position). The former reflects general displacement robustness relative to machine geometry, while the latter specifically measures the margin relative to noise amplitude, which often sets the limit of control. In contrast to the robust control (e.g. $\tilde{m}_s \sim 2$) found in ITER for the baseline design point, a higher growth rate ITER rampup scenario equilibrium is calculated by Caltrans and TokSys to have $\Delta Z_{\mathrm{max}} \sim 4.0$ cm, corresponding to $\Delta\tilde{Z}_a \sim 2\%$. Modeling of DIII-D and Alcator C-Mod control performance shows that operation with calculated $\Delta\tilde{Z}_a \sim 2\%$ in both devices corresponds to assured loss of control, while $\Delta\tilde{Z}_a \sim 4\%$ corresponds to marginal controllability. ITPA joint experiments in several devices have measured this quantity directly by disabling vertical control for varying intervals. For example, experiments in NSTX have shown that a measured $\Delta\tilde{Z}_a \sim 10\%$ corresponds to highly robust operation. Experiments in Alcator C-Mod (Fig. 2) find the practically controllable ΔZ_{max} to be somewhat smaller than that derived from calibrated Alcasim simulations, perhaps due to power supply noise in the experiments, which perturbs the vertical position during the growth of the instability and contributes to uncertainty in determining ΔZ_{max}. Control analysis including these types of perturbations is important for quantifying the robustness of the ITER design and transferring the experience of operating devices to ITER.

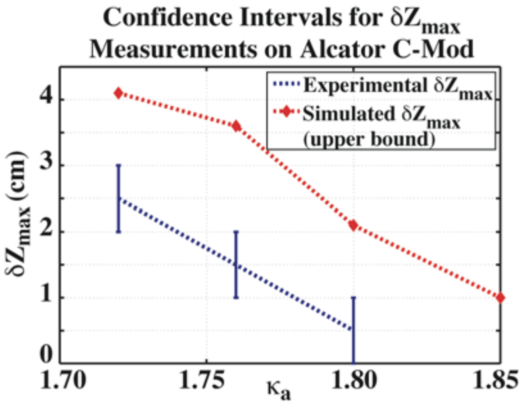

Fig. 2. Measured and Alcasim-calculated ΔZ_{max} values in Alcator C-Mod.

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