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DETAILED COMPARISON OF MHD STABILITY THEORY WITH MEASUREMENTS IN DIII–D

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Detailed Comparison of MHD Stability Theory with Measurements in DIII–D

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I. INTRODUCTION

Historically, predictions of the scaling of Magnetohydrodynamic (MHD) stability limits with key parameters, has provided guidance for improving tokamak performance, as exemplified by the Troyon scaling. With the advent of accurate equilibrium reconstructions, the predictive capability of MHD stability has entered a new phase in which the stability limits can be predicted accurately, and the growth rates and mode structures can be quantitatively tested against experimentally measured diagnostic fluctuations such as electron cyclotron emission (ECE), soft X-ray (SXR), and Mirnov signals [1]. It is now possible to test the importance of competing non-ideal effects in setting the stability limits. Several recent highlights are discussed. For global, ideal-like instabilities, linear theory can explain the dominant features of the observed growth and fluctuation signals. Detailed comparisons between predicted resistive wall modes (RWMs) with discharge behavior have resulted in the identification of a correlation between observed rotation slowdown and wall stabilization [2]. Predictions of unstable edge localized modes (ELMs) can also be compared with measured signals. For slower, resistive modes, comparisons of the predictions with diagnostic measurements have enabled identification of Resistive Interchange (RI) modes, classically destabilized tearing modes, and nonlinearly destabilized neoclassical tearing modes (NTMs).

II. IDEAL PLASMA INSTABILITIES

For predominantly ideal plasma instabilities such as global low toroidal mode number n modes, edge instabilities, and RWMs, ideal MHD theory provides a good, quantitative description of the observed stability limits for individual discharges. The key to obtaining accurate quantitative predictions is the reconstruction of the discharge equilibria using detailed, high quality measurements of the equilibrium internal profiles and plasma boundary, as well as a faithful reproduction of these details in the stability calculations. It is now possible to also test the mode characteristics – specifically growth rates and mode structures – against fluctuation measurements. Figure 1 shows the predicted poloidal distribution of the Mirnov signal for a DIII–D discharge (#87009) with peaked pressure and elevated safety factor q, compared to the measured signal from the precursor of the subsequent fast disruption in that discharge. The agreement is exceptional in this case; the calculated mode phase and amplitude are adjusted here to the toroidal Mirnov array leaving no free parameters in the comparison in Fig. 1. In addition, the growth of the mode is predicted [3] to increase as $\exp[(-t/\tau)^{3/2}]$ as the discharge passes through the ideal limit, with τ a hybrid of the heating time scale τ_H and an MHD time scale τ_{MHD}, estimated to within a factor two from stability calculations for a series of model equilibria with increasing β, as $\tau_{MHD} \sim 5$ µs. The observed growth of the SXR and Mirnov signals fits this dependence well and not a simple exponential growth at all. The best fit to the observed growth is $\tau_{MHD} \sim 9$ µs. It should be noted that this is an essentially linear prediction and the agreement is quite exceptional given the uncertainties in modeling the evolution of the discharge equilibria through the ideal limit [3].

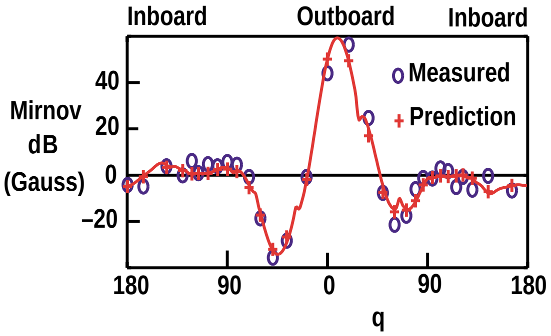

Fig. 1. Predicted and measured poloidal distribution of the Mirnov signal, for DIII–D discharge #87009.

Comparisons of ELM onset with intermediate n edge stability have similarly yielded new physics understanding. Considerable progress has been made here as well and there is good agreement between observed ELM onset and the predicted intermediate n ideal instabilities. This is discussed elsewhere [4].

Many DIII–D discharges are predicted from ideal stability calculations to exceed the ideal β limit with no wall by a substantial margin, consistent with stabilization from the resistive vacuum vessel coupled with plasma rotation [1,2]. Until recently, however, the plasma rotation was observed to begin slowing whenever the predicted no-wall β limit, $\beta^{\text{no-wall}}$ was exceeded. This correlation occurred in a wide variety of discharge types and under a variety of conditions [1]. When the rotation slowed below a critical value, an instability with the characteristics of the expected RWM appeared on the internal Mirnov probes and the saddle loops exterior to the vacuum vessel, as well as on the internal ECE diagnostic in some cases. A prediction of these signals can be obtained from ideal stability calculations assuming that the ideal mode penetrated the wall and is slowed down but is otherwise little modified. Figure 2 shows the predicted and measured radial ECE profile at two times and two phases. The phase and amplitude of the predicted signal at the later time were adjusted here to provide the best fit to the data at that time. However, the phase and amplitude difference between the two times was inferred from the Mirnov signals and this change applied to the calculated kink instability to obtain the prediction at the earlier time. This then has no free parameters and the agreement in profile and magnitude is clearly good.

In subsequent experiments, the rotation slowdown was determined to result from electromagnetic drag due to small inherent error fields amplified by the rotation-stabilized RW, and could be averted by statically reducing the error field using the DIII–D Error Field Correction (EFC) system. In a series of experiments exploiting this, discharges were maintained above $\beta^{\text{no-wall}}$ and then braked by removing the EFC. Figure 3 shows the evolution of two similar discharges in which β exceeded $\beta^{\text{no-wall}}$, but β was slowly reduced. In one case (#107611), the EFC was removed while $\beta > \beta^{\text{no-wall}}$, but in the other (#107607), when $\beta < \beta^{\text{no-wall}}$. In discharge #107611, the rotation slowed and the RWM appeared as expected. However, in the latter case, the removal of the EFC had no effect. This provided a value for the no-wall limit of $< \beta_N^{\text{no-wall}} \sim 2.0$ (here, $\beta_N = \beta/(I/aB)$ is the usual Troyon β) and the predicted and inferred limits are within the experimental error of ~ 8%.

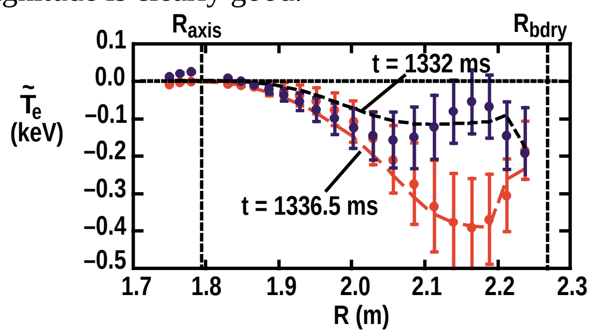

Fig. 2. Predicted and measured radial ECE profile for a RWM in discharge #96519 at two times and two phases.

III. RESISTIVE PLASMA INSTABILITIES

Given the success of ideal MHD, one can now meaningfully begin to test the importance of non ideal effects, in particular, the role of resistive instabilities. In this case, however, the stability is much more sensitive to the equilibrium details. Also, nonlinear and other nonideal effects are often crucial and the instabilities tend to be strongly localized, making accurate diagnostic measurements difficult. Nevertheless, it is possible to test the predicted instability onsets against experiments with a view to testing more detailed predictions once the basic onset mechanisms have been identified.

In recent experiments with L–mode edge conditions and peaked pressure profiles, bursts of MHD activity were observed that have the essential characteristics of the expected resistive interchange modes. These are discussed in depth elsewhere [5].

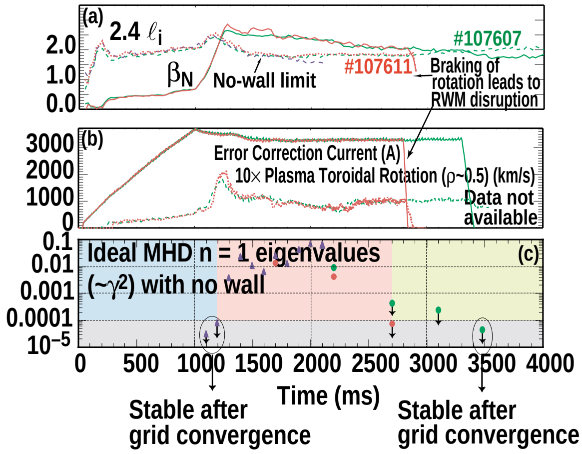

Fig. 3. (a) Evolution of two similar discharges in which β exceeded $\beta^{no\text{-}wall}$, but was slowly reduced. In one case (#107611), the EFC was removed while $\beta > \beta^{no\text{-}wall}$, but in the other (#107607), when $\beta < \beta^{no\text{-}wall}$. (b) In discharge #107611, the rotation slowed and the RWM appeared. (c) Calculations show positive growth rates with no wall when $\beta > \beta^{no\text{-}wall}$ but when $\beta < \beta^{no\text{-}wall}$, γ^2 converges to zero as indicated by the vertical arrow.

Tearing modes (TMs) occur in a wide variety of discharges with a variety of characteristics. Linear stability analyses, using the reconstructed discharge equilibria, have resolved these into three major categories. At low β, the classical TM can be destabilized by a current gradient at rational surfaces. In DIII–D experiments specifically designed to test the applicability of the linear theory, the observed onset of m/n = 2/1 TMs was found to coincide with Δ′ becoming positive at the q = 2 surface [6]. Thus, the linear theory is valid in this case when β is sufficiently low that nonlinear neoclassical and finite β threshold effects are expected to be negligible.

At high β, the picture is somewhat more complicated since it is well known that TMs can be excited by sawteeth and other MHD activity – these are usually identified as neoclassical TMs (NTMs) destabilized by nonlinear bootstrap current effects from seed islands induced by the MHD activity. However, in many cases, the TM appears with no seed. Recent detailed comparisons with Δ′ calculations have begun to resolve this and a new, more comprehensive model of TM stability with testable quantitative predictions is beginning to emerge. Figure 4(a) shows a discharge in which several successive sawtooth crashes each induced a 3/2 TM that subsequently decayed, until the final one where the 3/2 mode is unstable. Linear stability calculations for the equilibria immediately after each crash show that, for the early crashes, Δ′ < 0, indicating linear stability, but Δ′ is increasing steadily [Fig. 4(b)] and becomes positive just before the final sawtooth seeds the unstable 3/2 TM. This appears to be due to increasing pressure peaking during this time. The decay of the 3/2 island prior to this is consistent with the Modified Rutherford Equation dW/dt = Δ′ + N(W), where N(W) represents the Neo-classical and the finite β stabilization terms, if one assumes N(W) to be small. Figure 4(b) shows the dW/dt measured from the decay rate of each 3/2 mode and Δ′. The Rutherford Equation appears to describe this well with Δ′ calculated from the reconstructed equilibria at each time.

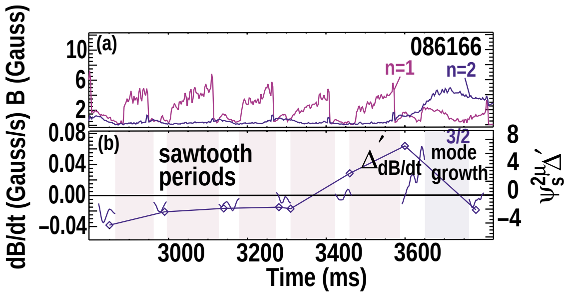

Fig. 4. (a) Sawtooth crashes in discharge #86166 and the induced 3/2 TMs, and (b) dW/dt measured from the decay rate of each 3/2 mode and the calculated Δ′.

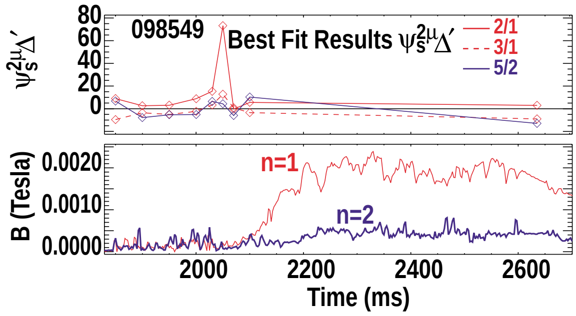

Fig. 5. (a) Calculated Δ' for discharge #98549 and (b) Observed tearing mode activity from Mirnov loop signals.

In several high β discharges, a TM island appears with no obvious seed, although its subsequent growth is consistent with the nonlinear NTM theory. Figure 5 shows one such case (discharge #98549). Here, calculations indicate that Δ' for the unseeded 2/1 TM at 2100 ms rapidly becomes very large and positive. Sensitivity analysis also suggests that this is due to the approach of Δ' to a pole and that this discharge is nearing an ideal stability limit at this time; at the ideal limit, one expects $D' \rightarrow \infty$. Thus, the interpretation is that, for this case, the TM is actually classically (linearly) destabilized by Δ' becoming large enough to overcome any stabilization thresholds, such as the finite β Glasser threshold or the polarization threshold. This suggests a new working model [7], where $\Delta' = \Delta'(t)$, approaches a pole at the ideal limit. The model makes several specific predictions and a series of experiments was carried out recently in DIII–D, designed specifically to test these. Analysis is still ongoing but the preliminary results are encouraging, with qualitative agreement between the predicted and observed trends.

IV. CONCLUSION

In summary, the quantitative comparisons of MHD stability predictions with detailed experimental data of the kind described here are yielding new understanding of the physics of tokamak plasmas and is opening up new questions and new avenues for research. With good equilibrium data, ideal predictions are generally in good quantitative agreement, yielding stability limits to within a few percent and mode characteristics to within experimental uncertainties. However, new questions have led to synergistic developments in both the theory and the experiments, for example, the surprising applicability of the essentially linear model for instabilities driven through an ideal limit, and new avenues of research on the interaction of rotation, the RWM and error fields. We are also beginning to isolate and understand the importance of resistive effects, which is leading to a more comprehensive understanding of the characteristics of resistive instabilities. This work is ongoing as new comparisons simultaneously yield better understanding and more questions to be resolved.

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