Looking Forward in Disruption Avoidance via Stability Analyses and Control

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Introduction

Since the earliest experiments in toroidal magnetic confinement in the 1950s, the plasma has been observed to develop violent instabilities which rotate and eventually disrupt as the confined energy is increased. Understanding these instabilities has been a major effort within the fusion energy program ever since. In modern tokamaks plasma cross section shaping, profile control, and real time feedback on perturbations are used to improve stability. Examples of quantitative prediction of experimental stability limits are becoming more common, though many puzzles remain, in several respects the prospect of controlling a stable burning plasma in ITER look to be promising. This paper reviews significant recent advances, gaps and challenges in theoretical and computational modeling, and the urgency and readiness of the US community to conduct a quantitative validated prediction of stability in current experiments. This effort could be used to avoid the resistive wall mode and the tearing mode, and thus substantially reduce the experimental disruption rate.

The primary objective a magnetic confinement fusion reactor is to maintain a quiescent steady state burn for long times, by remaining within the stable regions of operational parameter space. Disruptions will be highly intolerable and must be predicted and avoided. Despite the progress noted above, achieving this objective depends on quantitative predictions of plasma stability limits which do not yet exist to the level of confidence required. The primary theoretical tool for understanding these limits is linear extended magnetohydrodynamic theory, including kinetic effects of energetic particle distributions, rotation and a resistive wall. Accurate calculations with all of these effects are only now beginning to be studied. The current state of our understanding is advancing, but not yet sufficient, to predict the macroscopic stability of present day experimental tokamak operations fully and quantitatively. Thus, the development of validated, predictive theory and computation of stability, nonlinear behavior and control must rapidly advance now to prepare for future burning plasma experiments.

An emerging view on the RP-RWM

The most deleterious routinely encountered global instabilities that lead to disruptions are the resistive wall mode (RWM)[1] and the neoclassical tearing mode[2]. The RWM is a toroidal external kink mode [3] that is driven unstable as the plasma current and pressure are increased, which would be stable if surrounded by a perfectly conducting (ideal) wall. Finite resistivity of the wall will allow magnetic flux to penetrate the wall on its resistive time scale, allowing the RWM to grow. It is typically considered valid to model the RWM with an ideal plasma model, ie without resistivity in the plasma. RWMs rotate slowly in the laboratory frame, as the induced current in the wall will evolve on the wall flux penetration time. For slow growing RWMs with diamagnetic rotation, resistive layer physics can become important to the mode behavior. On the other hand, the tearing mode is an instability that forms due to finite resistivity in the plasma, allowing magnetic flux to penetrate resonant magnetic surfaces in a similar sense to that penetrating the wall for the RWM. Tearing modes generally propagate with the plasma and are therefore typically rotating at a higher frequency than the RWM in experimental observation, unless or until they begin to lock to the wall. The two modes are therefore often considered independent in stability analyses of experiment, and mode propagation is the simplest basis for experimental identification between the two modes, which are otherwise highly related in structure, growth, and root causes. Indeed, at low error field and rotation, repeated experiments have observed the emergence of either a RWM or a tearing mode [4], with no clear indication of what mechanism chooses between them.

In recent years it has become evident through theoretical and computational investigations that resonant surfaces in the resistive plasma can be an important factor for the RWM, altering its character significantly at low rotation and marginal stability. Resistivity at these tearing layers can be important as pressure is increased; specifically, as β is increased, the first stability boundary to be crossed will be that of the *resistive plasma - resistive wall mode, or RP-RWM [5]*. As we move toward more accurate predictions of experimental outcomes, it is crucial that we address this first stability boundary and how it is affected by other physical mechanisms, especially rotation. In effect the resistive MHD instabilities within the plasma cannot be formally separated from the resistive wall mode for the lowest global stability boundary, and we need a comprehensive treatment of the resistive plasma - resistive wall mode.

Stability maps and feedback control

Real time feedback control of plasmas uses a wide array of actuators, including various axisymmetric coils, a spectrum of magnetic feedback coils, current drive by neutral beam injection, and localized current drive by launching electromagnetic waves, in addition to other mechanisms. Calculations of a stable zone of operation using some of these schemes have been compared with experiment [5-7]. But a broader effort to validate integrated simulations against experiment, including the RP-RWM, which can lead to new insight into experimental operation, has yet to be realized.

The most useful characterization of a prediction of stable experimental operation is in terms of maps of stability in multiple operational parameter spaces. Target scenarios can then be mapped onto these spaces as trajectories. In this scenario the stability maps of a wide range of target configurations would be stored, in a multidimensional parameter space. This method would offer fast assessment of the proximity to a stability boundary, and instabilities could be effectively avoided. This could also be combined with realtime plasma response signals.

Calculating stability in real time is not a realistic near term goal, especially with energetic particles. The linear ideal MHD stability analysis could be done in real time, but fitting and solving the accurate equilibria needed to assess the stability require far too much effort and computation to be considered for real time application at this time. Also, having the calculated dependency on multiple parameters for a target configuration allows for a careful assessment of the physics driving the instability.

What are the gaps

- We do not fully understand many puzzling experimental measurements. Though our theoretical understanding has made tremendous progress, an integrated analysis in accurate configurations has yet to be developed to address them.
- Our understanding of extended MHD physics effects in the plasma is not fully developed. For example, the self-consistent kinetic effects of energetic particles on mode stability, Neoclassical Toroidal Viscosity, and equilibrium flow.

What are the needs

- We must conduct quantitative validation studies of extended MHD codes against experiments using calculated stability maps for target scenarios. These same maps could then be used in a control scheme for avoidance.
- Quantitative predictions of the lowest stability thresholds in ITER target scenarios.
- The validity of all computational stability analyses are dependent on the accuracy of the equilibrium calculation. More efficiency, higher accuracy, and a standardized approach will enable large scale experimental implementation and large data set mapping.

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