A Critical Role for Theory, Computational Models, and Simulations in Transients (and Maybe All) Fusion Research

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Applied computational modeling and simulation are essential to all areas of fusion energy development, and in particular to the development of effective control solutions, and the study and management of transients. However, it is particularly important to target specific kinds of modeling, simulation, and theoretical understanding in these areas which may be significantly different from the targets typically pursued by the theory community. In particular, the areas of transients physics and control science require with highest priority the development of models and other understanding that are sufficiently accurate and rapidly executable on typical analysis computers, but do not necessarily contain complete physics. Driven by the specific needs of scenario development, model-based control analysis and design, as well as design of devices themselves, such “control-level” models are critically needed to ensure the success of ITER, design Fusion Nuclear Science Facility (FNSF), and prepare for Demonstration Power Plant (DEMO).

There are many historical examples of such models driving remarkable advances in tokamak experiments and research programs. The Grad-Shafranov equation, a relatively simple description of toroidal plasma equilibrium derived many decades ago, has been used explicitly and successfully to guide plasma target design and sophisticated boundary control since at least the 1980s. Although much more complex physics effects than ideal MHD contribute to tokamak equilibria in experimental operation (e.g. plasma fluid flow, fast particle kinetic effects), fundamental MHD force balance has been sufficient to enable control algorithms to be designed and applied effectively. Similarly, the axisymmetric “vertical” instability was analyzed in relatively fundamental terms in the 1970s, leading to a range of MHD-based and related models, both analytic and computational in the 1980s. Not surprisingly, since that time we have learned that such instabilities are far more complex than the original modeling took into account, for example, the effects of finite plasma resistivity and realistic structure geometry. The initial ideal MHD models were found to be wrong in their prediction of vertical growth rates, since the induced surface currents predicted are typically dissipated on the relevant time scales because of significant edge resistivity. Thus, the simple models of the 1980’s that conserved plasma current rather than plasma flux proved to be much better representations of the relevant plasma physics. The fundamental lesson from these and many other similar cases is that enormous progress can be made from relatively simple, sufficiently accurate models of the relevant effects.

A key corollary of these historical observations is that in many cases a focus on producing such high-impact accurate-enough models can lead to much greater and more rapid progress than an unbalanced focus on high accuracy models and understanding. Had tokamak research waited for more detailed understanding of all these phenomena before attempting real-time control of highly shaped plasma boundaries, we would not be operating such plasmas, and would not have gained the experimental information needed to enable that understanding. Conversely, research in the fields of scenarios and control, among others, can be extremely powerful in helping guide the highest priority needs for this class of model, and thereby accelerate and amplify the impact of theory, modeling, and simulation to achieve a viable path to fusion energy. Many fields of research are capable of producing guidance on target types of models needed, as well as target levels of accuracy needed. Since accuracy requirements for effective achievement of a given plasma state or stabilization of a given instability are often far less than 75%, this process can serve to identify and accelerate key milestones in research that might otherwise fail to converge before achieving 99.99% or some other arbitrary level of validated accuracy.

Since the 2009 ReNeW workshop assessment, many such needed models have been identified and clarified through this strategic planning process, working backward from the end functional needs of scenarios and control. Examples of the highest priority types of models and simulation tools identified in this way as high-leverage for establishing the viability of the tokamak path to fusion energy include:

- models for (real-time) assessment of approximate proximity to stability and controllability boundaries for key instabilities (particularly tearing modes);
- descriptions of relevant dynamics for key instabilities (tearing modes, resistive wall modes, Alfven eigenmodes);
- faster-than-real-time-simulation of plasma profile evolution; and
- models for key disruption phenomena, including post-thermal quench plasma conditions, injected impurity assimilation, and runaway electron dynamics (generation, damping and deconfinement, stability)

A further implication of the need for such models is that the role of experimental validation is extremely critical, but quite different from what is often understood as the goal of “validation and verification.” In particular, the proposed research program should produce models well-designed for experimental validation (e.g. be configured with input-output relationships directly mappable to devices), should be tightly coupled to experimental programs (e.g. be produced in close collaboration and iteration with experimental and control teams), and should include explicit programmatic support for producing the necessary quantified validation. The goal of “quantified validation” is to quantify the accuracy of a model for a given parameter space and type of application, along with a certain level of confidence in that accuracy assessment.

Specific theory, modeling, and simulation efforts focused on providing sufficiently-accurate control-level models are critically needed in the era of burning plasmas (ITER) and engineering test reactors (e.g. FNSF, CF-ETR). Development of these models in close collaboration with experimental and control design efforts will greatly accelerate the progress of fusion energy development in the coming years.