Validating extended MHD models for fusion plasmas

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Motivation: That predictive capability is a major gap in fusion plasma research [1] is nowhere more apparent than in the case of disruptions in burning plasma systems.

Approach: The goal of predictive capability puts the focus on validated modeling at the center of a systematic, coordinated program of experiment and theory.

Impact: Disruptions could prevent regular operation of a burning plasma experiment or even cause catastrophic damage to the device.

Recommendations

- We need a range of experiments across toroidal configuration space in order to validate physics models, including extended MHD, that pertain to the prediction, avoidance, mitigation, and consequences of disruptions in burning plasma systems.
- The committee should note the demanding requirements of formally validating even a relatively self-contained nonlinear model of high-temperature plasmas, let alone the globally integrated modeling needed to fully simulate disruption physics for a burning plasma.
- Validation is only a part of what is needed to address disruptions, along with a broad range of study including exploratory experimentation, interpretive simulations, and analytic theory.

Validation background

Learning how to control disruptions in burning plasma scenarios during the ITER construction phase will require validated numerical modeling [2]. Validation as a formal methodology [3] is being adopted by plasma and fusion researchers [4,5] and is widely considered prerequisite to gaining rigorous predictive capability for fusion plasmas [6,7]. A robust validation program entails a spectrum of validation metrics across hierarchies of physical scales and mathematical complexity, implying a broad array of advanced diagnostics in individual experiments, as well as an array of experiments broadly covering the multidimensional domain of plasma operating regimes to which the model in question is applicable. Ideally, all adjustable model coefficients should be directly measured in experiment as input to the simulation code to be validated, but since this tends to be infeasible for an experimental plasma governed by multiple types of mutually interacting nonlinear effects, key code inputs must often be estimated or derived from preliminary code tuning, increasing the uncertainties appearing in final validation metrics. To our knowledge, the most well-established method of uncertainty quantification for the code outputs of nonlinear simulations is to perform sensitivity studies with respect to a sampling of the inputs, involving several runs for the varied parameters [8]. However, given the computational power expected to be available within the near term, even a single nonlinear run is very expensive for parameter ranges approaching those of burning plasmas, prohibitively so for closely matching parameters. For all these reasons, attaining true predictive capability from a formal validation program will only be possible with a sustained, large-scale effort at significant cost.

MHD simulations of disruption physics

Three-dimensional resistive MHD models provide a useful framework for simulating various aspects of disruptions [9,10], such as divertor heat flux [11], onset dynamics [12], MGI mitigation [13,14,15], VDEs [16], wall forces [17], and runaway electrons [18,19]. Such work tends to focus on combinations of single-fluid resistive MHD with one or a few of the many extended-MHD or non-MHD effects understood to be related to disruptive behavior, such as finite thermal pressure, low collisionality, neoclassical geometry, wall interactions, majority and minority density evolution, radiation, turbulent transport, and electron energization. This underscores the importance of validating MHD and its extensions as a conceptual foundation in order to address disruptions.

MHD validation activities using the reversed-field pinch

Since prediction in the context of burning plasmas involves extrapolation beyond presently available operating regimes, validation is best done using data from experiments spanning a broad range of model parameters and geometric configurations. The standard reversed-field pinch (RFP) [20] exhibits a sawtooth cycle [21] providing a near relative of a disrupting tokamak and so presents an opportunity to expand the array of devices used in validating MHD beyond tokamaks alone. Both cases involve a sequence of tearing modes nonlinearly coupling core and edge regions of the plasma, as exemplified in Fig. 1 for the RFP case.

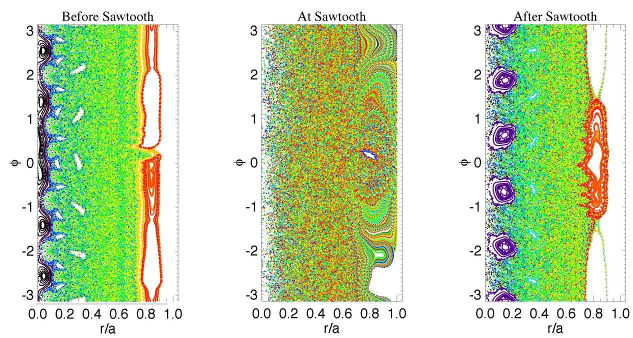

Figure 1: Magnetic field puncture plots for a standard RFP before, at, and after the time of peak fluctuation amplitudes for a sawtooth magnetic reconnection event. Experimental surface measurements of fluctuation amplitudes are combined with radial structures simulated using the DEBS code. Compare to [12,13,14,18].

Increasing our confidence in extended MHD involves more than just validating a particular model: understanding which models should be validated requires exploratory experiments and interpretive simulations coupled with analytic theory. For example, using the DEBS code [22], zero-beta, single-fluid simulations of MST [23] plasmas at the experimental Lundquist number reproduce dynamically evolving magnetic equilibrium quantities and the qualitative behavior of magnetic fluctuations, but the simulated tearing-mode fluctuation amplitudes are much larger than in the experiment [24]. The additional Hall effect and warm-ion gyroviscosity used in two-fluid NIMROD [25] simulations may be needed to resolve such discrepancies [26]. Comparisons of NIMROD simulations to MST magnetic and flow profile behavior expose complicated interactions between nonlinear fluctuation-induced quantities in the momentum equation and generalized Ohm's law [27], which are further elucidated by new experiments using deeply inserted probes [28].

The MST group is embarking on an MHD validation project as a first step in formal validation activities. We have begun to develop and apply MHD validation metrics for comparisons of DEBS and NIMROD simulations to standard RFP experiments [29]. An overall goal of this effort is to use an experimentally determined Lundquist-number scaling of magnetic fluctuation amplitudes [30], enabled by MST's advanced diagnostic set and integrated data analysis [31,32], as a test case for assessing and developing comprehensive validation techniques. Also, since MST can be run as a tokamak, there may be an opportunity to study tokamak disruptions directly.

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