Crossing the Threshold to Prediction-Driven Research and Device Design

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Primary Area: Integrated Simulations: Whole Device Modeling, Boundary, Disruptions

Abstract

We recommend a new Validated, Highly Integrated Models and Simulations (VHIMS) initiative to dramatically enhance the impact and effectiveness of theory and simulation, maintain US leadership in this important area, enable scientific discovery, and ultimately provide an essential tool for the realization of cost-effective fusion energy. The initiative addresses all four of the highest priority ReNeW thrusts from the 2012 priorities panel, and builds upon and leverages existing efforts in several areas of theory, simulation, and diagnostics/validation.

Background

Theory and simulation, validated via extensive comparison to observation, is a critical tool not only for fundamental scientific understanding, but also for the prediction and optimization of advanced fusion systems. The present generation of flexible, well-diagnosed experiments enables detailed validation across an enormous range of spatiotemporal scales. Comprehensive diagnostic sets, including planned improvements over the next decade, allow sufficient determination of equilibrium and fluctuating quantities to enable rigorous, quantitative tests of numerical simulations, and associated models and analytic theory. Together with substantial advancements in computing capability and development of sophisticated theoretical models, this has enabled enormous progress in understanding key isolated aspects of fusion plasma physics and predicting new phenomena prior to discovery in experiment. However, for the planning and design of next generation burning plasma experiments that require multi-billion dollar investments, a predictive understanding of tokamak behavior as a tightly integrated system of many parts is essential. Coupling multiple physics aspects to develop a fully predictive capability, across plasma regions and scales, remains a challenge. The regions of the plasma where gaps in predictive understanding are largest, such as the plasma material interface, are themselves strongly coupled systems, which require integration of many elements to fully understand.

Motivation and Urgency

The next decade offers the opportunity, and the necessity, to meet this challenge. The task is urgent, because ITER is a significant step beyond existing devices, and the long duration and value of each ITER plasma necessitates a central role for theory and simulation in planning and execution, as well as analysis, of ITER experiments. Indeed, using theory and simulation to develop solutions to key issues and optimize scenarios will allow the US to extract the full benefits of ITER. Furthermore, next generation burning plasma devices (eg FNSF and DEMO) will lack the flexibility, comprehensive diagnostics, and tolerance of off-normal events of today's experiments. The optimization of these devices, including both performance optimization and robust avoidance/mitigation of off-normal events, must largely be done prior to construction, and built into the design via validated integrated simulation and modeling.

Theory and simulation has traditionally been an area of leadership for the US fusion program, and the importance of developing validated, predictive models has been widely recognized. To address the critical needs of the program, a strong, vital program to develop highly integrated models and simulations is needed. This is clearly illustrated, for example, by examination of the highest priority research thrusts, as identified by the 2012 FESAC Priorities Panel (https://www.burningplasma.org/web/fesac2012/Report-revised-final-final.pdf). Here we list top priority thrusts and comment on the need for a VHIMS initiative to address them:

[6] Develop predictive models of fusion plasmas supported by theory and challenged by experimental measurement: Development of validated predictive models has been a primary focus of the US Theory program and SciDAC projects, and enormous progress has been made in recent years in understanding many isolated phenomena. Vigorous efforts are ongoing to address remaining questions, and these efforts must be strongly supported. One important gap that remains is the integration of understanding to incorporate multiple scales and multiple physics processes. For example, predicting core profiles from transport simulations typically requires a boundary condition given near the top of the edge pedestal. The pedestal boundary condition must be determined by modeling/simulation of the pedestal, which couples to the core via fluxes and the global Shafranov shift effect on peeling-ballooning modes in the pedestal. Recent work in the AToM project provides a demonstration of simple core-pedestal coupling (using TGLF/NEO/EPED), enabling predictions beyond what either core or pedestal modeling by itself could generate, providing a foundation for more comprehensive efforts.

[2] Control transient events in burning plasmas: Studies of the approach to, onset, and mitigation of transient events such as disruptions and Edge localized modules (ELM) is a highly coupled problem, and incorporating the role of atomic and runaway electron physics requires additional coupling of physics across multiple scales.

[9] Unfold the physics of the boundary layer plasma. & [10] Decode and advance the science and technology of plasma-surface interactions: The boundary plasma and plasma-surface interface are strongly coupled systems with an enormous range of physics on multiple scales, requiring coupling of a wide range of numerical tools to study completely. Extensive validation which focuses on testing isolated physics elements and the coupled system is needed to make progress in this challenging area. In addition, the boundary couples strongly to the pedestal via neutral and impurity sources, and the coupled pedestal-SOL problem represents an important future step for integrated modeling. Furthermore, the impact of transient events involves strong coupling to the boundary plasma and material surface, and fully assessing this impact couples together all regions of the plasma.

We recommend strong efforts to develop validated, highly integrated models and simulations (VHIMS), building upon a) strong advances in theory and simulation, b) flexible and well-diagnosed experiments, and c) next generation computing resources, to enhance and extend integrated modeling capabilities, and cross the threshold to prediction-driven experiments and device design. Key elements of this initiative include 1) integrating and applying the results of past progress in validated models of transport, Magneto-hydrodynamic (MHD), source and energetic particle physics, 2) building upon and enhancing existing integrated modeling tools by coupling to advanced simulations on next-generation high performance computers, 3) accelerating efforts to develop advanced kinetic simulations and improved fluid simulations incorporating the full complexity the boundary plasma, and 4) strong coupling of PMI simulations to advanced kinetic and fluid simulations of the boundary plasma. We suggest a focus on the investigation of three coupled systems: core+pedestal to optimize core performance consistent with a radiative boundary, transport+MHD+sources to address long-pulse, steady-state and, SOL+divertor+PMI to address plasma and materials solution for high heat flux. Experimental validation is essential at all stages, progressing rapidly from validation of single elements, to validation of strongly coupled systems of increasing complexity. The initiative should emphasize open access and strong user support, to enable a vibrant collaborative program across universities, labs, and industry in the US, and could serve as a training ground for the next generation of fusion scientists.