Crossing the Threshold to Prediction-Driven Research and Device Design

Philip Snyder and Vincent Chan, General Atomics

The validation of theory and simulation through extensive comparison to observation is a critical tool for fundamental scientific understanding and 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, associated models and analytic theory. Substantial advancements in computing capability and the development of sophisticated theoretical models 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 grand challenge. Indeed, 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.

The next decade offers the opportunity to meet this grand challenge. The task is urgent because next generation burning plasma devices (e.g., FNSF and DEMO) will lack the flexibility, comprehensive diagnostics, and tolerance of off-normal events from 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 using validated, highly integrated models and simulations (VHIMS). We propose a VHIMS initiative to build 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: (a) integrating and applying the results of past progress in validated models of transport, MHD, source and energetic particle physics, (b) building upon and enhancing existing integrated modeling tools by coupling to advanced simulations on next-generation high performance computers, and (c) strong coupling of PMI simulations to advanced kinetic and fluid simulations of the boundary plasma. The initiative will focus on the investigation of three coupled systems: (1) core+pedestal to optimize core performance consistent with a radiative boundary, (2) transport+MHD+sources to address long-pulse, steady-state, and (3) 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 will emphasize open access and strong user support, to enable a vibrant collaborative program across universities, labs, and industry in the U.S., and will serve as a training ground for the next generation of fusion scientists.

This initiative will dramatically enhance the impact and effectiveness of theory and simulation, maintain US leadership, enable scientific discovery, and ultimately provide an essential tool for the realization of cost-effective fusion energy.