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Integrated modeling: limits, challenges and path forward to ensure the success of burning plasmas.

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Super-conducting tokamaks are challenging the current understanding of advanced operation and control based on our experience with "copper" tokamaks. At the same time they provide a valuable bridge to ITER and burning plasmas by providing unique opportunities to test control algorithms for access and sustainment of advanced operating regimes and to optimized trajectories for current ramp-up and ramp-down compatible with coil limits. Simulations that integrate virtually all the relevant engineering and physics aspects of a real tokamak experiment are in fact a power tool for experimental interpretation, model validation and planning for both present and future devices. Simulations with simplified transport and accurate free-boundary solvers have guided the operational space and finalized the optimization of the poloidal field coils geometry on ITER [1,2]. However, higher fidelity physics models are needed to assess details of the plasma dynamics in realistic conditions. Independent simulations for exploration of steady-state operation on ITER over the past ten years indicate that a combination of flexible heating and current drive systems with variable radial deposition is necessary to control the current profile and sustain steady-state [3]. As opposed to static, steady-state solutions, time-dependent simulations that model the entire plasma discharge have highlighted the importance of the current ramp-up phase as a recipe for access and sustainment of steady-state, reverse shear and high safety factor [4,5,6,7]. In addition, long pulse experiments have confirmed that good edge conditions are required to dissipate power radiatively and to maintain high core confinement [8]. Simulations that model the plasma response to external actuators with high fidelity physics are important to develop more robust control algorithms. For example, modeling ITER plasmas with sawtooth and NTM control has indicated that the control schemes used in present devices might not work on ITER, because of dominating alpha stabilization and because of hardware constraints [9]. We will review the progress in integrated modeling in the USA and address critical gaps that should be addressed over the next five to ten years towards a Whole Device Model, to ensure the success of ITER and inform the design of future power plants. Notable examples of critical gaps include inclusion of fast ion sources (including alpha particles) in thermal transport, self-consistent modeling of synergy between RF and fast ions, wave losses in the SOL, low-n instability driven anomalous fast ion transport, non-axisymmetric effects on transport [8]. Differences and complementarity in the integrated modeling research program across the EU and Asia will be analyzed, with focus on how respective strengths can be leveraged to benefit advancement of integrated modeling across the three continents. This includes the role of the long pulse, superconducting tokamaks experimental program in filling critical gaps for plasma control and for access and sustainment of steady state operation.

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