Importance of Coupling of Plasma, SOL and Wall Regions for Plasma Boundary Problems

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Tokamak plasmas are complex nonlinear systems, and the evolution of these plasmas are determined by large numbers of interdependent physical effects that span vast time and spatial scales. The different regions of tokamak are described by a variety of models that require the tracking of dynamics that often span several regions. The tokamak boundary region includes the H-mode pedestal, the scrape-off-layer (SOL) and the tokamak wall. These three regions are often considered independently. However, the three regions are tightly coupled to each other as well as to the plasma core region. The particle, heat, and momentum fluxes from the plasma core contribute to the development of the H-mode pedestal. The H-mode pedestal sets the boundary conditions for the plasma core region and provides important sources to both the core and the SOL. Neutrals from SOL supply particles to the edge and core plasmas. Plasma wall recycling and sputtering are important to understand the dynamics of SOL profiles. Models that treat these regions as isolated cannot reliably produce predictive computations that describe the behavior of tokamak plasmas.

The coupling of various plasma regions has been considered in recent SciDAC projects and is investigated with several integrated modeling codes. The experience with the FACETS code proves that the coupling of high-fidelity components for the plasma core, edge, SOL, and tokamak wall is a necessary step towards the development of a truly predictive whole-device modeling (WDM) code. During the development of the FACETS code, several coupling techniques were investigated, and it was demonstrated that tight explicit coupling is important for addressing many physics problems associated with the tokamak boundary regions. Examples of these problems include H-mode pedestal buildup and recovery after an ELM crash, L-I-H mode transitions, transient events in the H-mode pedestal region, and prediction of the heat load on the divertor and first wall during ELM crashes.

Importance of coupling of core-edge regions

The nonlinear coupling between different plasma regions can significantly alter the evolution of the plasma. The coupling of several components that have been previously validated independently of one another also requires a separate validation. The coupling of plasma core and edge regions has been previously investigated using the FACETS simulation of the pedestal recovery after an ELM crash in a DIII-D discharge [1]. The two-dimensional UEDGE and one-dimensional FACETS:Core components have been coupled with a transition region that extends from the pedestal top towards the plasma core. In the initial simulation, the UEDGE component utilized the energy and particle fluxes found in the standalone interpretive UEDGE simulations. However, it is observed that the coupling of the pedestal region with the core region changes the H-mode pedestal profiles. In particular, the ion pedestal temperature has been found to be over-predicted relative to that computed in stand-alone UEDGE, indicating a greater flow of ion thermal energy into the edge region. The density buildup in the edge was under-predicted in the coupled core-edge simulation. To obtain the experimental density pedestal height and density level in the scrape-off-layer region, the neutral influx required in the coupled simulation was a factor of two greater than that obtained in stand-alone interpretive UEDGE simulation.

Transient effects in the SOL region

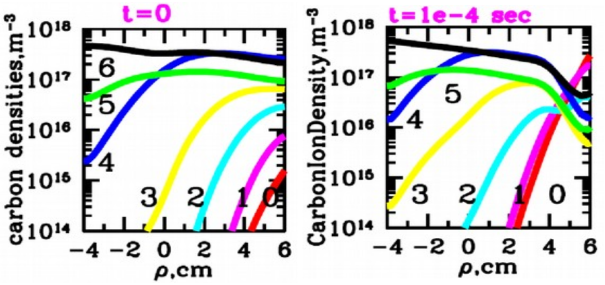

Fig. 1. Distribution of carbon charge state in the tokamak boundary region before (left panel) and after (right panel) an ELM crash.

The importance of SOL-wall coupling for the investigation of the dynamics of plasma boundary profiles after an ELM crash has been recently shown in Ref. [2]. The SOL profiles and wall recycling parameters change on a very short time scale after an ELM crash. Depending on the type of ELM, the distribution of densities and energies in the SOL region can be very different after an ELM crash. Fig. 1 shows the Carbon charge states after an ELM crash represented by so called Marco-Blobs (MB) in the UEDGE-MB model [2]. The carbon species with lower charge states move toward the pedestal region, and the species with higher charge states move toward the wall. These changes in the distribution of charge species affect the plasma-wall interactions and the H-mode pedestal recovery dynamics. The profiles of these and other species in SOL as well as fluxes from the plasma core affect the pedestal recovery dynamics.

Addressing the uncertainties in the edge models and in the experimental measurements

The physics models in boundary tokamak region have somewhat larger uncertainties than the core physics models. This is related to the complexity of the physics problems in this region and to the difficulties with the validation of these models. In order to account for the uncertainties, appropriate methods and techniques need to be incorporated in the whole-device integrated modeling codes. The uncertainty quantification (UQ) and sensitivity analysis tools such as the DAKOTA toolkit can be used for the computation of the error bars for derived quantities in the analysis of experimental data and for the validation of theory based models. In predictive simulations, the UQ tools can be used for the evaluation of probability of events, for the computation of confidence intervals of predicted quantities, and for the optimization of plasma performance.

Gaps and action items

- WDM codes need to include a selection of theory-based models of different fidelity levels for all tokamak regions. This choice of multiple components will facilitate the verification and validation of individual physics models and the verification of coupled physics components. The validity range of each physics component needs to be incorporated in the WDM codes.
- Modeling results obtained with standalone plasma boundary codes need to be verified using codes that include the contributions from all the relevant regions.
- The complexity of coupled treatment of the boundary region due to the wide range of spatial and time scales to be resolved, and the different dimensionality of the physics modules, imposes rigorous computational requirements for the coupling framework. Special attention needs to be given to the load balancing, alternative coupling schemes, uncertainty quantification, components interchangeability, regression analysis, and exception handling. Collaboration with ASCR is critical to the large-scale computing needed in WDM.
- Access to the experimental databases, standardized input/output formats and collaboration with experimentalists are essential in the validation of WDM codes and in planning experiments. Development of synthetic diagnostics as well as visualization and data analysis tools will promote collaboration with experiments.

[1] A. H. Hakim *et al.*, "Coupled Core-Edge Simulations of H-Mode Buildup Using the Fusion Application for Core-Edge Transport Simulations (FACETS) Code", *Phys. Plasmas* **19**, 032505 (2012).

[2] A.Yu. Pigarov *et al.*, "Multi-fluid transport code modeling of time-dependent recycling in ELMy H-mode", *Phys. Plasmas* **21**, 062514 (2014).