Integrated Edge-Plasma and Plasma-Wall Interaction Research

Submitted by the DOE Edge Coordinating Committee
(http://www.lehigh.edu/~inecc/)
Contacts: dstotler@pppl.gov , trognlien@llnl.gov, kritz@lehigh.edu, kruger@txcorp.com

Scope: The edge plasma is defined here as the region of a confinement device on either side of the last closed flux surface that is dominated by steep plasma parameter gradients across flux surfaces and significant variations along them. In H-mode tokamak discharges, for example, the edge region thus extends from the top of the pedestal to the bounding material surfaces. Plasma-wall interactions (PWI) include interactions of plasma particles with all material surfaces such as divertor plates, main-chamber walls, and baffles. Making fundamental progress requires not only a thorough understanding of the interactions of plasmas, neutrals, materials, and photons, but the ability to treat self-consistently all of the associated tightly coupled processes, encompassing phenomena ranging over 18 orders of magnitude in time and 10 in space.

Historical perspective: In our view, research in the edge and PWI areas has previously been modestly funded, in part, because past and present-day devices have typically operated at power levels below critical materials heat-flux limits. Substantial effort has been expended on experimental wall conditioning techniques in the interest of improving core confinement. However, the resulting empirical knowledge may have limited applicability in future devices, and it may not be possible to confidently predict core confinement in future devices even in instances when the empirical knowledge is applicable.

Importance to magnetic fusion: The success, and even viability, of higher power fusion devices will hinge on our understanding of the edge plasma physics and on our ability to control plasma wall interactions. The urgent need for progress in these areas is evidenced by the substantial number of wall related issues for ITER and the establishment of three consecutive edge/PWI focused DOE Joint Research ("Joule") Milestones; i.e., hydrogen retention (FY09), divertor heat-flux width (FY10), and pedestal structure (FY11).

Edge plasmas play an essential role in the success of fusion devices by setting the boundary condition for the core plasma. For example, predictions of the fusion gain in ITER made with existing core plasma transport models are strongly correlated with the plasma parameters at the top of the pedestal. The edge plasma is crucial in the determining the viability of future devices since it governs the distribution of plasma and particle exhaust to the surrounding material surfaces. The associated heating and erosion of wall materials can generate impurities that can migrate into the core plasma, reducing fusion gain. If the energy and particle fluxes to the wall are substantially greater than anticipated, the operational lifetime of the plasma facing surfaces will be correspondingly shortened. Just as serious are the safety concerns associated with the potential buildup of the tritium inventory in walls. In all of these instances, our present understanding is insufficient to allow us to make definitive statements about the edge plasma in future devices.

Areas of critical need: The edge region is often separated into three regions for convenience: the pedestal, the scrape-off layer (SOL), and the wall, although we maintain that all three are tightly coupled and must be considered as an integrated system. The issues associated with the wall are well represented in the ReNeW Theme III ("Taming the plasma material interface") PWI sub-panel's matrix ("PWI Gaps vs. Tools to Develop Understanding and Control", V. 2.3) and are not repeated here. Likewise, the central role of the SOL in the distribution of fluxes to the wall and of the influx of wall material is acknowledged. For the pedestal, only the issue of ELM control is addressed in the Theme III PWI chart, while the height and width of the pedestal and the L-H transition are not included. Both the SOL and pedestal are appropriate for inclusion in Theme II ("Predictable steady-state plasmas"), perhaps within the integration sub-panel; however, progress on specific physics topics should be explicitly noted. The importance of private flux region (PFR) is underestimated within the chart. Experimental data for it are rare, and models of PFR plasma behavior are largely untested. Successful integrated modeling will require a realistic characterization of plasma and neutral transport through the PFR.

A call for edge integration: While Theme II's model integration sub-panel is intended to encompass all aspects of tokamak phenomena, presumably including the wall, we believe that the edge/wall region is unique in that the processes throughout the pedestal, SOL, and wall have physical processes that are tightly coupled and frequently require kinetic treatment. The gradient scale lengths of both the pedestal and the adjacent SOL are comparable to the ion banana width. Edge Localize Modes ("ELMs") and intermittent micro-turbulence ("blobs") produce plasma fluctuations with amplitudes as large as the time-averaged values, resulting in particle and heat fluxes to surrounding materials that vary strongly in time. The materials' response is also time-dependent, and the evolved impurities and recycled neutrals can penetrate significantly across the edge region. Since these materials determine the boundary condition for the plasma, the predictive capability of an integrated model will be only as good as that of the model for the plasma facing surfaces. Rudimentary models for characterizing the evolution of the structure and composition of the wall materials are now in development and need to be nurtured and the associated research expanded.

And a call for an integrated effort: Confident predictions of the behavior of the edge plasma in future devices that permit optimization of core plasma performance and the mitigation of PWI related problems can only be based on a fundamental understanding the physical processes at play in the edge plasma. That understanding is the final result of the scientific interplay between theorists, modelers, and experimentalists; for the most sophisticated models, computer scientists and mathematicians also play key roles. As in the past, experimental measurements will identify broad trends and highlight the most critical physical processes. And, theorists and modelers will again use these results as guidance for model development. Making progress beyond the status quo, however, will require increased collaboration between modelers and experimentalists to design experiments and even devices that can quantitatively discriminate between various similar models, objectively identifying their relative successes and failures. This iterative process of model validation will not only point the way toward better models, but indicate shortcomings in diagnostics and experimental design. More detailed information will also need to be exchanged: modelers will have to develop synthetic diagnostics; experimentalists will have to be aware of the capabilities and limitations of the physical models underlying a simulation.

A research thrust: The scope of the issues involved in edge plasmas makes the identification of a single, integrated research thrust that can address the bulk of them a daunting task. Nonetheless, the quintessential needs can be succinctly stated. Namely, research on the edge plasma and PWI must move beyond empirical wall conditioning and interpretive plasma analysis to fundamental model development, validation, and, finally, to understanding. On the experimental side, this will entail adding diagnostics to existing machines and developing new diagnostics that can provide greater resolution in the various dimensions of phase space. The resources devoted to all of these diagnostics will undoubtedly have to be increased, as will the amount of time for dedicated experiments. In parallel, the existing modeling capabilities must be more fully exploited; much can be learned from them as our European colleagues are demonstrating. Projects targeted at developing first principles modeling capabilities are well underway, but their budgets should be augmented to permit the level of verification and documentation required for these codes to serve as the basis for the long term goal of a fully predictive capability. All of these efforts should be embedded in an over-arching framework that facilitates the close interaction between experimentalist and modelers described above, i.e., model validation.