Comments on Verification and Validation in Edge Research

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Importance of edge research: Much has already been written about the importance of edge research to fusion. Rather than repeat those arguments here, we refer to the white paper by the Edge Coordinating Committee (ECC) which highlights the role of edge physics in confinement (e.g. the L-H transition and role of pedestal height in determining fusion gain) and in the possibly deleterious interactions of the intermittent scrape-off-layer (SOL) with plasma-facing-components (PFCs). Here, we comment on some important components for a future edge physics initiative, including physics integration, improved treatment of sources and sinks, and the role of hierarchies of models and experiments, all of which will require extensive verification and validation. Significant gaps in the current program are identified in each area.

Physics integration: Integration of the relevant physics is the first step in any validation effort with experiment. The ECC paper comments on the need for edge integration (with core and top-of-pedestal physics and with wall physics). Integration with core physics will require, among other things, support of ongoing development projects for kinetic physics models for the edge, and their subsequent verification and validation. Another more specialized (but critical) integration topic that is not often discussed concerns the SOL plasma environment for rf heating systems. For example, as discussed in a separate white paper on rf sheath physics [1], the SOL plasma environment for rf heating systems is of critical importance in determining the coupling properties, heating efficiency and durability of rf antennas. Of interest are the SOL density near the antenna (mean profile and intermittency properties), plasma fluctuations and electric fields. At present, it is impossible to make predictions of the SOL plasma in the vicinity of the rf antennas for ITER with our present codes, and this introduces a great uncertainty in the antenna assessments. Relevant physics includes turbulent transport, nonlinear rf-plasma interactions, and plasma-wall interactions. The desired SOL modeling capability would allow quantitative estimates of antenna and PFC damage (enhanced in some cases by rf-specific effects) and the coupling properties of the plasma presented to the rf launcher. This is another example of the need for, and the expected benefit from, multi-disciplinary physics integration in edge plasma studies, which must precede validation efforts.

Sources and sinks: An appropriate description of the plasma edge will require increased attention to sources and sinks for particles, momentum, current and energy in the SOL, which implies integration with neutral and wall physics to describe processes such as ionization, charge exchange, radiation and recycling. This physics is currently described in 2D (toroidally averaged "transport") codes, but the role of such physics on edge and SOL turbulence remains largely open in terms of verification and validation (V&V). Integration of transport and turbulence codes is a difficult computational problem. A critical goal is attainment of a predictive capability for the edge/SOL plasma (e.g. profiles, fluxes, flows).

Hierarchies in experiments and models for confidence and understanding: It is well appreciated that the complexity and diversity of (likely coupled) effects important for edge turbulence motivates development of first principles, relatively complete, kinetic physics codes. Our goal is confidence-building in our predictive capabilities and fundamental understanding of the issues (so we can be clever about mitigation strategies). This goal can best be achieved by strong community support of a hierarchy of models and codes ranging from analytic and 1D fluid, through 2D and 3D fluid, to 5D kinetic. Smaller models and codes can lack important physics in some applications, but when they are relevant, they are extremely valuable for elucidating the essential physics important to a given class of phenomena. In terms of verification studies, the simpler models play an important role in establishing confidence in the more complete codes. A hierarchy of experiments (from university sized to big tokamaks) is similarly needed for V&V over a wide range of conditions. For example, 2D turbulence codes can be validated against linear 2D experiments before using them to assess edge turbulence in tokamaks.

<u>Other V&V activities</u>: The development of standardized community-accepted verification test cases for edge turbulence codes should be strongly supported. These should include *linear* test cases which verify all the major edge instabilities and *nonlinear* cases for verification of saturation mechanisms in edge turbulence. Validation against experiment will benefit from the continued development and use of simulated diagnostics (especially for 2D imaging). Both areas of V&V are at present severely manpower limited.

<u>Available tools</u>:

Some of the theory/modeling tools necessary for integration of rf and edge/SOL physics exist separately in the respective communities. These include codes to calculate rf fields and SOL turbulence. In the near future, reduced models (e.g. simplified antenna models and 2D turbulence codes) will be useful, as full integration with the most sophisticated models may not be practical yet. Experimentally, while the density near antennas is accessible from reflectometers, additional diagnostics, especially for plasma temperature, and for rf and dc electric fields in the vicinity of antennas will eventually be necessary for a quality V&V effort.

Reduced models, such as the Lodestar SOLT 2D edge turbulence code, are presently being employed to investigate processes such as ionization, sheath effects, and simulated edge diagnostics, in the context of edge turbulence and blob propagation. There are good opportunities for V&V efforts on SOL turbulence and particle/power flow studies with NSTX, C-Mod and DIII-D using existing diagnostics (e.g. 2D imaging and probes) and with CSDX on sheared flows and momentum transport.

In the area of turbulence code verification, a full diverted geometry "global" edge eigenvalue code (the Lodestar 2DX code), and a suite of associated verification tests (first with BOUT and eventually with the 5D kinetic edge codes) is presently under development.

[1] D. A. D’Ippolito and J. R. Myra, ReNew white paper on “ICRF-Edge and Surface Interactions”