ReNeW White Paper:

Prediction of PFC plasma fluxes by improved edge/scrape-off-layer simulations

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Motivation and significance: Large, localized plasma heat exhaust, subsequent inward transport of eroded impurities, and distribution of tritium to walls comprise one of the most critical class of problems for the development of tokamak fusion reactors. The magnitude and temporal duration of the heat fluxes is controlled by two factors: (1) the plasma power coming into the edge from the core, and (2), the physics processes in the edge/scrape-off-layer (SOL) that distribute the power to Plasma Facing Components (PFCs), both in space and in time. Given that the plasma power is largely determined by the fusion power desired, here I address model development needs for item (2), the distribution of power to PFCs, which naturally carries with it the capability for transport of impurities and tritium. Another key issue not addressed here is the impact of edge plasma transport on the plasma pedestal parameters.

Experimental characteristics: The nature of plasma transport in the edge/SOL region has long be differentiated from that in the bulk core, initially because of the larger fluctuation amplitudes that are observed, with density fluctuations relative to the time-average sometimes approaching as high as unity in the SOL. More recent measurements have shown addition effects such as strong intermittency, filamentation, toroidal asymmetry, and large flows [1]. These characteristics have a direct impact on plasma energy and particle fluxes to PFCs and on the flow of impurities in the edge.

Status of predictive theory/simulation models: The theory of the edge/SOL is complicated by the steep gradients, multi-dimensional nature of plasma/neutral variations, and as mentioned above, the strong relative fluctuation levels compared to the core region. Furthermore, the strong interaction of the plasma with neutrals and the associated radiative effects for partially ionized plasma are important, Consequently, theoretical models typically need to be, or should be, more complicated, which may be one reason model development has lagged that in the core (funding being another reason).

Simulation models of the edge/SOL can be divided into transport codes, which give the slow evolution of the plasma profiles and fluxes in a complex environment, and turbulence codes, which model the unstable, strongly fluctuating plasma state and thus (ideally) provide transport coefficients to the transport codes; this latter connect has only been made for a very limited set of simulations. The edge transport codes are either 2D fluid or now emerging 4D (2r,2v) kinetic. The turbulence codes are 2D and 3D fluid (only one U.S. 3D code spans the separatrix), and emerging 5D gryrokinetic codes.

Many of the transport simulations to model plasma fluxes use ad hoc radial transport coefficients, rendering them more in the class of “interpretive” simulations, not predictive; this limitation makes fundamental prediction for heat-flux widths and edge/SOL transport in general unobtainable at present. Even if there was a strong connection made between transport and turbulence codes, there is not yet a clear consensus in the community concerning the controlling instabilities and turbulence features, even for fixed plasma profiles. In comparison, the core turbulence simulations/theory/experiment have standard benchmarks (e.g., the Cyclone case), agree on many aspects of the big picture of the dominant ion transport, and have made good progress on electron transport. Again this core/edge difference can at least partially be traced to both the inherent difficulty of the edge problem and the stronger historical support for core simulation development; as the edge issue for high-power devices, the funding prior should be change.

Experimental diagnostic needs: No theory/simulation can be trusted without substantial experimental validation. The edge/SOL area is physically more accessible, but also more complex (2D – 3D variations) and also different plasma parameters than for core diagnostics. Among the valuable diagnostics for transport are IRTV, thermocouples, Langmuir probes (but with maximum incident plasma power limitations), Thomson scattering, and visible. For turbulence diagnostics, we have spectroscopy, beam-emission spectroscopy (BES), again Langmuir probes, microwave backscatter, and gas-puff imaging. This list can be extended, but the point is that while significant diagnostics exist, improvements are clearly needed; for example, the characterization of the turbulence spanning the separatrix is modest except for BES at the midplane (probes have difficulty crossing the separatrix owing to heat-flux limitations). The residual turbulence in H-mode is generally not well characterized because of its lower (but still important?) magnitude.

Strawman Edge/SOL Transport Thrust outline:

0-3 years:

- Provide standard benchmark results for 3D fluid turbulence simulations first for closed B-field edge, then edge/SOL combined, include microturbulence/ELMs (MHD codes?) identify modes, utilize existing codes
- Validate models with relevant experimental diagnostics (collisional, with C-Mod likely most relevant) – turbulence/transport characteristics, heat flux, particle flux
- Identify key diagnostic needs, begin implementation

3-6 years:

- Extend benchmarks to gyrokinetic codes with development upgrades; validate with experimental data
- Begin coupling transport coefficients to transport codes & wall codes for predictive capability
- Continue required diagnostic upgrades

7+ years:

- Continue code/diagnostic upgrades for small spatial scale kinetic electron transport
- Continue validation, emphasizing hot, very kinetic edge/SOL merging to collisional divertor plasma
- Participate in model coupling for whole-device modeling

References:

[1] A. Loarte et al., "Chapter 4, Power and Particle Control," Nucl. Fusion **47** (2007) S203.