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Title:	Understanding the SOL: Fundamental Physics Challenges
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Understanding the SOL: Fundamental Physics Challenges

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Challenges in understanding the scrape-off layer (SOL) have received much attention in previous documents, including the 2014 Fusion Energy Sciences Advisory Committee *Report on Strategic Planning*[1] and the 2009 *Report on Research Needs for Magnetic Fusion Energy Sciences* (ReNew).[2] In this whitepaper we highlight only a few of several important topics in SOL physics with particular emphasis on the need for sufficient breadth in both the scientific scope and methods of these studies.

SOL turbulence, transport and the heat flux width

Background – One of the main challenges facing the fusion community is understanding the physics that sets basic time and space scales at the separatrix and in the near and far SOL. Ideally, a useful understanding will encompass a broad range of relevant operating conditions for present day and future experiments and will result in insights about how to manipulate these scales to our advantage.

In the area of theory and modeling, since the ReNew 2009 report, several reduced fluid model simulations of turbulence and the SOL heat flux width in H mode and limited L mode plasmas[3-9] and a range of corresponding analytical scaling predictions have been made.[8,10] A heuristic drift model for the SOL heat flux width has been developed;[11] neoclassical orbit width effects on the SOL width have been described using 2D[12] and turbulent 3D[13] PIC simulations. Time-dependent convective blob-filament transport is being implemented in 2D transport codes,[14] improving model fidelity over the conventional diffusive description.

While considerable progress has been made in characterizing intermittency, the role of blob-filaments, convective transport, etc., reliable predictive tools for calculating heat and particle fluxes on plasma facing components at the divertor and first wall are not presently available. The competing and/or synergistic effects of neoclassical orbit widths[11-13] and turbulence is not understood in the important narrow heat flux channel closest to the separatrix. Considerable progress has been made on the propagation of, and resulting cross-field transport by, blob-filaments in the SOL, including recent simulations with electromagnetic and 3D effects,[15-19] but there remain many challenges in a quantitative description of their generation, presumed to be through turbulence of the edge plasma. These challenges include plasma shaping with divertor X-point geometry, large fluctuation levels, sonic flows and sheaths, kinetic effects on both electrons and ions, and the role of particle momentum and energy sources and sinks, neutral and atomic physics such as friction, ionization and radiation. Recent studies of separatrix profile stability might impact our understanding of SOL profiles[20] and/or the Greenwald density limit.[21] Finally SOL transport impacts every other important boundary topic including peak heat fluxes, divertor detachment and material interactions.

Proposal – A vigorous program in fundamental studies of SOL transport should be supported, including experiments, basic theory and simulation. The ultimate goal of these studies should be qualitative analytical, and quantitative numerical, scaling predictions of the SOL particle and heat flux spatial profiles and temporal statistics in L and H mode, limited and diverted plasmas, including the effects of gas influx, impurities, rf power and surface conditioning. Obviously analytic or reduced model studies will be restricted to particular regimes and assumptions, but as discussed subsequently, such studies should form a critical part of the methods strategy.

Interaction of rf waves with the boundary plasma

Background – Technologies for high efficiency continuous electron cyclotron and neutral beam heating at DEMO parameters are problematic at best, and possibly non-existent. In the ion cyclotron (ICRF) regime, however, viable sources already exist and the wave physics is reactor core-compatible.

The main concern for ICRF operation resides in SOL and materials interactions. A fundamental understanding of the SOL should include the effects of wave fields on basic SOL properties including rf-driven sheaths,[22] impurity generation by sputtering and impurity transport by rf-induced convection, e.g. through spatially-varying rf-induced plasma biasing and flows.[23] A more complete discussion of these issues may be found in accompanying whitepapers.[24,25] Other considerations, including wave scattering, parametric decay and ponderomotive effects are of interest for lower hybrid driven plasmas and merit additional study. Properties of the SOL, such as plasma density and intermittency at the launcher surface and in the wave path between the launcher and the core are critical for rf applications in order to deliver the wave energy to the main plasma in ITER and future devices.[26] Furthermore, it is important to understand the fate of any power lost in the SOL, to avoid its spatial concentration on, and concomitant damage to, material surfaces not designed for power handling. Parenthetically, spin-off applications such as ICRF wall conditioning, may prove valuable to the fusion program. Since the 2009 ReNew report, a nonlinear rf sheath boundary condition[27] has been implemented in 2D and 3D rf codes,[28,29] better rf sheath micro-models describing rf sheath power dissipation are being developed and there has been improved modeling of antenna near fields and of global edge rf wave propagation.[30] Some efforts to include rf effects in turbulence codes has begun.[31] Much work remains before a validated understanding of rf-SOL physics is in hand.

Proposal – The US program in rf-SOL physics, presently in a strong world-wide position, should be maintained and strengthened. The effort should include fundamental experiments, supporting theory and simulation. Innovative solutions to rf-SOL issues should be strongly encouraged.

Role of analytic theory and the hierarchy of models

Background – Given the relatively immature state of fundamental SOL physics, analytical theory and reduced models should play an important role alongside the development of comprehensive numerical simulation tools. It is well appreciated that the complexity and diversity of (likely coupled) effects important for SOL-divertor studies motivates development of first principles, relatively complete, kinetic physics codes. However, confidence building in predictive capabilities and fundamental understanding can best be achieved by strong support of a hierarchy of models and codes ranging from heuristic, intuitive models, to more rigorous analytic models, reduced numerical models and finally "first principles" numerical simulation. As argued in a 2014 FESAC whitepaper by Terry,[32] the hierarchical approach is necessary to establish the validity of intuitive concepts, identify important physics not in existing simulation models, and to understand complex simulations and experiments. Ultimately the fusion program needs both quantitative answers and intuitive understanding. The Terry paper notes that the emphasis today has shifted to the quantitative side, but intuition is essential for the field to develop new concepts, be they to advance science or improve fusion component design. Furthermore analytic theory has capabilities that are essentially orthogonal to those of numerical simulation, but in a highly complementary fashion. These include properties of systems such as scalings and symmetries, and the capacity to conceptualize the workings of complex systems.

Proposal – The US program should strongly endorse the strategies proposed in the Terry whitepaper for addressing adverse trends that threaten analytic theory and the model hierarchy. Specifically, we note the recommendation therein that *large-scale simulation projects carry a dedicated analytic theory component.*

Summary

In addition to supporting fundamental studies of SOL physics, which is likely non-controversial, this paper argues for the importance of (i) understanding rf-edge interactions in the SOL, and (ii) an explicit recognition of the important role of the model hierarchy and of analytical theory in the overall boundary plasma effort, complementary to large-scale simulation.

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