Lodestar White Papers for ReNew 2009

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Overview and Background

ReNeW is the acronym for "Research Needs Workshop", a planning activity of the Office of Fusion Energy Sciences. The first ReNeW conference will convene in June of 2009 with the goal of defining a long range research plan for the U.S. fusion program. This planning activity was divided into five broad themes, and each was further divided into several sub-themes in order to facilitate detailed discussions of technical issues of importance to fusion research. White papers on these technical issues were solicited from the fusion research community, and a number of workshops were held to discuss them. Lodestar scientists participated in two of these workshops. The present report contains two white papers which we prepared on issues related to our expertise in rf sheath physics and tokamak edge physics.

ICRF-Edge and Surface Interactions

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Background: Plasma heating and current drive with ion cyclotron range of frequency (ICRF) antennas has been quite successful in past tokamak experiments and is foreseen to play an important role in ITER. However, in long-pulse or steady-state experiments the requirements are much more severe for control of rf sheaths and other unwanted interactions with the edge plasma and with material boundaries (antenna, limiters and wall). Necessary quantitative modeling tools do not yet exist. This white paper discusses some of the mechanisms that will impact the success of ITER and the future research that is needed.

Physical picture:

The goal of ICRF heating is to launch a fast wave (FW) which propagates into the core plasma and is completely absorbed there. In practice, the ideal is not always achieved. The fast wave can propagate around the scrape-off-layer (SOL) and be partially absorbed by boundary structures; the single pass absorption in the core plasma can be low for some wave components, so that wave energy is large at the wall; and the FW antenna can also launch a slow wave (SW) component (either evanescent or propagating) in the SOL when the magnetic field is not perfectly aligned with the antenna structure. When the FW encounters a material structure, the Maxwell equation boundary conditions require that it couple to the SW at the wall.

Thus, in all of the situations just described, the problem stems from that fact that SWs come in contact with a material boundary (wall, antenna or divertor) and drive *rf sheaths* there. The parallel electric field in the slow wave accelerates electrons out of the plasma, with the result that a large (up to kV) rf sheath potential forms to confine the electrons. The plasma acquires a positive DC bias with respect to the wall, so the DC (rectified) sheath potential also accelerates ions out of the plasma. This provides a source of energetic ions for sputtering the boundary, and results in an unwanted edge power dissipation channel. The sheath power dissipation reduces the overall heating efficiency and can also cause hot spots and physical damage on material structures (antennas, limiters and walls), especially in long-pulse experiments. Finally, the rf sheath potential drives radial $E\times B$ convection in front of the antenna, which increases the radial flux of plasma to the wall. All of these effects have been verified by detailed comparison of models with experimental data from tokamaks (JET, TFTR, Tore Supra, C-MOD, ASDEX-U, etc.)

Challenges:

(1) *rf sheath modeling*: The parasitic rf sheath interactions need to be minimized in future long-pulse, high-power experiments (ITER, DEMO). This will require accurate quantitative modeling of sheath formation in both antenna coupling codes and ICRF wave propagation codes. This is a difficult computational problem because (a) it is sensitive to the detailed geometry of antenna and PFCs (plasma facing components) in the SOL, (b) it requires treatment of both the ion and electron Debye length space scales, either explicitly, or by a sheath boundary condition which is nonlinear. The present rf SciDAC project has begun the work of classifying all of the sheath mechanisms and exploring ways of incorporating the sheath BC into rf codes, but a much greater effort is needed.

(2) *physics integration*: The physics of rf sheath formation, and more generally all nonlinear rf-plasma interactions, must be coupled to other important edge problems [1]. This will require a new

interdisciplinary approach. Examples of such problems are (a) quantitative prediction of the self-consistent properties of the SOL plasma (e.g. density and temperature, both mean and intermittent properties) in the presence of intense rf waves, and (b) understanding the effect of rf waves on plasma-wall interactions. These are discussed in more detail below.

Predicting the characteristics of the SOL plasma: Having a quantitative, predictive modeling capability for the SOL plasma is important for several reasons. The SOL profiles impact the divertor, the antenna and the plasma-wall coupling. For example, sheath-driven interactions (such as sputtering and power dissipation) are proportional to the flux of the plasma into the surface (antenna or wall), and the antenna coupling is sensitive to the edge density. Thus, both the antenna coupling and antenna heating efficiency in ITER are dependent on the radial "profile" of the SOL density, which at present cannot be computed from first principles. Actually the plasma density is intermittent in both time and space, and antenna plasma interaction will depend as well on SOL electric fields. A goal of future work should be to develop the physics integration necessary for this problem. This would include e.g. turbulent (blob) transport in the SOL, rf-sheath-driven radial convection, and atomic physics to understand the sources (ionization, sputtering, and recycling).

Plasma-wall interaction studies: There is a long history of experimental data pointing towards rf interactions with the wall, including fast density rise and impurity generation when the rf is turned on. The physics of rf sheaths provides one important mechanism. As discussed above, any radiofrequency wave striking a material surface generates a slow wave, and thus an rf sheath potential. In many cases, the rf sheath potential can greatly exceed the Bohm potential. Past work has shown that enhanced self-sputtering of high-Z materials (and in extreme cases, impurity avalanche) is possible when ion acceleration in the rf sheath potential is taken into account. If a high-Z material is chosen for the first wall material in ITER, this could be an important issue.

Available tools:

The rf SciDAC project, together with collaborators in Europe, are developing a set of rf codes to describe the antenna coupling (TOPICA) and wave propagation (AORSA, TORIC). Some preliminary work has been done on use of a sheath boundary condition in these codes. In addition, a new code is being developed at MIT to describe rf sheaths in the SOL plasma. This work is guided by a number of models developed by the Lodestar group to describe rf sheath formation under various assumptions. Some studies of rf-induced sputtering and self-sputtering have also been carried out and compared with JET and TFTR data.

Very little work on physics integration has been carried out except for a preliminary study by Lodestar and ORNL using the SOLT 2D turbulence code coupled with a 2D antenna code. Incorporation of a SOL wave-sheath code is necessary for quantitative work. Edge physics tools which are available for this project include SOLT, BOUT, UEDGE, neutral physics codes, and wall sputtering codes.

Future work: A long-term plan to improve our quantitative modeling in this area would include the following elements:

- incorporation of a sheath boundary condition and realistic geometry in rf antenna and wave propagation codes,
- integration of SOL turbulence codes (including sources and sinks), wave codes (including sheath physics), and plasma-wall modeling codes.

[1] J.R. Myra and D.A. D'Ippolito, ReNew white paper on "Comments on Verification and Validation in Edge Research"

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.

Other V&V activities: 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.

Available tools:

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”