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×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"