RF Sustainment Simulation Opportunities for Steady State Fusion Reactor Plasmas

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RF (radiofrequency) actuators for current drive, heating, and flow drive with high system efficiency (~70% wall-plug to plasma) and ability for continuous operation have long been recognized as essential tools for realizing a steady state tokamak.[1] A number of physics and technological challenges remain including efficient coupling, load tolerance, and impurity contamination. These challenges are compounded in a reactor environment where plasma material interaction (PMI) issues associated with coupling structures are similar to the first wall and have been identified as a potential show-stopper, with no apparent solutions.[2] Without current drive in particular, the tokamak concept as the basis for a steady-state, electricity producing power plant is unachievable. Among a number of heating and current drive actuators, lower hybrid range of frequency (LHRF) is among the most promising for off axis current drive with high efficiency and proper profile to augment bootstrap current. Ion cyclotron range of frequency (ICRF) power provides efficient bulk heating and promising flow drive. While the core physics of ICRF and LHRF are well understood, RF simulation tools to determine actuator performance, model antenna interaction and core wave absorption, are at an early developmental state.

One of the primary outputs from fusion related research is to develop the physics models that can be used to guide and design future reactors. An area of high leverage is developing simulation capability for assessing and predicting the performance of an actuator in achieving its intended task - current drive, heating, or flow drive. At present, the core wave physics is well described (except for flow drive) and simulated but the integration with antenna/coupler interaction and RF power propagation in the scrape-off layer are less well developed. The emergence of open source FEM codes combined with core simulation solvers [3,4] and time domain simulations of plasma immersed antenna with detailed 3D geometry have shown significant promise.[5] The next challenge is to include an accurate model of the scrape-off layer and PMI.

RF Sustainment Simulation Opportunities:

For RF plasma sustainment, *high-field-side (HFS) RF launch* as a means to dramatically improve launcher robustness in a reactor environment has potential to be transformational. In near-double null plasmas, a low heat-flux, quiescent boundary layer naturally forms on the high field side: (1) no heat/particle pulses reach there from ELMs [6], essentially zero fluctuation-induced fluxes [7] and no 'blobs'; (2) local plasma recycling fluxes are low, which minimizes neutral pressures in the vicinity of antenna/waveguide structures, leading to improved RF voltage handling [8]; (3) the flux of energetic ion orbit loss on the high-field side is virtually nonexistent; (4) there is no impact from runaway electrons at this location; (5) impurity ions produced from the launcher are expected to be very well screened (factor of ~10 compared to low-field side), based on results from impurity transport experiments [9]; (6) RF driven convective cells that lead to RF enhanced heat loads and impurity sources at the antenna are half compared to those on the low field side[10]; (7) local density at high-field side launch structures can be precisely controlled via upper/lower X-point flux balance due to steep SOL density profile, [11] and/or distance from the last-closed flux surface (LCFS) to launcher. High-field side launch also has significant RF wave physics advantages. For lower hybrid current drive, wave penetration is vastly improved resulting in driven current at mid-minor radius [12], precisely the location where current needs to be driven to enable flat or reverse magnetic shear.[13] The current drive efficiency is also improved by up to ~50% [14]. For ICRF, high-field launch leads to efficient electron heating via direct mode conversion of fast waves. Moreover, mode conversion could have significant power to bulk ions. Mode converted waves transferring power to the ions has been demonstrated to drive plasma flow [15,16] – a potentially powerful tool to enhance core plasma confinement via flow shear in a reactor.

A second recent development is the remarkable improvement in coupler performance. In LHRF, a passive active coupler has demonstrated remarkable coupling resilience over a broad range of plasma conditions.[17] A passive active coupler also has the inherent capacity for integrated cooling of the coupler. For ICRF, a field aligned (current straps are perpendicular to the total magnetic field) ICRF antenna has demonstrated the near elimination of the local RF enhanced impurity source and heat flux.[18] Thus, a field aligned ICRF antenna can be made from materials compatible with reactor environment without resorting to low Z films or armor that would likely negatively impact component lifetime. The field aligned antenna also shows inherent load tolerance over wide range of plasma conditions and loading transients due to edge perturbations. A PAM coupler and field aligned ICRF antenna located on the high field side potentially provides a good physics/technological solution for reliably coupling RF power in reactor environment.

Path Forward

To make progress on developing RF actuators for plasma sustainment, experimental demonstration of efficient RF actuators for off-axis current drive, heating, and flow drive that solve plasma-material interaction challenges, scale to long-pulse operation and project to effective current profile control is of paramount importance. In parallel, simulation capability for the analysis and assessment needs further development. Due to the critical requirement for current drive in tokamaks, expanding simulation capability to include SOL and PMI in LHCD and ICRF simulations should be given a high priority.

The highest priority should be to predict the density and temperature profiles for the LFS and HFS plasma edge; of particular importance is the dependence of profiles on magnetic geometry, target density, plasma current, and confinement mode. With reduced turbulent transport on the HFS, this may be a more tractable situation compared to the LFS with turbulent transport. The importance of predicting the SOL density profile has a very high leverage by accurately determining both the real and reactive components of the plasma impedance. An outstanding question that is difficult to assess experimentally is the sensitivity to misalignment. Potential candidate devices for validation experiments could include ASDEX-U, C-Mod (archived data), WEST, and ADX [19] (if funded) where the first wall materials are made of high Z metals. To take advantage of SOL modeling, the antenna electromagnetic models will need to include short wavelength phenomena in the near field of the antenna. To design LHRF couplers, an accurate model of the plasma impedance imposed on each aperture could significantly improve the overall system efficiency by minimizing the reflected power. In ICRF, the difference in load tolerance between a field aligned and classic antenna design suggests the interaction near the antenna is having a large influence on the overall electrical behavior of the antenna rather than just the resistive loading. For example, the field pitch is 10° for C-Mod or roughly 17% of the launch field is the unwanted parallel electric field for the classic antenna and the antenna is sensitive to the precise edge SOL conditions. For the field aligned antenna, the parallel electric field is <5% for the range of accessible plasmas and the antenna is load tolerant and insensitive to edge SOL conditions.

Another critical area is erosion and material lifetime. Erosion includes flux due to transport but also RF enhanced flux due to convective cells and near field energetic particle generation. Comparison with experiments for the plasma flux could again be done on existing devices in the near term. Some information regarding RF enhanced convective flux could be obtained on existing devices with antennas/couplers located on the LFS, but these will likely be complicated by turbulent transport. Exploring the importance of RF induced fluxes on the HFS would require new experiments. A third area is impurity penetration into the plasma from RF related sources or RF enhanced transport. This is an emerging explanation for ICRF impurity contamination [20] and is likely applicable to LHRF as well. Impurity penetration has already been examined in ohmic plasmas where the HFS wall had a factor of 10 lower impurity penetration than the LFS. Simulation capability to assess impurity penetration both from LFS and HFS launch would be very beneficial for evaluating different antenna concepts, magnetic geometry, and plasma confinement conditions.

A concerted effort on these questions could lead to reasonable simulation capability that can be used to guide and design RF actuators for future reactors.

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