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Whole Device Modeling with Novel Radio-frequency Actuator Schemes in Steady-State Reactor Designs

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Since the 1990's US studies of tokamak-based reactor concepts, in particular the ARIES series, have consistently emphasized the need for steady-state operation. All steady-state scenarios require high bootstrap fractions (>50%), but in order to provide control, as well as to optimize β_n, external current drive is required. While neutral beam current drive (NBCD) cannot be ruled out, most reactor studies have used RF current drive due to the high impact of beamlines on the reactor design, e.g., extension of the radio nuclide confinement boundary and reduction of the outer wall space available for breeding, as well as concerns regarding the feasibility of reliable, steady-state beams with the energy required to penetrate the large size and relatively high density of reactor designs. Consistent with the 2007 FESAC "Gaps" study, the ARIES studies have identified RF as the current drive method of choice for steady-state nuclear devices.

The proper design of reactor-grade steady-state tokamaks involves coping with a complex interplay of the effects of transport, external CD and heating profiles, MHD stability, and control of edge pedestals and SOL parameters. While great strides have been made in developing modeling capability for most critical areas, very little progress has been made in modeling the whole device, i.e., integrating the advances that have been made in transport, core and edge MHD, RF current drive, and scrape-off layer simulations in order to determine optimal reactor configurations and operating scenarios. Instead, reactor projections are often based on empirical or semi-empirical extrapolations, for example using confinement scaling laws, requiring β_n to be less than a critical value, and choosing an arbitrary value for the engineering current drive efficiency. Internal transport barriers are often assumed without justification in order to increase the bootstrap current and improve the RF driven current efficiency by requiring most of the current to be driven in the plasma periphery where the density is relatively low. This white paper suggests that the increased maturity of simulations in nearly all essential areas has presented an opportunity for carrying out more realistic integrated simulations, thereby enabling better identification of optimal pathways for efficient and attractive physics-based reactor or FNSF designs.

As an example of recent progress that strengthens the case for whole device modeling, we cite the area of lower hybrid current drive (LHCD) simulations. The slow lower hybrid wave has long been identified as particularly well suited for current drive in reactors due to its high intrinsic efficiency and attractive launching system, typically a phased array of waveguides with polarization in the toroidal direction. Until relatively recently, predictions of LHCD performance were based solely on ray tracing, where the rays are specularly reflected at a fixed plasma boundary. Primarily because this model failed to predict the performance of LHCD experiments in Alcator C-Mod, especially at high density, full wave codes have been developed which overcome the limitations inherent in ray tracing [1-3]. In addition, more realistic edge models that include a scrape-off layer have been incorporated, initially in ray-tracing [4] and subsequently in the full-wave simulations. Thus a full wave model which seamlessly treats LH wave propagation from the launcher to absorption in the plasma bulk as well as in the SOL is now available for incorporation into a whole device model.

In seeking to optimize current drive efficiency in these simulations, advantage has been taken of a result known for many years, namely that LHCD efficiency can be improved by optimizing the location of the launcher as a function of poloidal angle. This, together with the need to address the antenna-PMI issues, has led to the concept of “high field side launch” [5]. With the conventional low field side midplane launch, the accessibility condition together with the high temperatures needed for reactor operation generally lead to non-optimal current deposition near the plasma edge. Also, accessibility requires the launch of a slow wave with index of refraction parallel to the field $n_{\parallel} > 1$ which means that $\omega_p > \omega$ is required for propagation. With frequency of about 5 GHz, the vacuum decay length is ~ 6 mm so the waveguide array must be in close contact with the edge plasma where it is susceptible to erosion and damage due to ELMs, blobs and other consequences of edge turbulence. The issue of plasma-material interactions with RF actuators was raised in the ReNeW study and it is arguably the case that no “conventional” RF launcher could survive long in a reactor environment. Fortunately, inside launch for lower hybrid and ICRF systems in reactors not only optimizes the wave physics, it simultaneously addresses the PMI issue by locating the antennas on the inner wall in double null equilibria where the SOL plasma is relatively quiescent.

Summarizing the advantages that accrue for LHCD from this change in paradigm:

- The accessibility condition is eased, due to the higher field, leading to deeper penetration of the driven current profile with higher efficiency – a feature that also naturally occurs in high field reactor designs regardless of antenna location;

- For the double null configurations foreseen for reactors, the SOL plasma near the inner wall is inherently quiescent and may be more predictable, reducing the potential for PMI issues with the antenna, as well as loss of useful current drive power due to the onset of decay instabilities [6] and scattering by density perturbations;

- Assuming similar wall area is lost independent of launcher location, inner wall launch incurs a lower penalty for the breeding ratio, due to the natural asymmetry in the neutron flux.

While this discussion has emphasized the advantages of launching the slow lower hybrid wave from the inner wall, similar physics and technological gains occur for ECRF, ICRF, and lower hybrid fast wave (aka helicon) schemes as well. For example, in the case of ICRF heating, locating the antenna on the inner wall allows direct access to the ion-ion hybrid mode-conversion layer, which avoids the production of fast particles, allows flexibility in the fraction of RF power deposited to electrons and ions, and facilitates flow drive [7].

With launcher position as a new variable, integrated edge to core reactor studies can be undertaken to identify new pathways toward efficient steady-state regimes. State-of-the art transport codes together with advances in MHD, edge and SOL, and RF simulation capabilities should be integrated to identify more realistic solutions, by addressing and resolving critical issues such as ITB formation, optimized bootstrap fraction and current drive efficiency, and PMI issues for the RF launcher as well as for the divertor. In this way reactor and FNSF designs can move away from a semi-empirical approach and be put on a more realistic, physics-based platform.

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