Progress of LHCD experiments on Alcator C-Mod towards reactor relevant high density

S. Shiraiwa, S. G. Baek, P. Bonoli, I. Faust, A. Hubbard, O. Meneghini, R. Mumgaard, R. Parker, S. Scott\textsuperscript{1}, G. Wallace, J. R. Wilson\textsuperscript{1}, and Alcator C-Mod group
PSFC, MIT, Cambridge, MA, USA
PPPL, Princeton, NJ, USA

Lower hybrid current drive (LHCD) is an important actuator to provide the off-axis CD ($r/a \sim 0.6-0.8$) required to sustain steady-state (SS) configurations on tokamak reactors. LHCD has demonstrated high efficiency, off-axis CD, and long pulses in many tokamaks. However, integrated demonstration of efficient off-axis current drive at reactor relevant parameters ($B_t$, $f_{LH}$, $n_e$, magnetic configuration) has not yet been achieved. Such a demonstration is critical to inform H&CD upgrade for SS experiments on ITER and future reactor designs such as FNSF. Alcator C-Mod is equipped with a 3MW 4.6GHz LHCD system and has studied LHCD in the density range of $0.5 - 1.5 \times 10^{20}\text{m}^{-3}$ at 5-8 T. In this density range, it was discovered that a large decrease of CD efficiency occurred as the density increased. In order to ensure the success of ITER to achieve its SS mission ($Q=5$, 1000 s), the large loss of LHCD at high $n_e$ has been tackled experimentally and by using advanced LHCD codes. Experimentally, the observation of changes in scrape off layer (SOL) ionization and density profiles suggest that significant power is transferred from the LH waves to the SOL at high $n_e$. More recently, we performed a survey of LH wave spectra using Langmuir probes as RF antennas, which revealed a localized threshold-like excitation of a non-linear interaction when $n_e > 1\times 10^{20}\text{m}^{-3}$. Two LHCD simulation models, one based on ray-tracing and the other based on a fullwave solution of Maxwell’s equations, showed a significant shift of power deposition profiles towards the edge at high $n_e$, contributing to a loss of CD. These results show that, when single pass power absorption is weak, the loss of CD is caused by multiple mechanisms. Based on this understanding, a design of an additional LH launcher is selected not only to double the net LHCD power but also to enhance the single pass power absorption. The high absorption is a result of a synergistic interaction in velocity space between the LH waves launched from two launchers, and simulations predict recovery of efficient CD at $1.4\times 10^{20}\text{m}^{-3}$. The strong single-pass absorption also results in localized current drive around $r/a \sim 0.6-0.7$, closely replicating the LHCD profile expected on ITER. Demonstrating the recovery of LHCD efficiency with a strong single pass absorption will open a possibility of LHCD at even higher demo relevant density ($\sim 2\times 10^{20}\text{m}^{-3}$) by launching the LH wave from the high field side. The Integrated Plasma Simulator (IPS) framework was recently expanded to include the 3D Fokker-Planck code which enables accurate time-domain LHCD discharge simulation. Operational scenario modeling using IPS to access SS advance tokamak regime with high bootstrap current on C-Mod will be discussed.