Status of DIII-D High Field Side Lower Hybrid Current Drive Experiment

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The first high-field side lower hybrid current drive (HFS LHCD) system has been installed on the DIII-D tokamak, and first experiments are planned for 2025. HFS LHCD has the potential to provide efficient off-axis current drive consistent with advanced steady-state tokamak scenarios. Utilizing HFS launch, LH waves are expected to have improved wave accessibility [1] and single-pass absorption compared to low-field side launch [2]. From simulations of high q_{min} DIII-D discharges, efficient off-axis current at r/a~0.6-0.8 with 0.14 MA/MW coupled is achievable using $n_{||}$~2.7 at 4.6 GHz [3]. In nominal operating conditions, the launcher is expected to couple 1.6 MW with a power density ~32 MW/m^2.

Figure 1. The HFS LHCD launcher installed on the DIII-D tokamak. The launcher includes 8 modules arranged toroidally, which are each fed by individual waveguides capable of transmitting 200 kW.

For the HFS LHCD system on DIII-D, a novel, compact launcher is comprised of 8 launcher modules and is shown in Figure 1. The module has six 4-way traveling wave splitters to distribute power poloidally and a multijunction to distribute power toroidally. Launched $n_{||}$ can be controlled via the relative phasing between each launcher module. Each aperture within the 4-way splitter includes internal impedance matching elements, optimized to minimize electric fields and reflections, to enable operation in a wide range of plasma conditions. The construction of this complex internal structure, is enabled by additive manufacturing (AM) using a copper alloy, GRCop-84, originally developed for aerospace applications. GRCop-84 also has the benefit of high strength, thermal and electrical conductivity required for the demanding fusion environment [4]. In the future, the Laves-phase precipitate, Nb2Cr4, can replaced by another suitable Laves-phase precipitate compatible with a high flux neutron environment, for example Ta2V4. Following the additive manufacturing process, chemical surface finishing techniques are utilizes to minimize RF losses and optimized joining techniques of AM components, such as electron beam welding, are used in finish assembly of the launcher [5]. To minimize power conditioning, a half-wavelength alumina vacuum window is located at the input of the poloidal splitter as the largest electric fields are located in the phase shifters within the pressurized waveguide section. The vacuum window is brazed into a copper plated CuCrZr window sleeve; the copper plating promotes braze wetting on the sleeve and braze flow between the metalized surface of the vacuum window and the sleeve. The latest simulations, design and system status will be presented.

In preparation for HFS LHCD operation, detailed simulation of HFS LHCD has been performed using the ray-tracing/Fokker–Planck codes GENRAY/CQL3D [2]. It is found that the LH waves can achieve strong single-pass damping in a wide array of scenarios, and this is achieved via a double mode conversion mechanism (slow → fast → slow) shown in Figure 2. Depending on the scenario, this mechanism often enhances $n_{||}$ upshift, resulting in improved wave absorption. Additionally, it is known that the local scrape-off layer (SOL) conditions play a critical role in LHCD wave coupling and overall current drive efficiency. It is expected that the HFS SOL will be less turbulent, steeper, and more controllable than the LFS, helping to mitigate coupling challenges in previous LHCD systems. In preparation for experiments, the HFS scrape-off layer density profile has been characterized using a dedicated HFS SOL profile reflectometer. The local density profile is found to be highly sensitive to the magnetic configuration, and preliminary results suggest less fluctuations compared to the low-field side. Using machine learning techniques and a data set of over 2 million profile measurements, the HFS SOL density profile can be accurately predicted using global plasma parameters, as shown in Figure 3. Both XGBoost and neural networks were used to predict SOL density profiles using the discharge I_p, β_n, B_t, and a few magnetic configuration parameters, such as triangularity and inner gap. Mean absolute error of the predicted profile is less than 2 mm and error analysis shows that the profile predictions are sufficiently accurate to be used in HFS LHCD coupling simulations to predict arcing risk and coupled power. This capability allows for rapid, accurate prediction of local HFS SOL conditions, optimization of LHCD coupling, and more detailed study of RF-SOL interactions. This experiment will be the first application of LHCD from the HFS and provides an excellent opportunity to validate HFS RF wave physics, LHCD physics models, and RF AM technologies.

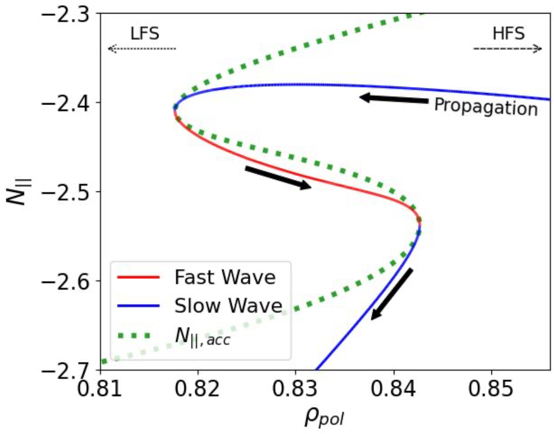

Figure 2. Example evolution of a simulated ray in DIII-D discharge 147634 with $n_{||} = -2.7$. The ray converts from the slow wave, to the fast wave and back to the slow wave before continuing on to be absorbed off-axis.

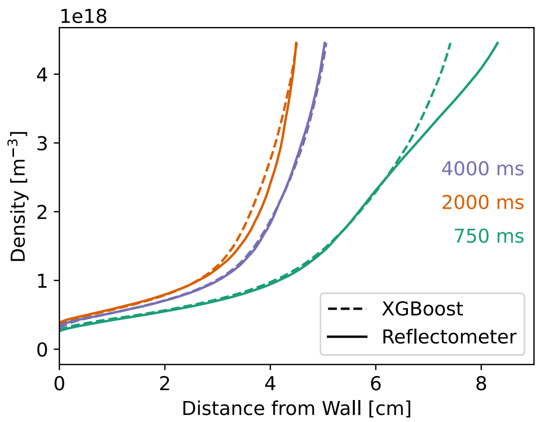

Figure 3. HFS SOL density profile measurements from reflectometry for DIII-D discharge 192868 compared with machine learning predictions of the density profile using XGBoost with global plasma parameters as input.

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