High field side LHCD in DIII-D: physics demonstration of reactor relevant current drive

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Calculations show that high field side (HFS) launch of lower hybrid range of frequencies (LHRF) waves represents an integrated solution that both improves core wave physics (high current drive efficiency at the proper location) and mitigates plasma material interaction (PMI)/coupling issues [1]. To demonstrate the benefits associated with HFS lower hybrid current drive (LHCD) (wave coupling, propagation, absorption, and current drive efficiency), a conceptual HFS LHCD system has been developed for DIII-D, which represents the first fully developed HFS LHRF system design for an operating tokamak.

Using existing DIII-D discharges, we have identified high performance scenarios with excellent wave penetration, single pass absorption and high off-axis current drive efficiency (r/a 0.6-0.8, FWHM of r/a=0.2 and driven current up to 0.21 MA/MW). Figure 1 shows ray trajectories and the driven current profile for simulated DIII-D discharge with HFS LHCD. The rays penetrate readily through the edge plasma and into the mid-radius region before damping, driving up to 0.4 MA/m^2 in the region from ρ = 0.6=0.8 for a net power of 1 MW with peak $n_{||} = 2.7$ and frequency of 4.6 GHz. The excellent off-axis current drive efficiency $\eta \equiv \bar{n}_e I_{LH} R_0 / P_{LH} \sim 0.2 \times 10^{20}$ AW^{-1}m^{-2} will fill a need for current profile control in

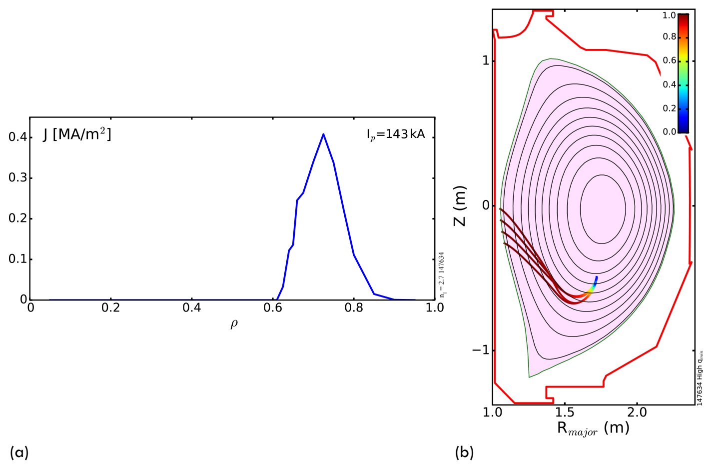

Figure 1: (a) Simulated driven current profile and (b) ray trajectories for a DIII-D "high q_{min}" discharge with HFS LHCD.

AT discharges on DIII-D and future tokamak reactors.

The DIII-D antenna design utilizes proven launching technology (slotted waveguide array [2, 3] and multijunction[4, 5, 6]) while remaining within established power density limits (less than 50 MW/m^2). A 4-way 90° multijunction is oriented vertically along the HFS wall to provide toroidal power splitting and phase shift, with a 4-way slotted waveguide array connected to each of the multijunction outputs for a 16-way split of the power from each klystron. Eight klystrons (250 kW each) will be connected to eight multijunction modules for a total of 128 radiating waveguide apertures, with a column of four passive waveguides between each module. Figure 2 shows the simulated electric fields in the splitter structure for 200 kW input power at the bottom port. Each radiating aperture is 5 mm in the toroidal direction by 43.75 mm vertically. The 5 mm dimension sets the peak $n_{||}$ at 2.7 for 90° phasing, while the 43.75 mm dimension is chosen to filter out higher order modes in the short "fingers" extending towards the plasma from the slotted waveguide. The performance of the antenna was simulated by ALOHA[7], COMSOL Multiphysics, and 3D MFEM[8] and shows low reflected power for a range of plasma conditions (Figure 3(a)) with good directivity (Figure 3(b)) with an evanescent vacuum gap between the antenna and the plasma of 1 mm or less.

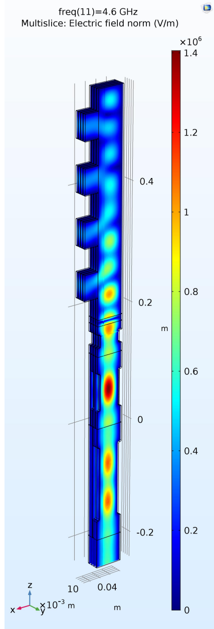

Figure 2: Simulated electric fields in the multijunction/slotted waveguide array.

From an operational perspective, antenna placement on the HFS has potential issues: reduction of the plasma-inner wall gap

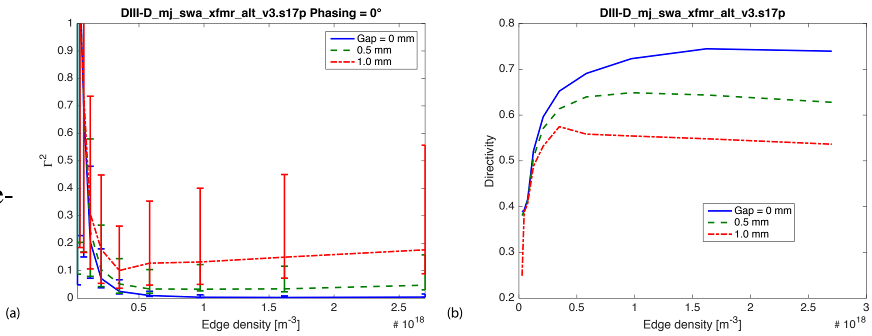

Figure 3: (a) Mean module power reflection coefficients for the DIII-D antenna. Error bars indicate minimum and maximum reflection coefficients for the eight modules. (b) Directivity of multijunction antenna for DIII-D as a function of edge density and vacuum gap thickness.

and launcher material compatibility. The former was investigated through a scan of the plasma-HFS wall gap. Little or no impact of these plasma shape changes was found on discharge confinement or stability. A mockup antenna constructed of same plasma facing materials as the proposed high power antenna (graphite limiter tiles and molybdenum "dummy" waveguides) was installed on the high field side wall of DIII-D prior to the end of the 2018 run campaign (Figure 4). The molybdenum waveguides were recessed at least 0.5 mm behind the graphite protection tiles, as is planned for the high power antenna. Two weeks of operation with the mockup in place showed no appreciable changes in impurity generation or plasma performance. Post-run campaign inspection of the mockup showed little to no damage to the Molybdenum waveguides with some erosion of the graphite protection tiles. Most of the damage to the graphite tiles was localized to the upper-right region of the mockup, which protruded to a slightly larger major radius due to unevenness of the underlying structure. Figure 4(b) shows the condition of the mockup following the two weeks of operation. Discoloration on the molybdenum "waveguides" appears mostly to the left of the graphite protection limiters (when viewed from the plasma), suggesting that beam shine-through from the left may have ablated/redeposited carbon in these areas. Beam shine-through is not expected to be an issue for the high power antenna as it will be located at a different toroidal location not in the path of the neutral beams. Furthermore, a detailed dimensional survey of the HFS wall is planned prior to installation of the high power antenna such that high spots in the structure can be avoided, thereby spreading plasma heat flux uniformly.

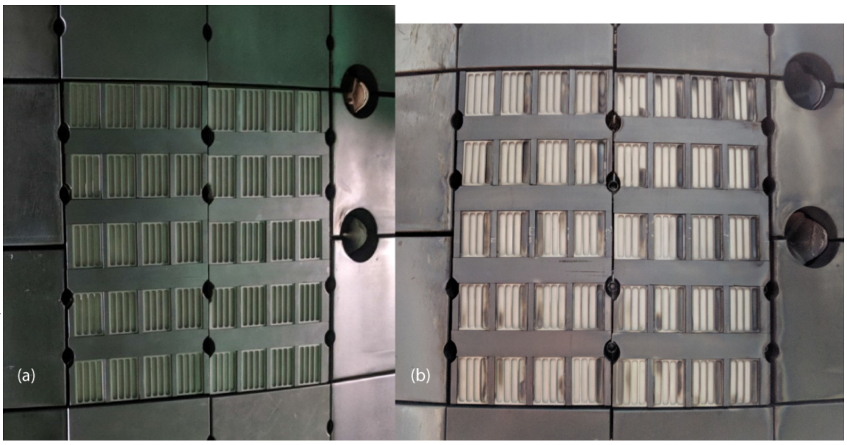

Figure 4: Mockup antenna installed on the high field side of DIII-D (a) before and (b) after the run campaign.

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