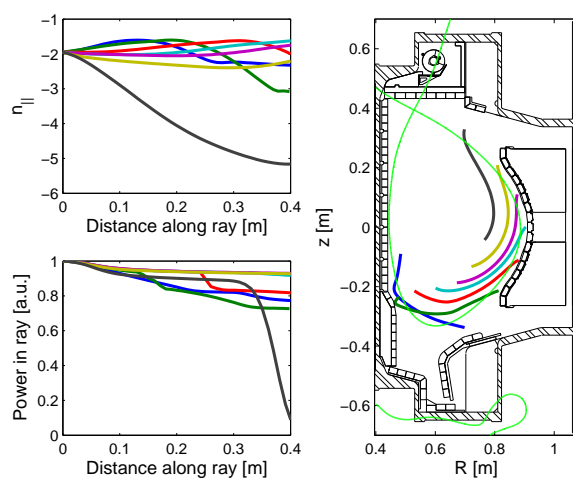


## Development of lower hybrid current drive actuators for reactor relevant conditions

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The high efficiency of lower hybrid current drive (LHCD),  $\eta \equiv n_e I_{LH} R_0 / P_{LH} \approx 2.5 \times 10^{19} \text{ AW}^{-1} \text{ m}^{-2}$ , makes it an attractive non-inductive current drive source for a steady-state tokamak fusion reactor, although unresolved physics and engineering issues must still be addressed. Experiments on Alcator C-Mod and other tokamaks have shown that lower hybrid (LH) waves can be absorbed near the last closed flux surface, rather than the desired mid-radius location, at high density [1]. Experimental and modeling studies at MIT indicate that the deleterious edge absorption is due to weak damping in the multi-pass regime, although other theories point towards prompt absorption in front of the LH antenna.

A new LHCD antenna, located above the mid-plane to improve quasi-linear absorption of the LH waves when combined with the existing (mid-plane) launcher, will be installed on C-Mod to confirm that stronger single-pass damping will improve LHCD efficiency at high density, as predicted by simulation codes. Figure 1 shows that the  $n_{\parallel}$  evolution along a ray is sensitive to the poloidal launch point. Rays launched



above the plasma mid-plane (for this direction of magnetic field and plasma current) experience a significant up-shift in  $n_{\parallel}$ , leading to stronger single-pass damping. Electrons resonant with the waves launched above the mid-plane interact synergistically with the waves launched from near the mid-plane, which do not experience a significant up-shift in  $n_{\parallel}$ . This leads to stronger absorption and higher current drive efficiency at high densities. The addition of a second launcher with additional source power will also expand the non-inductive operating range by approximately doubling the net LH power. A CAD rendering of the off-mid-plane antenna is shown in Figure 2.

Figure 1: Ray trajectories for different poloidal launch points. The initial  $n_{\parallel}$  is 1.95 for all rays.

Moving the LH launcher from the outer mid-plane to the high field side (HFS) of a tokamak has additional advantages for LHCD. The bad curvature on the low field side (LFS) causes turbulent heat and particle transport to exit primarily near the LFS mid-plane, along with poorly confined fast ions and runaway electrons. The heat and particle fluxes on the LFS can exceed acceptable limits and damage the launcher even with large distances between the LCFS and the antenna. The HFS scrape off layer (SOL) has much lower levels of turbulent transport [2], particularly in the double null configuration. A more quiescent plasma with reduce heat loads on plasma facing components will allow the antenna to be located close to the plasma without subjecting it to damage. Also, moving the antenna to the HFS with the launcher structure integrated into the breeding blanket opens up valuable real estate on the LFS which could be better used for diagnostics or tritium breeding. In addition, strong impurity screening on the HFS [3] reduces the negative impact of any impurities generated by the LH launcher.

Some reactor design studies, such as FDF [4], require high density and temperature pedestals to achieve the desired performance given other system constraints. This can pose a problem for the use of LHCD since the minimum allowable  $n_{||}$  (for accessibility at high density), and the maximum allowable  $n_{||}$  (to avoid damping in the pedestal), may overlap on the LFS, leaving no ability for the LH waves to penetrate to the desired damping location ( $r/a \sim 0.7 - 0.8$ ). The inability for LH waves to penetrate beyond the pedestal of a high density/high temperature reactor on the low field side can be overcome by launching waves from the HFS [5]. The green regions of Figure 3 show the “accessibility window” (region of the plasma where wave accessibility and strong Landau damping do not overlap) on the low and high field sides for the profiles used in FDF (Figure 11 of [4]). On the LFS, the inaccessible ( $n_{||} < \sqrt{1 - \omega_{pi}^2 \omega^{-2} + \omega_{pe}^2 \omega_{ce}^{-2} + \omega_{pe} |\omega_{ce}^{-1}|}$ ) and strong damping ( $n_{||} > \sim \sqrt{30/T_e}$ ) regions overlap for  $r/a < 0.9$ , while on the HFS the accessibility window extends in to  $r/a \sim 0.6$ . Ray tracing/Fokker-Planck simulations predict broad off-axis LH current drive ( $0.7 < r/a < 0.9$ ) if LH waves are launched from the HFS, while LH current drive is confined to the outer edge and pedestal ( $0.9 < r/a$ ) for waves launched from the LFS.

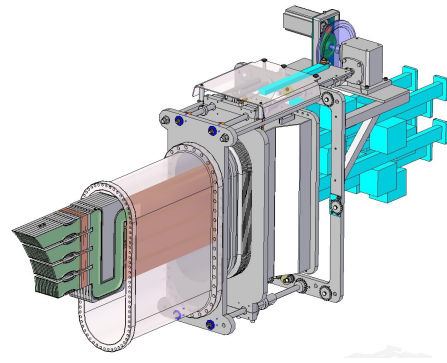


Figure 2: CAD model of the off mid-plane “LH3” antenna design for Alcator C-Mod.

To demonstrate technological feasibility, we have designed a LHCD antenna for the high field side of Alcator C-Mod. The conceptual design consists of 8 columns arranged in 4 rows located off mid-plane to take advantage of the  $n_{\parallel}$  upshift described previously. The output waveguides from each klystron are routed through vertical ports and run along the inner wall to a 4-way poloidal splitter assembly. After the poloidal split, the microwaves travel toroidally through the four “fingers” where a 90° bi-junction divides the power into two columns. Finally, a 90° miter bend directs the microwaves towards the plasma. The radial extent of the launcher structure is only  $\sim 3$  cm, allowing the launcher to be hidden behind and protected by refractory metal (Mo or W) plasma facing tiles. Sufficient real estate is available for 3-4 HFS LHCD antennas on C-Mod for a total of 3-4 MW of source power.

The Advanced Divertor Experiment (ADX) is an innovative tokamak proposed for construction to study plasma-wall interaction and RF current drive physics at reactor relevant parameters [6]. Innovative divertor configurations (super-x, x-point target, snowflake, etc) are made possible by the set of divertor control coils surrounding the outer divertor leg. ADX will verify the predicted benefits of launching LH waves from the HFS in a double null configuration, including a quiescent scrape off layer (SOL) for improved launcher durability, good impurity screening, and more direct wave penetration for stronger single pass absorption and higher current drive efficiency at high density. Figure 4 shows a cross section of the ADX design. The HFS LHCD antenna is visible to the left of the plasma.

High field side antennas are a practical solution for a reactor if integrated into the design process at an early stage. Blanket modules on the HFS wall will require many high reliability, nuclear certified, connections for structural support, cooling, breeding, and diagnostics. Remote handling technologies must be developed to allow for maintenance of blanket modules, including all connections to and through the vacuum vessel structure. If the LH antenna is designed as an integral part of the blanket module structure, then the only added complexity to replace-

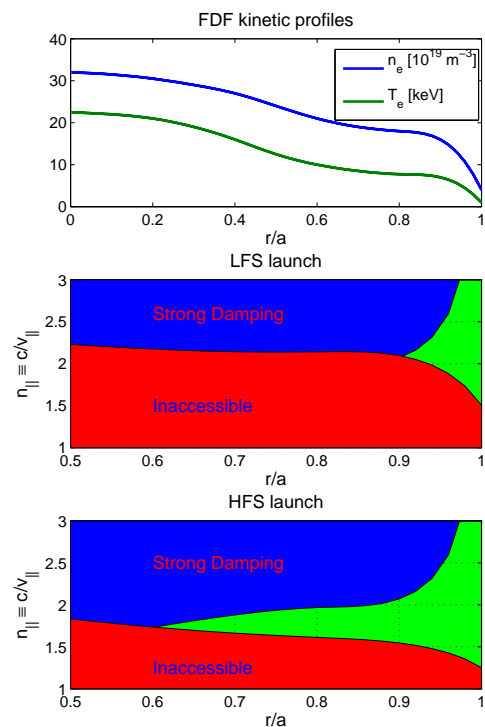


Figure 3: (top) FDF temperature and density profiles, adapted from Figure 11 of [4]. Accessibility windows on the LFS (middle) and HFS (bottom) are indicated in green.

ment of the blanket module is a few additional waveguide connections on top of the existing structural/cooling/breeding/diagnostic connections. Moving the antenna to the HFS with the launcher structure integrated into the breeding blanket opens up valuable real estate on the LFS which could be used for diagnostics or tritium breeding.

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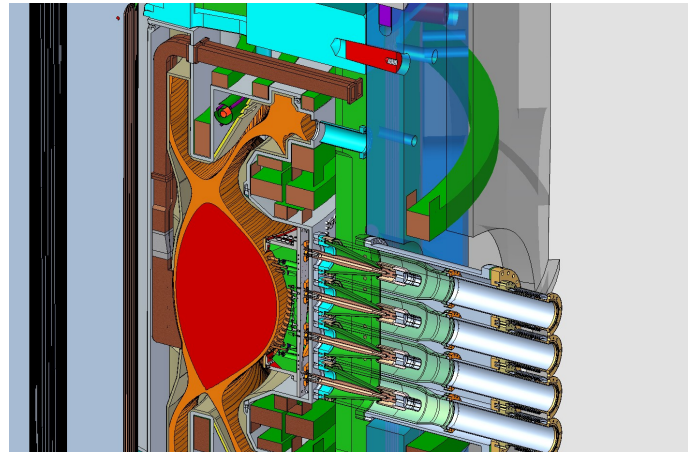


Figure 4: CAD model cutaway of the Advanced Divertor Experiment. The HFS LHCD launcher can be seen to the left of the plasma.