HIGH FIELD SIDE LAUNCH OF LOWER HYBRID WAVES: A SCOPING STUDY FOR ADX

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Abstract—Launching lower hybrid (LH) waves from the high field side (HFS) of a tokamak offers significant advantages over low field side (LFS) launch with respect to both wave physics and plasma material interactions (PMI). The higher magnetic field opens the window between wave accessibility and the condition for strong electron Landau damping, allowing LH waves from the HFS to penetrate into the core of a burning plasma, while waves launched from the LFS are restricted to the periphery of the plasma. The lower parallel refractive index ($n_p$) of waves launched from the HFS yields a higher current drive efficiency as well. The absence of turbulent heat and particle fluxes on the HFS, particularly in double null configuration, makes it the ideal location to minimize PMI damage to the antenna structure. The quiescent SOL also eliminates the need to couple LH waves across a long distance to the separatrix, as the antenna can be located close to plasma without risking damage to the structure.

The Advanced Divertor eXperiment (ADX) will include an LH launcher located on the HFS. Scoping studies with the GENRAY/CQL3D ray tracing/Fokker-Planck simulation package show good absorption for rays launched from the HFS into target discharges with C-Mod-like plasma parameters. These studies identify optimum wave launch parameters ($n_p$, vertical position, number of rows, net power) for non-inductive operation of ADX.

The LH system for ADX will make use of existing infrastructure from Alcator C-Mod, including sixteen 250 kW klystrons at 4.6 GHz (total source power of 4 MW), high voltage power supply, and controls. The ADX vacuum vessel design includes dedicated space for waveguide runs, pressure windows, and vacuum feedthrus for accessing the HFS wall. Compact antenna designs based on proven technologies (e.g. multi-junction and ‘4-way splitter’ antennas) fit within the available space on the HFS of ADX. Wave coupling simulations of these launchers with HFS SOL density profiles show good coupling can be obtained by adjusting the distance between the separatrix and the HFS wall. Guard limiters on each side of the LH antenna protect the structure during ramp-up, ramp-down, and off-normal events.

Keywords—ADX, LHCD, current drive, tokamak, RF

I. INTRODUCTION

High capacity factor, and thus very long pulse operation (i.e. steady state) will be required to make the tokamak concept viable for electricity production. Inductive current drive is efficient and convenient for use in short pulse devices, but cannot sustain the plasma indefinitely. Therefore it is necessary to develop non-inductive current drive actuators to supplement the self-generated bootstrap current [1]. Neutral beams are a workhorse heating and current drive source in present tokamaks, but may not be applicable to a reactor due to difficulty developing high energy steady state sources [2], neutron damage along the beam duct, and negative impact on tritium breeding.

Radio frequency (RF) actuators also face challenges extrapolating to a reactor environment. Experiments conducted to date operate in a much less extreme environment compared to what is foreseen in a reactor [3,4]. There are concerns about the survivability of RF antennas located near the plasma on the low field side (LFS), and fundamental physics limits on the use of RF actuators in a high temperature, high density reactor. The Advanced Divertor and Radio Frequency Experiment (ADX) [5] will explore the use of high field side (HFS) launch RF actuators to improve performance and longevity in a reactor-like environment. This paper will describe the benefits of HFS launch RF actuators and the plans for using lower hybrid (LH) waves launched from the HFS for current drive in ADX.

II. PHYSICS BENEFITS OF HFS LAUNCH FOR FUSION REACTORS

High field side launch of RF waves has been tested in the ion cyclotron [6] and electron cyclotron [7] range of frequencies, but has not been attempted in the LH range of frequencies. The benefits of HFS launch of LH waves was first identified in the Vulcan study [8]. The absorption and propagation of LH waves are determined by the parallel index of refraction, $n_{||} \equiv c k_{||}/\omega$. The accessibility condition sets a lower bound for propagation at

$$n_{||,acc} > \frac{1 - \omega_P^2/\omega^2 + \omega_{pe}^2/\omega_e^2}{\omega_{ce}/|\omega_{ce}|} \quad [9],$$

while the condition for strong electron Landau damping sets an upper bound at $n_{||,damp} < \sqrt{30/T_e}$ with $T_e$ in keV [10]. A gap must exist between these two inequalities for the LH wave to propagate without damping too far off axis (a result of a plasma which is too hot for the choice of $n_i$) or reaching the slow wave/fast wave mode conversion point (a result of a plasma which is too dense for the choice of $n_i$). Moving to a higher magnetic field, which increases the magnitude of the $\omega_{ce}$ terms in the denominator of the accessibility condition, opens the gap between the accessibility and damping conditions. This can be achieved by increasing the on-axis toroidal field, but it can also be achieved by moving the antenna location from the LFS to the HFS. Setting the accessibility and damping conditions equal to each other...
results in the curves of Fig. 1(a). The benefit to HFS launch can be seen in that LH waves can propagate to a higher temperature at a given density, or alternately to a higher density at a given temperature. In a reactor, where temperature and density are expected to both be high, the benefit from using HFS launch is particularly acute. Fig. 1(b) shows the kinetic profiles for FDF [11], a proposed fusion nuclear facility, along with the corresponding accessibility windows for waves launched from the LFS and HFS. The waves launched from the HFS can penetrate to near r/a = 0.6, while waves launched from the LFS only penetrate to r/a = 0.9 due to the high temperature and density pedestals. The lower accessible $n_{||}$ also improves current drive efficiency [12].

In addition to the improved wave penetration for waves launched from the HFS, the HFS scrape off layer (SOL) has properties beneficial to RF actuators. Plasma transport into the SOL is dominated by peeling/ballooning transport in the bad curvature region near the LFS mid-plane. In a near double-null configuration, the HFS SOL does not see the turbulent “blobs” of plasma ejected on the LFS [13]. As a result, the HFS SOL is quiescent, which will decrease plasma material interactions (PMI) and wave scattering from density fluctuations. The HFS SOL also exhibits a factor of 10 reduction in impurity penetration compared to the LFS [14]. Generation and accumulation of high-Z impurities in the presence of high power RF actuators is a major hurdle, and the improved impurity screening on the HFS will lessen the impact of high-Z wall materials on tokamak performance. The HFS wall also has lower energetic particle loading [15] and neutron loading [16, 17] than the LFS wall. Damage due to unconfined fast particles (trapped ion banana orbits and runaway electron orbits) observed on existing experiments is concentrated near the LFS mid-plane. Moving RF antennas to the HFS will not only increase antenna longevity but also improve tritium production by freeing up additional space for breeding on the LFS mid-plane where the peak neutron flux is located.

III. A COMPACT MULTI-JUNCTION FOR HIGH FIELD SIDE LAUNCH

A compact multi-junction [18] has been designed to for use on the HFS wall. The design frequency is 4.6 GHz with a conventional WR187 input waveguide size. The 4-way multijunction uses a (0°, 180°) phase shift for the first split, production by freeing up additional space for breeding on the LFS mid-plane where the peak neutron flux is located.

![Fig. 1.](image1.png)

![Fig. 2.](image2.png)
followed by a $(0^\circ, 90^\circ)$ phase shift for the second split for an output phase progression of $90^\circ$. With output waveguides of 5.5x60 mm and a septum thickness of 1.5 mm, this gives a launched $n_0$ spectrum peaked at 2.33. Fig. 2 shows the geometry of the air-space for a single multi-junction module as well as the simulated $|E|$ with matched loads on the output ports. The feed waveguide for the module runs vertically along the HFS wall, then splits into the four output waveguides (with phase shifts discussed above) before a $90^\circ$ miter-bend towards the radiating apertures. The overall radial extend of the launching structure is only slightly larger than a WR187 waveguide (~5 cm), resulting in a very compact antenna that can be placed on the HFS wall of a tokamak. The antenna is designed as a fully-active multi-junction (FAM), although could be adapted to a passive-active multi-junction (PAM) to include active cooling if necessary.

Antenna coupling has been assessed for a range of plasma conditions using the ALOHA code [19]. Fig. 3 shows the simulated input reflection coefficients for the multi-junction antenna for the seven plasma scenarios described in Table I. Each plasma scenario is defined by a density at the grill location, $n_0$, and a density gradient, $dn/dx$. Power reflection coefficients of less than 10% are achieved with a value of $l_{shift1}$ (distance between the final split and the miter bend) of 187.5 mm.

**TABLE I. ALOHA PLASMA SCENARIOS**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tbody>
<tr>
<td>$n_0 \left(10^{18} \text{ m}^{-3}\right)$</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.54</td>
<td>0.54</td>
<td>1.35</td>
<td>1.35</td>
</tr>
<tr>
<td>$dn/dx \left(10^{21} \text{ m}^{-4}\right)$</td>
<td>2.36</td>
<td>1.18</td>
<td>0.47</td>
<td>2.36</td>
<td>1.18</td>
<td>3.36</td>
<td>1.18</td>
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</table>

IV. THE ADX LHCD SYSTEM

The Advanced Divertor and Radio Frequency Experiment (ADX) [5] is a proposed tokamak with a twofold mission: to investigate the use of advanced divertor configurations and validate the benefits of HFS launch of RF waves. The ADX design is an evolution of the successful Alcator series and builds upon the established engineering systems of Alcator C-Mod, such as demountable toroidal field coils with sliding joints. Table II includes a summary of several key parameters for ADX.
The ADX design includes LH antennas for non-inductive current drive. Power is provided to the antenna by sixteen Varian (now CPI) VKC-7849 klystrons operating at 4.6 GHz with a nominal output power of 0.25 MW (CW). A Thales Electron Devices (now Ampegon) high voltage power supply provides 208 A at 50 kV for 5 s pulses every 1000 s.

ADX will include three HFS LH antennas and one LFS LH antenna. Two antenna design concepts are under consideration: the four-way multi-junction described in the previous section, and a poloidal 4-way splitter with 90° bi-junction shown in Fig. 4. For option 1, each antenna will consist of 16 columns and 2 rows with waveguide feeds from both the top and bottom, for a total of 8 modules (and 8 vacuum feedthrus) per antenna. The poloidal position of each antenna will be different to maximize flexibility in the use of “poloidal steering” to influence the upshift of $n_i$ as waves propagate through the plasma. In option 2, each antenna will have 8 columns and 4 rows with waveguide feeds from the top, with a total of 4 modules (and 4 vacuum feedthrus) per antenna. Option 2 has the advantage of increased flexibility in the launched $n_i$ afforded by the bi-junction (vs multi-junction) design, although with a slightly wider spectral peak. A LFS LH antenna of 16x4 waveguides will be installed for performance comparison between LFS and HFS launch. Net power of 1.25 MW from the HFS antennas and 1.0 MW from the LFS antenna is expected based on an experimentally proven power density of 40 MW/m².

The ADX vacuum vessel is specifically designed to incorporate the use of HFS LH antennas. Fig. 4 shows the feed waveguide traversing radially above the upper divertor and below the arm of the toroidal field coil. The vacuum windows are located inside the envelope of the toroidal field coils to minimize the chance of cyclotron resonance breakdown inside the waveguide. The waveguide penetrates through the vacuum vessel, then turns down along the HFS wall towards the plasma mid-plane.

The HFS LH antennas are protected from damage during ramp-up and off-normal events (e.g. disruptions) by guard limiters located on either side of the antenna as shown in Fig. 5. Protection tiles will cover the vertical waveguide runs as shown in Fig. 4. Two of the HFS LH antennas are located away from the HFS ICRF antenna, although one LH antenna is next to the ICRF antenna to assess the impact of ICRF on LH wave coupling on the HFS. Stresses on the waveguide during disruptions exceed allowable limits for copper [20]; copper-plated stainless steel will be used to both reduce eddy current

<table>
<thead>
<tr>
<th>TABLE II. ADX PARAMETERS</th>
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<tbody>
<tr>
<td>Major/Minor Radius</td>
</tr>
<tr>
<td>Magnetic Field</td>
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<tr>
<td>Plasma current</td>
</tr>
<tr>
<td>$P_{aux}$ (net)</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Divertor and first-wall material</td>
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<tr>
<td>Pulse length</td>
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</tbody>
</table>

Fig 4. The ADX experiment design includes a flexible set of shaping coils to test advanced divertor configurations. High field side RF antennas are also included in the design. The feed waveguides (brown) for the HFS LH antenna traverse radially above the upper divertor before passing through a pressure window into the vacuum vessel (grey). The feed waveguide then turns downward and runs along the HFS wall to the launch point slightly below the plasma mid-plane.
forces and improve the structural integrity of the antenna.

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REFERENCES


