Status of Diagnostic Development to Measure Parallel Wavenumber of Lower Hybrid Waves on Alcator C-Mod

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Abstract. Recent lower hybrid (LH) current drive experiments on Alcator C-Mod have motivated measurement of the parallel wavenumber of LH waves with an aim to understand the significance of the k|| up-shift mechanisms such as scattering by turbulence or parametric decay instabilities. To this end, a new diagnostic system is under development, consisting of two rows of three RF magnetic loop probes (one row sensitive to B||, the other row B⊥) and three Langmuir probes. These will be mounted on a radially movable probe system on the low field side of the tokamak, which is magnetically mapped to the LH launcher but toroidally separated by about 110 deg from the launcher. This location is expected to be ideal for detecting the parallel wavenumber spectrum of the pump and sideband LH waves up to n|| of 6.5. The use of the loop probes will help unambiguously resolve the polarization of these waves. These loop probes have been developed under the collaboration with the University of Tokyo, and vacuum-compatible versions have recently been fabricated and tested on the bench. To evaluate the phase of the detected waves, the signals at 4.6 GHz will be frequency down-converted to 25 MHz in an intermediate frequency stage, and directly digitized at a sampling rate of 100 MS/sec. This system will output the dominant parallel wavenumber for each frequency, selected by controlling the frequency of a local oscillator in the IF stage. In addition to these loop probes, the Langmuir probes will be used to provide the density and temperature information at the measurement location to perform instability analyses. The Langmuir probes will be also used to examine the sensitivity of the radial measurement location on the strength of the sideband LH waves. Details of this proposed diagnostic system and the latest status will be presented.

MOTIVATION FOR N|| MEASUREMENTS OF LOWER HYBRID WAVES

Lower hybrid current drive (LHCD) system on the Alcator C-Mod tokamak operates at ITER-relevant frequency (4.6 GHz), magnetic field (5.4 T), plasma densities (n_e~1.0 – 2.0 × 10^20 m^-3), and magnetic configurations [1]. A grill antenna, consisting of 4 rows of 16 active waveguide (7 mm x 60 mm) is located at the outer midplane of the C-Mod tokamak, which is used to couple lower hybrid (LH) waves to the plasma. The initial parallel refractive index (n||= ck||/ω0) of the launched LH waves (along the background magnetic field) is set by the relative phase between the adjacent waveguide grills. Here, c is the speed of light, k|| is the parallel wavenumber, and ω0 is the wave frequency in radian. In C-Mod, the typical launched peak n|| is 1.9. In the toroidal plasma, along the resonance cone propagation, k|| evolves due to toroidal and poloidal magnetic fields, and can be expressed as the following [2]:

\[
\frac{\partial k||}{\partial z} = \frac{\omega}{c} \frac{\partial B}{\partial r} - \frac{1}{\rho} \frac{\partial B}{\partial \phi}
\]

where ρ is the magnetic surface radius and B is the magnetic field. This evolution of k|| with the toroidal and poloidal magnetic fields plays a critical role in determining the parallel wavenumber spectrum of the sideband LH waves. The measurement of k|| will help in understanding the significance of the up-shift mechanisms, such as scattering by turbulence or parametric decay instabilities, which are known to affect the LH wave propagation in tokamak plasmas. Understanding these mechanisms is crucial for optimizing LHCD performance and improving the efficiency of plasma heating and current drive.
where $m \equiv rk_\theta$ is the poloidal mode number, and $n \equiv Rk_\phi$ is the toroidal mode number which is a conserved quantity in the toroidal geometry $(r, \theta, \phi)$. Tracking the $k_\parallel$ evolution in the plasma is important because $k_\parallel$ determines not only propagation but also Landau absorption condition: $n_\parallel \geq 7/\sqrt{T_e}$(keV). Moreover, recent experimental results [3] suggest that additional $n_\parallel$ up-shift mechanisms due to scattering by turbulence or parametric decay instabilities might play a role in understanding the LH wave propagation and absorption in high-density C-Mod plasmas [4]. Further, recent simulations [5] indicate that the inclusion of small high-$n_\parallel$ components in the launched $n_\parallel$ spectrum could also lead to a non-negligible change in both the driven current and the LH power deposition profiles. Thus, the direct measurement of $n_\parallel$ spectrum away from the launcher could help examine the evolution of $n_\parallel$ in tokomaks. To this end, we are developing an array of magnetic loop probes, which will allow measuring the $n_\parallel$ and polarization of LH waves near the separatrix away from the launcher. We plan to intercept the resonance cone on the first pass from the launcher to the plasma as will be shown later in the ray-tracing simulation, and measure the dominant $n_\parallel$ component of the LH wave-field.

**DEVELOPMENT OF MAGNETIC LOOP PROBES**

Magnetic loop probes are useful in measuring the phase and polarization of the wave-field. Loop probes measure the induced voltage due to time varying magnetic flux within the coil, as indicated by Faraday’s Law: $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$. By placing an array of probes, one can determine the phase of the wave-field. Since the typical launched $n_\parallel$ at the LH grill antenna is 1.9, which is equivalent to $\lambda_\parallel/2 = 17.2$ mm, this implies that the relative distance between the probes need to be on the order of 5 mm. Figure 1(a) shows the CAD drawing of the magnetic loop antenna which is designed in the University of Tokyo [6]. The inner diameter of the circular coil is 1.2 mm, and a shield that encloses the loop antenna minimizes noise pickups. The diameter of the shield is 5 mm. The slit has the dimension of 4 mm $\times$ 0.5 mm, and will allow the wave-field to penetrate inside the shield. The orientation of the coil with respect to the slit is such that the coil is sensitive to the magnetic fluctuation along the longer dimension side of the slit. Figures 1(b) and (c) show the photos of a C-Mod vacuum compatible version. A center conductor is silver solder brazed to the outer stainless steel jacket using Easy Flo 35 (35% silver with a melting point of 1124 degrees Fahrenheit).

The probe response has been tested using a slotted waveguide on the bench. The surface of the WR187 waveguide (47.55 mm $\times$ 22.15 mm) on the narrower dimension side has been slotted to place a probe and intercept the magnetic field within the waveguide. Using a network analyzer, the TE10 mode was excited at one end of the waveguide. By connecting the other end of the network analyzer to the probe, one could measure the S-parameters of the probe. Figure 2(a) shows the transmission coefficient when the coil surface is aligned to maximally detect the B-field.
within the waveguide, as compared to the transmission coefficient when the surface normal vector of the coil surface makes \( \theta = 90 \) deg with respect to the background B-field. In the latter case, theoretically, the probe is not expected to detect any signals from the background B-field. The measurements show that the magnetic probe can measure the signals by about 20 dB stronger than the latter case, and the transmission coefficient in this case is about -55 dB. It also shows a flat frequency response in the 4.5 – 4.7 GHz range without anomalous resonance behaviors. While not shown here, the angular dependence of the coil surface to the background B-field exhibits the \( \cos^2 \theta \) dependence, consistent with the expectation. Figure 2(b) shows the measured phase variation when moving the probe along the slotted surface. The measurement indicates that the measured propagation constant \( \beta \) is 69.9 (1/m), which is consistent with the theoretical value of 70.1 (1/m) at 4.6 GHz in the WR187 waveguide.

**DEVELOPMENT OF DETECTION SYSTEM**

These probes will be mounted on a radially movable probe head on the Surface Science Station (S3) [7]. This system had previously been used to study wave in the ion cyclotron range of frequencies. A new probe head has been designed and under fabrication to mount magnetic probes and Langmuir probes. As shown in Figure 2(c), two rows of three magnetic probes will be installed on the probe head. One row will be sensitive to the wave field associated with magnetic fluctuations parallel to the background magnetic field, and the other row will be sensitive to magnetic fluctuations perpendicular to the background magnetic field. By placing three probes in each row, it is expected that the dominant \( n_\parallel \) could be measured for each polarization. Langmuir probes installed below the magnetic probes will be used to measure the local density and temperature at the measurement location.

The S3 is located about 110 deg. toroidally away from the LH grill antenna. The polodial location of the S3 probe head is about 20 cm below the midplane, as shown in Figure 3(a). It can be radially moved near the separatrix at that location \( (R \approx 78 \text{ cm}) \). Figure 3(a) also show rays that are launched at the launcher with \( n_\parallel = 1.75 \) in the plasma at \( n_e = 1.2 \times 10^{20} \text{ m}^{-3}, B_{\parallel 0} = 5.4 \text{ T}, \) and \( I_p = 1.1 \text{ MA}. \) The GENRAY ray-tracing code is used [8]. The rays are terminated when they propagate about 110 deg toroidally. Rays with a higher \( n_\parallel \) than 1.75 are found to radially penetrate inward, suggesting that the probes are expected to detect the waves with low \( n_\parallel \) that has a limited radial penetration. Assuming that the probe intercepts the resonance cone with the power density of 33 W/mm², we expect that the measured power with the probe is about -10 dBm based on the dimension of the slit (4 mm x 0.5 mm) and S-parameter of the probe (-60 dB). The power density of the resonance cone is estimated by assuming the net injected power of 1 MW with the grill surface area of 3x10⁴ mm². Electric field variations due to the presence of plasma is not considered in this estimation.
To directly digitize the signals at 4.6 GHz, an intermediate frequency stage has been developed. Figure 3(b) shows the two-step frequency down-conversion from 4.6 GHz to 25 MHz using a narrow band pass filter at 300 MHz and two mixers. The first local oscillator (LO) at 4.9 GHz will be controlled using a function generator. The band-pass filter selects the frequency bandwidth of 300 ± 12.5 MHz. The frequency of the second LO is fixed at 275 MHz, so that the output frequency of the signal is down-converted to 25 MHz. The amplification in this stage is 20 dB with an amplifier after the second mixer. The output of the IF chain will be fed to a fast digitizer at 100 MSample/sec to directly digitize the signals.

With this approach, we will not be able to measure a wide frequency range (e.g., 4.5 – 4.7 GHz) in each measurement event, unlike a typical spectrum analyzer. However, this approach will allow studying the phase of the measured wave at the given frequency by measuring the relative phase between the channels. It was tested on the bench that over a wide range of the input powers (-50 – 0 dBm), the relative phase between the two IF channels maintain its accuracy as long as the IF channels were pre-calibrated to each other. We have built six identical IF chains, which will be connected to the six magnetic probes shown in Figure 2(c). The capability of controlling the frequency of the first LO will also allow studying the phase of the observed sideband LH waves in high density plasmas, although the amplitude sensitivity will need to be verified experimentally.

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