Measurements of ion cyclotron parametric decay of lower hybrid waves at the high-field side of Alcator C-Mod

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Abstract. Ion cyclotron parametric decay instability (PDI) of lower hybrid (LH) waves is surveyed using edge Langmuir probes on the Alcator C-Mod tokamak. The measurement is performed simultaneously at the high-field side (HFS) and low-field side (LFS) mid-plane of the tokamak, as well as in the outer divertor region. Different LH spectra are observed depending on the location of the probes and magnetic configuration in L-mode plasmas, with $\mathbf{B} \times \nabla B$ drift direction downward. In lower single null (LSN) plasmas, strong ion cyclotron PDI occurring at the HFS is observed for the first time. This instability is characterized by a frequency separation in sidebands corresponding to the ion cyclotron frequency ($\omega_{ci}$) near the HFS scrape-off layer (SOL) and develops with threshold-like behavior as density increases. In inner wall limited (IWL) plasmas, this HFS instability shows a higher density threshold compared to that in LSN plasmas. The pump width becomes broadened even in the absence of the sidebands. In upper single null (USN) plasmas with similar plasma parameters, ion cyclotron PDI sidebands have a frequency separation corresponding to $\omega_{ci}$ near the low field side and are weaker than those observed in the LSN and IWL plasmas. Correlation between the onset of ion cyclotron PDI and the observed loss of lower hybrid current drive efficiency[1] is discussed.
1. Introduction

The anomalous loss of lower hybrid current drive (LHCD) efficiency has been observed\[2\] on Alcator C-Mod (major radius of $R \approx 0.67$ m, minor radius of $a \approx 0.21$ m)\[3\] when the line-averaged plasma electron density ($\bar{n}_e$) is raised above $0.5 \times 10^{20} \text{ m}^{-3}$ in ohmically heated L-mode plasmas. In these plasmas, $\bar{n}_e$ remained below the limit imposed by accessibility, and no strong parametric decay instability (PDI) \[4, 5, 6\] was observed. Two models have been proposed to explain this phenomenon: (1) strong collisional absorption of LH waves in the scrape-off layer (SOL)\[7\] and (2) full-wave effects through which the parallel refractive index ($n_\parallel$) of LH waves is strongly up-shifted\[8\]. However, there is a remaining discrepancy above $\bar{n}_e \approx 1.0 \times 10^{20} \text{ m}^{-3}$ between the experimentally measured non-thermal hard X-ray (HXR) emission and the HXR emission from synthetic diagnostics predicted by these models (e.g., Figure 9 of \[1\]).

To assess the role of non-linear effects to explain this discrepancy, pump broadening near the LH launcher has been studied in this density range. Using a Langmuir probe installed on the LH launcher, pump broadening was examined as a function of $\bar{n}_e$\[9\] and the distance between the inner wall and the last closed flux surface (LCFS) at the inboard mid-plane\[10\]. Focus was given to ion sound PDI\[11, 12, 13, 14, 15, 16\] and scattering by turbulence\[17, 18, 19, 20, 21, 22, 23\]. While the pump broadening increased with line averaged density, the change in the pump width, defined as the full width at 10 dB below the peak power, was not significant (~ 1 MHz). Nonetheless, the question remained whether those spectra measured at the launcher represented the spectra away from the launcher in diverted plasmas. Previous work in other limited tokamaks\[6, 24\] reported that the broadband feature of the parametrically excited LH spectrum was more or less independent of the probe location. In these tokamaks, decay spectra indicated ion cyclotron parametric instabilities occurring at the low field side (large major radius side).

This led us to measure LH frequency spectra at various locations around Alcator C-Mod using multiple probes\[25\]. We used Langmuir probes installed on the inner wall\[26\], LH launcher, and outer divertor regions. A multi-channel spectral recorder was developed to measure LH frequency spectra continuously. The measurements were performed on lower single null (LSN), upper single null (USN) and inner wall limited (IWL) plasmas. Measured LH spectra show different PDI behavior in the density range above $\bar{n}_e \approx 1.0 \times 10^{20} \text{ m}^{-3}$. In particular, we report the first observations of ion cyclotron PDI occurring at the HFS of a tokamak, and show that it depends on the magnetic configuration. We concentrate our discussion more on the observed ion cyclotron sidebands than pump broadening because, as shown later, the strength of ion cyclotron LH sidebands can be comparable to that of pump wave, suggesting that ion cyclotron PDI can form a significant power loss channel.

In this paper, the dependence of parametric decay spectra on magnetic configuration and density is reported. While local plasma parameters are more relevant in determining the characteristics of PDI, we take $\bar{n}_e$ as a representative plasma parameter in interpreting PDI behavior, consistent with the observations\[2\] that the decrease in HXR emission rate is clearly correlated with the increase in $\bar{n}_e$. The organization for this paper is as follows. Section 2 describes the experimental setup and diagnostics used to measure the LH frequency spectra. Section 3 presents the observations of LH frequency spectra in LSN, IWL and USN plasmas. Section 4 discusses physics implications of these observations and Section 5 summarizes this
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Figure 1. Poloidal cross-section of Alcator C-Mod showing the location of three Langmuir probes: LFS probe (the probe on the LH launcher), HFS Probe (the probe on the inner wall), and outer divertor probe (JDiv7). Plots of the LCFS for the LSN (1120710008), IWL (1120710013), and two USN (1120710009 and 1120601014) plasmas are overlapped in black, green, blue, and red, respectively. An example of the LH ray trajectory is over-plotted.

2. Experimental Setup

LH current drive experiments\cite{27, 28} in Alcator C-Mod use a single grill antenna with 4 rows of 16 active waveguides at a frequency of 4.6 GHz. For the data presented in Section 3, the peak \( n_\parallel \) of the launched LH spectrum is 1.9 and the coupled LH power
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Table 1. The central magnetic field \(B_{T0}\), plasma current \(I_p\), mid-plane mapped distance between the primary and secondary X-points (SSEP), right gap (R.G.), left gap (L.G.), and coupled LH power \(P_{LH}\) of the four discharges represented in Figure 1.

<table>
<thead>
<tr>
<th>Shot</th>
<th>(B_{T0}) (T)</th>
<th>(I_p) (kA)</th>
<th>SSEP (cm)</th>
<th>R.G. (cm)</th>
<th>L.G. (cm)</th>
<th>(P_{LH}) (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1120710008 (LSN)</td>
<td>5.4</td>
<td>550</td>
<td>-1.77</td>
<td>0.89</td>
<td>0.79</td>
<td>620</td>
</tr>
<tr>
<td>1120710009 (USN)</td>
<td>5.4</td>
<td>550</td>
<td>2.57</td>
<td>1.38</td>
<td>1.27</td>
<td>660</td>
</tr>
<tr>
<td>1120710013 (IWL)</td>
<td>5.4</td>
<td>550</td>
<td>-</td>
<td>2.21</td>
<td>0.00</td>
<td>560</td>
</tr>
<tr>
<td>1120601014 (USN)</td>
<td>5.25</td>
<td>800</td>
<td>0.96</td>
<td>2.32</td>
<td>1.10</td>
<td>440</td>
</tr>
</tbody>
</table>

is about 600 kW. Figure 1 shows plots of the LCFS for the four deuterium plasma discharges \((\text{H}/(\text{H}+\text{D})\text{ ratio} < 10\%)\) that are discussed in this paper. With \(\overrightarrow{B} \times \nabla B\) drift direction downward, the plasma has three different magnetic configurations: LSN, IWL, and USN. Table 1 lists experimental parameters, including the left (inner) gap and the right (outer) gap of these plasmas to the machine wall, according to the EFIT code.

Figure 1 also shows the locations of the Langmuir probes used to measure LH frequency spectra. At the HFS, two probes mounted on the inner wall \([26]\) are used. Details of these inner wall probes can be found in \([26]\). Although the inner wall probes may be radially scanned, they remained 2 mm behind the inner wall tiles during these experiments. Because measured density at the inner wall is typically above the slow LH wave cutoff \((n_e = 2.6 \times 10^{17} \text{m}^{-3})\), the signals collected by the HFS probes are due to the LH waves propagating toward the HFS probes. At the LFS, the Langmuir probes mounted on the LH launcher and the probes on the outer divertor were used.

We have developed for this study a set of spectral recorders to continuously measure LH frequency spectra within a single plasma discharge. The new recorders have a bandwidth of \(\sim 300\) MHz, resolution bandwidth of \(\sim 100\) kHz, dynamic range of \(\sim 60\) dB, and repetition rate of \(\sim 16\) ms \([29]\). Previous LH frequency spectral measurements were limited to a single measurement at one location per discharge. With this new diagnostic, approximately 50 LH frequency spectra are measured per probe for a typical plasma discharge with 800 ms of LHCD. The electrical connection from the probes to the spectral recorders is made via 50 Ω coaxial cables, which minimizes transmission losses and parasitic pickup around the LH operating frequency (4.6 GHz).

Using these high repetition recorders, we can study how LH spectra at multiple locations change with plasma parameters, in particular \(n_e\) and magnetic configuration. By examining the relative strength of the sidebands to that of the pump wave and the frequency separation between the sidebands and pump wave, we can infer the radial region where dominant ion cyclotron PDI occurs. Note that we do not directly compare the measured spectral power among the probes because neither the probe design nor the transmission loss among the probes is exactly the same, although the recorders are absolutely calibrated using a commercial signal generator.
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3. Spectral measurements of LH waves

3.1. LSN plasma

Figure 2 shows the experimental results in a LSN L-mode plasma. In this discharge, after LHCD turns on at 0.6 sec, $n_e$ is gradually raised from $0.9 \times 10^{20}$ m$^{-3}$ to $1.2 \times 10^{20}$ m$^{-3}$. As shown in Figure 2 (c), between 0.9 sec and 1.2 sec, the intensity of edge non-thermal electron cyclotron emission (ECE) drops by 50 %, even though the density is increased only by 20 %, indicating anomalous loss of LHCD efficiency[2]. The ECE channel shown in this paper measures the relativistically down-shifted second harmonic ECE at a frequency of $f_0 / f_{ce0} \approx 1.43$, where $f_{ce0}$ is the central electron cyclotron frequency.

Figure 2(d), (e) and (f) show the time traces of the LH frequency spectra measured at the three different locations. Three noticeable features are seen among these spectra. First, no significant PDI activity is observed at the LH launcher and outer divertor. Yet, the inner wall probe detects the parametrically excited sidebands after 0.95 sec, when the edge non-thermal ECE starts to decrease. Second, the frequency difference between the pump wave and the first down-shifted sideband (60–65 MHz) corresponds to the ion cyclotron frequency ($\omega_i$) approximately evaluated near the HFS mid-plane SOL (smaller major radius side). Third, the onset of this ion cyclotron PDI is abrupt. The peak intensity of the sidebands increases more than 20 dB within 20 ms, consistent with the non-linear nature of PDI.

Figure 3 compares the LH spectra of the discharge shown in Figure 2 before (in black) and after (in red) the onset of PDI at 0.95 sec. Note that the noise floor of the spectral recorder is the same in each power detector system. As shown in Figure 3 (c), peaks of the down-shifted sidebands are seen in the LH spectrum when measured at
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Figure 3. LH frequency spectrum taken at the time $t = 0.67$ sec (black) and $t = 1.30$ sec (red) from the discharge (1120710008) shown in Figure 2 with the (a) LFS probe, (b) outer divertor probe, and (c) HFS probe. In this figure and the rest of this paper, the pump width refers to the full width of the pump wave below 10 dB from the peak power.

In addition to the presence of the ion cyclotron sidebands, the pump wave is broadened at measurement locations other than the LH launcher. Pump broadening at the LH launcher is not significant, in agreement with previous observations[9]. At 1.3 sec, the pump width at the HFS is approximately 7 MHz, while the pump width at the LFS is less than 2 MHz. In the divertor region, the pump is generally observed to be broadened by more than 2 MHz. These observations suggest that either ion sound parametric decay or turbulent scattering may also play a role away from the launcher, although the interaction region may not be easily identified.

3.2. IWL plasma

IWL plasmas exhibit higher non-thermal HXR emission as compared to diverted discharges at $\bar{n}_e$ above $1.0 \times 10^{20}$ m$^{-3}$[7]. The observed parametrically excited sidebands have higher density threshold for the onset of HFS PDI (i.e., ion cyclotron PDI occurring at the HFS), but, in general, show similar behavior to that observed in the LSN plasmas. The IWL configuration minimizes the cold SOL region and increases the density gradient between the wall and plasma near the HFS mid-plane, which may suppress the growth of the instabilities.

Figure 4 compares the LH spectra measured at the inboard side before ($\bar{n}_e \approx 1.2 \times 10^{20}$ m$^{-3}$) and after ($\bar{n}_e \approx 1.3 \times 10^{20}$ m$^{-3}$) the onset of HFS PDI. When $\bar{n}_e \approx 1.2 \times 10^{20}$ m$^{-3}$
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Figure 4. LH frequency spectra in the IWL plasma with $n_e \approx 1.2 \times 10^{20}$ m$^{-3}$ (black) and $n_e \approx 1.3 \times 10^{20}$ m$^{-3}$ (red) measured with the (a) LFS probe, (b) outer divertor probe, and (c) HFS probe.

At $1.3 \times 10^{20}$ m$^{-3}$, the sidebands excited at the HFS are observed with the inner wall probe and outer divertor probe. The LH spectrum measured by the inner wall probe is dominated by the sidebands excited near the HFS SOL, similar to those seen in the LSN plasmas. However, the density threshold to excite HFS PDI is higher in IWL plasmas. The density threshold ($\pi_e \approx 1.25 \times 10^{20}$ m$^{-3}$) is about 20% higher as compared to that in LSN plasmas. This change in the density results in a decrease of edge non-thermal ECE from 2 keV to 1 keV. Both probes at the LFS detect a relatively weaker sideband that is down-shifted by about 31 ∼ 33 MHz. This mode is due to parametric excitation at the LFS, which is generally observed to be weak in this density range[9].

Another distinct feature seen in Figure 4 (c) is that the width of the pump wave remains broadened down to 30 dB below the peak power, independent of the presence of the ion cyclotron sidebands. The width of the pump wave measured at the LH launcher is narrow and is similar to that observed in LSN plasmas.

3.3. USN plasma

Figure 5 shows the time history of two USN plasmas with $n_e \approx 0.9 \times 10^{20}$ m$^{-3}$ and $n_e \approx 1.15 \times 10^{20}$ m$^{-3}$. Although the change in $n_e$ is less than 30 % in the two discharges, the non-thermal ECE drops by an order of magnitude. Figure 5 (d), (e) and (f) show the LH frequency spectra measured near 1.1 sec in both discharges. Above $n_e \approx 1.1 \times 10^{20}$ m$^{-3}$, all three probes detect the sidebands displaced by 31 ∼ 33 MHz, which are absent within the detector sensitivity in the lower density plasma. This instability is expected to occur at the outer edge but slightly inside (major radius of 82 ∼ 87 cm), based on the frequency separation of the sidebands.

This instability is clearly different from the instability observed in LSN plasmas, although the threshold density is similar. The peak amplitude of the first downshifted sideband is about 20 dB below the peak power of the pump and there is much less spectral power in the sidebands than in the pump. Moreover, the spectral shape appears to be independent of the probe locations, as previously reported in the limited tokamaks[6, 24]. Finally, the degree of pump broadening is smaller than that in LSN plasmas, although the pump width is broadened when measured away from the LH launcher. This suggests that the pump waves suffer less from either ion-sound
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Figure 5. Time history of the two USN plasmas with $n_e \approx 0.9 \times 10^{20} \text{ m}^{-3}$ (black) and $n_e \approx 1.15 \times 10^{20} \text{ m}^{-3}$ (red): (a) Coupled LH power, (b) line averaged density, (c) edge non-thermal electron emission, LH frequency spectra measured with the (d) LFS probe, (e) outer divertor probe, and (f) HFS probe, near 1.1 sec.

Figure 6. LH Spectrum measured with the HFS probe measured in the discharge 1120601014. Experimental parameters are listed in Table 1, and the contour of the LCFS is shown in Figure 1.

parametric decay or scattering by turbulence in USN plasmas.

Throughout the 2012 run campaign, no HFS PDI was observed in most of the USN plasmas with the $\vec{B} \times \nabla B$ drift direction downward. The only exception to this
general observation is the plasma discharge (1120610014) shown in Figure 1. In this USN plasma, strong HFS PDI occurred when $n_e > 1.4 \times 10^{20} \text{m}^{-3}$. Figure 6 shows the LH frequency spectrum measured by the inner wall probe. Although it is not clear why HFS PDI is excited in this plasma, as shown in Figure 1 this plasma has a larger elongation than the other USN plasmas, and the shape of the LCFS near the HFS is similar to that of the LSN plasmas. We also note that the sideband corresponding to the LFS PDI (i.e., ion cyclotron PDI occurring at the LFS) is weaker than that observed in the typical USN plasmas.

In the reversed magnetic field and plasma current configuration ($ \vec{B} \times \nabla B$ upward), HFS PDI was observed only in USN plasmas (in these USN plasmas, $n_e$ was below $1.0 \times 10^{20} \text{m}^{-3}$, and the peak amplitude of the sideband was usually 15 dB below that of the pump). LH wave propagation in the LSN plasma with the $ \vec{B} \times \nabla B$ drift direction upward is expected to be similar to that in the USN plasma with the $ \vec{B} \times \nabla B$ downward.

4. Relation to the loss of current drive efficiency

As shown in the previous section, we have compared the LH frequency spectra for various plasmas using Langmuir probes located around the Alcator C-Mod tokamak. We find that different types of non-linear phenomena are detected for different magnetic configurations in L-mode plasmas. In this section, we discuss ion cyclotron PDI occurring at the HFS (HFS PDI) and the correlation between the observed non-linear effects and the loss of current drive efficiency in high density plasmas.

Our measurements show that strong HFS PDI can occur below the traditional limit of ion cyclotron PDI occurring at the LFS (LFS PDI)[5, 6]. The ratio $\omega/\omega_{LH}$ has been used as an indicator of how close the plasma condition is to PDI excitation, where $\omega$ is the operating frequency and $\omega_{LH}$ is the lower hybrid frequency. The frequency $\omega_{LH}$ was often evaluated at the center of the plasma, and strong LFS PDI was observed when $\omega/\omega_{LH}(0) \rightarrow 2[5, 6]$. For the discharge shown in Figure 2, $\omega/\omega_{LH}(0)$ is approximately 3 with $B_T(0) \approx 5.4 \text{T}$ and $n_e(0) \approx 1.8 \times 10^{20} \text{m}^{-3}$.

We observe that, using the above criteria, the local condition near the HFS SOL is more prone to PDI compared with the local condition near the LFS SOL, consistent with our observations in LSN and IWL plasmas. When evaluated using the local density (Figure 7) and magnetic field, $\omega/\omega_{LH}$ at the inner mid-plane LCFS is approximately 3.3 with $B_T \approx 8.1 \text{T}$ and $n_e \approx 1.0 \times 10^{20} \text{m}^{-3}$, whereas at the outer mid-plane LCFS with $B_T \approx 4.1 \text{T}$ and $n_e \approx 0.6 \times 10^{20} \text{m}^{-3}$ it is about 4.7. Thus, the local $\omega/\omega_{LH}$ is lower near the HFS SOL than near the LFS SOL.

In addition, the temperature at the HFS SOL tends to be lower as compared to that at the LFS SOL. Figure 7 (a) shows the SOL density profile both at the high- and low-field side, as a function of $\rho$ (i.e., mapped along magnetic flux surfaces to the outer mid-plane: $R - R_{LCFS}$). Note that lower SOL temperature and higher SOL density at the HFS are due to the presence of a parallel temperature gradient along the open field lines[30]. The growth rate of the ion cyclotron quasi-mode is calculated to decrease with increasing temperature[6].

Reduced convective threshold[6, 11] may also explain the observed strong parametric instabilities at the HFS SOL below the conventional limit. In the plasmas reported in this paper, LH waves tend to propagate around the torus multiple times before absorption by the plasma due to relatively low core temperature ($T_e(0) \approx 2 \text{keV}$). In the multi-pass regime, the pump wave can fill the inner plasma...
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periphery. This effect becomes important when $n_e \geq 1.0 \times 10^{20}\text{ m}^{-3}$ because LH waves start to propagate near the inner plasma periphery more due to the refraction effect ($v_{gi} \approx \omega / k = \omega_{pe} / k$). In addition, the scattering of LH waves by turbulence at the plasma periphery can further broaden the resonance cone[11], so that the pump can fill in the inner edge. Both of these effects can reduce the convective threshold.

Figure 8 shows the frequency integrated spectral power of the pump and the first down-shifted sideband at the HFS and that of the pump at the LFS as a function of $n_e$ when $P_{LH} = 800\text{ kW}$ and peak $n_{||} = 1.6$. Lower $n_{||}$ does not significantly affect the onset of HFS PDI. The strength of the first down-shifted sideband power shows a threshold behavior above $n_e \approx 1.0 \times 10^{20}\text{ m}^{-3}$, similar to the case when peak $n_{||} = 1.9$ (e.g., Figure 2). However, in contrast to the previous case, the strength of the first-downshifted sideband power decreases when $n_e$ is raised above $n_e \approx 1.1 \times 10^{20}\text{ m}^{-3}$. This could be due to a combination of multiple effects such as accessibility condition and different LH wave propagation behavior. We also cannot rule out the possibility that HFS PDI originates toroidally or poloidally away from the location of the probe.

One of the most important questions is whether the observed HFS PDI is responsible for the loss of LHCD at high density. For the LSN plasmas, the HFS probe measurements show the decrease in the pump wave power when HFS PDI becomes strong. For example, Figure 8 shows that the first down-shifted sideband power becomes comparable to the pump power at $n_e \approx 1.1 \times 10^{20}\text{ m}^{-3}$. At the same density, the pump wave power at the HFS starts to decrease, whereas that at the LFS remains nearly unchanged. As shown in the ray trajectory in Figure 1, LH waves are reflected at the HFS before absorbed by electron Landau-damping. Thus, the observed decrease in pump power with the onset of ion cyclotron PDI at the HFS suggests that PDI can be partially responsible for the loss of current drive efficiency, especially in the multi-pass regime. In addition, the onset of PDI activity is observed in the density range where the discrepancy exists between experiments and simulations that do not include any non-linear effects.

HFS PDI may have also played a role in LH current drive experiments in Alcator
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Figure 8. The frequency-integrated spectral power of the pump measured with the LFS probe (black), the pump measured with the HFS probe (blue), and the first down-shifted sideband measured with the HFS probe (red). LSN, $B_{T0} = 5.4$ T, $I_p = 550$ kA, $P_{LH} = 800$ kW, peak $n_{||} = 1.6$.

In this limited tokamak, PDI was observed by RF probes located at the LFS and was characterized by the sidebands modulated by $\omega_{ci}$ at the LFS. In some circumstances, little PDI was detected on the RF probes, even when the electron tail formation was already weak[33]. HFS PDI may be a key to explain those observations. However, it is difficult to quantitatively assess the amount of power loss due to non-linear effects as compared to previously studied loss mechanisms without detailed modeling work. Ray-tracing/Fokker-Planck simulations[1] showed that more than 50 % of launched power should be lost via collisional absorption in the SOL to match the measured non-thermal hard X-ray emission rate. Full-wave simulations[1] predicted a similar level of non-thermal HXR emission rate to that calculated by the ray-tracing/Fokker-Planck simulations, although collisional losses were estimated to be less than 10 % of the total power. Other possible edge loss mechanisms such as ionization in the SOL[34] and the generation of fast electrons in front of the launcher[9] can still be important in high density plasmas. In C-Mod, no detailed study has been performed yet to quantify the amount of power loss due to these processes. Note that measurements in TdeV[35, 36] indicated that at least 10 % of the launched power could be lost via the second process.

In general, our observations show that the strength of ion cyclotron PDI is correlated with the decrease in edge non-thermal ECE and non-thermal HXR emission in each magnetic configuration, but several questions remain. For example, IWL
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...plasmas exhibit stronger non-thermal HXR emission as compared to other single null plasmas[7], although relatively strong HFS PDI is observed (e.g., Figure 4). Moreover, the observed pump broadening at the HFS is more severe than that observed in the single null plasmas, although spectral broadening can degrade the current drive efficiency. Finally, we observe different ion cyclotron PDI behavior between LSN and USN plasmas, yet a similar level of non-thermal HXR emission[7]. When LFS PDI is excited, the sideband power appears to be too weak to cause any significant pump depletion. The probes may not be sensitive enough to detect LFS PDI because this process occurs inside the LCFS and LH sidebands may have damped when propagating toward the probes due to their relatively higher $n_{||}$. However, more experimental work is needed to be conclusive. For example, the use of scattering techniques[6] could identify spatially localized LH spectra inside the LCFS. More modeling work using detailed measurements of local plasma parameters will be necessary to understand the role of the observed non-linear effects (i.e., ion cyclotron sidebands and pump broadening) on the loss of LHCD efficiency in Alcator C-Mod.

5. Conclusion

Ion cyclotron PDI is found to be excited at the inner as well as at the outer plasma edge in the Alcator C-Mod tokamak when $n_e > 1.0 \times 10^{20} \text{m}^{-3}$, depending on the plasma configuration in L-mode plasmas with $\vec{B} \times \nabla B$ drift direction downward. In LSN plasmas, ion cyclotron PDI occurs near the HFS SOL. A decrease in pump power is found to correlate with the onset of PDI. In IWL plasmas, the threshold density for HFS PDI is higher, but, once excited, HFS PDI shows similar behavior as observed in LSN plasmas. In USN plasmas, ion cyclotron PDI generally occurs near the LFS. The observed spectral power of the sideband is not as strong as that of the sideband observed in the LSN plasmas. This dependence of ion cyclotron PDI on magnetic configurations was not reported in the past. Therefore, it should be taken into account when assessing the role of non-linear effects in the observed anomalous loss of LH current drive efficiency.

6. Acknowledgements

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