Lower Hybrid Current Drive Experiments at Reactor Relevant Densities on Alcator C-Mod

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Lower hybrid current drive (LHCD) has been recognized as the most efficient method to drive off-axis current in tokamaks, which can supplement bootstrap current in realizing non-inductive advanced tokamak operations. However, at reactor-relevant densities ($\bar{n}_e > 1.0 \times 10^{20} m^{-3}$), an anomalous loss of current drive efficiency has been observed in L-mode plasmas (T_{e0} ~ 2 keV) on Alcator C-Mod [1]. Such a loss has been attributed to parasitic wave-edge interactions that become particularly enhanced in multi pass absorption regimes [2], unlike in future reactor conditions where the plasma temperature will be much higher and where strong Landau absorption is expected on the first pass. Identified loss mechanisms include collisional absorption [1], wave diffraction effects [2], wave scattering by turbulence [3], ionization [4], and parametric decay instabilities (PDI) [5, 6]. In particular, PDI are identified to occur, not only at the low-field-side (LFS), but also at high-field-side (HFS) in Alcator C-Mod, which can be evidence of weak single pass absorption of the launched LH waves [7]. This paper presents the latest experimental PDI studies on Alcator C-Mod and an experimental plan to measure the instability wavenumber spectra in order to assess the role of PDI on the "density limit", with particular attention given to the location in front of the launcher.

Recent experiments have examined the onset of PDI in high-density plasmas up to $\bar{n}_e \approx 1.5 \times 10^{20} m^{-3}$ with $n_{\|}$ =1.9. In the previous campaign, the density ramp was limited up to $\bar{n}_e \approx 1.2 \times 10^{20} m^{-3}$. In addition to internal Langmuir probes as RF electric probes, an RF magnetic (loop) antenna is also placed outside the vacuum vessel to compare the intensities between magnetic and electric PDI spectra. Experiments are conducted in the reversed field configuration and confirm the previously observed magnetic-configuration dependencies of ion cyclotron PDI at $\bar{n}_e \approx 1.1 \times 10^{20} m^{-3}$. (Note that the reversed-field denotes that the direction of the toroidal magnetic field and plasma current is counter-clockwise when looking down the C-Mod tokamak from above.) For example, ion cyclotron PDI that are excited at HFS (HFS PDI) are observed to be much more intense in upper-single-null (USN) plasmas with the reversed-field (Figure 1) and in lower-single-null (LSN) plasmas with the forward-field. It is expected that LH wave-propagation behaviors

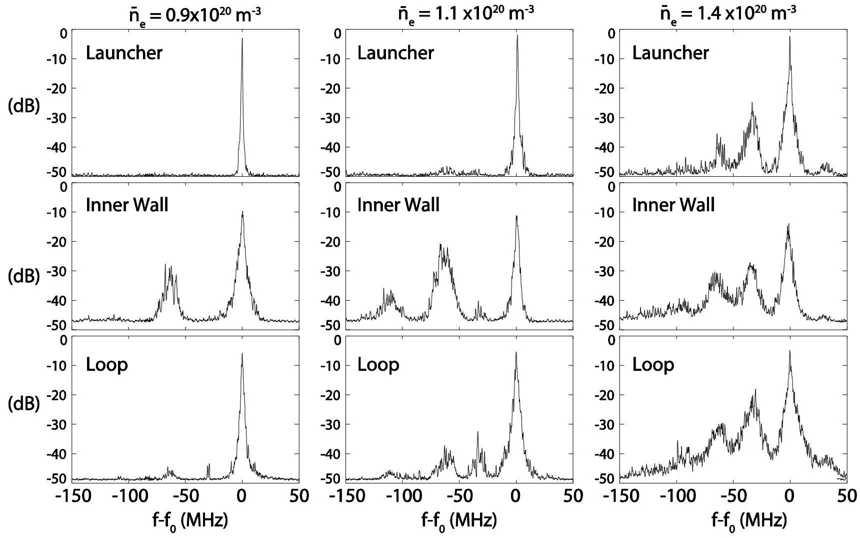

Figure 1. LH frequency spectra at three different densities ($\bar{n}_e = 0.9, 1.1, 1.4 \times 10^{20} m^{-3}$) measured with internal probes at the launcher and inner wall, and with a RF loop antenna placed outside of the C-Mod vacuum vessel. Measurements are performed in upper-null plasmas with the reversed-field configuration. Here, f_0 = 4600 MHz.

in these two plasmas should be symmetrical. As shown in Figure 1, an inner-wall probe detects that the strength of HFS PDI peaks with ω_{ci}~60 MHz at around $\bar{n}_e \approx 1.1 \times 10^{20} m^{-3}$ in contrast to the frequency spectra dominated by LFS PDI (ω_{ci}~ 30 MHz) at high densities. Indeed, the local ω_0/ω_{lh} at the HFS edge is lower than that at the LFS edge due to higher magnetic field, where ω_0/ω_{lh} has been used an indicator of how plasma conditions are susceptible to ion cyclotron PDI, and $\omega_0/\omega_{lh}(0) \approx 2$ has been considered as the PDI limit [5]. Conversely, both LSN plasmas with the reversed-field and USN plasmas with the forward-field tend to exhibit ion cyclotron PDI excited at LFS (LFS PDI) at $\bar{n}_e \approx 1.1 \times 10^{20}\ m^{-3}$. While the reason for the observed configuration dependency is not clear at the moment, complicated toroidal and poloidal variations in edge plasma parameters are expected to play a role. For example, recent measurements with Langmuir probes installed at the upper divertor indicate a different level of densities, depending on magnetic configurations, even when $\bar{n}_e$ remains fixed.

Figure 1 also shows an important experimental result that, when $\bar{n}_e \gg 1 \times 10^{20} m^{-3}$, the ion cyclotron PDI spectra excited at LFS edge is consistent with previous observations on limited tokamaks [6]. As shown in the third column of Figure 1, at high densities, regardless of the location of probes, all probes detect harmonics of sidebands that are displaced by an ion cyclotron frequency corresponding to the magnetic field at the LFS. At high densities, these kinds of instabilities are commonly observed in other magnetic configurations (lower-single-null and double-null plasmas) as well. While this decay process is expected to occur on the first pass from the launcher to the plasma, it is difficult to evaluate how much pump power is lost via this process. Although the density range of interest is well below the classical PDI limit, to further study the role of PDI in Alcator C-Mod, new RF loop antennas will be installed near the LH launcher, which will be further discussed at the end of this paper.

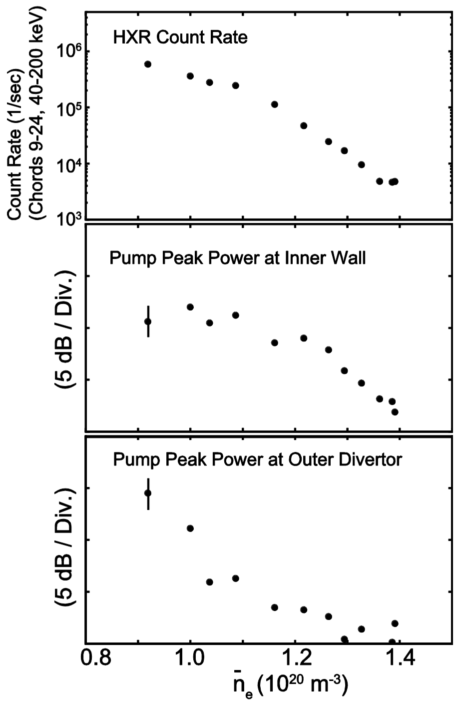

Figure 2. Hard X-ray count rate, pump peak power at the inner wall and at the outer divertor as a function of $\bar{n}_e$ in an LSN plasma with the reversed-field.

While the role of PDI on the loss of efficiency needs further investigation, the pump peak power measurements away from the launcher suggest that Landau absorption should not rely on geometric $n_{||}$ up-shift mechanisms via multiple passes. For example, Figure 2 shows a decrease of hard X-ray count rates as a function of $\bar{n}_e$, which correlates with a decrease in the pump peak power measured at the inner-wall and at the lower outer divertor. The pump peak intensities at the inner wall maintain its strength up to $\bar{n}_e \approx 1.2 \times 10^{20} m^{-3}$, whereas the pump peak power intensities at the outer divertor rapidly decrease above $\bar{n}_e \approx 1.0 \times 10^{20} m^{-3}$. Note that these probes are located at places where LH waves need to propagate across the last-closed-flux-surface more than twice, as evidenced with ray-tracing simulations. Note also that in this LSN plasma, only LFS PDI is observed in the density range of interest. While the decrease in the pump peak power at high densities could be partly due either to the accessibility condition or due to changes in wave propagation direction, these data strongly suggest that most of the launched power could reach at the HFS edge up to $\bar{n}_e \approx 1.3 \times 10^{20} m^{-3}$ without much damping. Given that the pump peak power at the outer divertor decreases rapidly, it appears that parasitic loss mechanisms start to be particularly problematic after the first pass, i.e., after LH waves are reflected at the inner wall. This observation is in line with previous simulation results that collisional absorption becomes severe in multi-pass regimes and/or that wave-diffraction effects strongly up-shift n|| only after the reflection at the inner wall. In addition, although

HFS PDI are not observed in this case, they might have occurred toroidally and poloidally away from the location of the existing inner-wall probe. Thus, it is expected that if Landau absorption is strong enough on the first pass, the current drive efficiency will be recovered to the expected level, because most of loss mechanisms will be avoided. To test this idea, new additional off-midplane launcher [8, 9] is under design in Alcator C-Mod to increase the single pass absorption rate up to 80% at $\bar{n}_e \approx 1.3 \times 10^{20} m^{-3}$. If successful, non-inductive advanced scenarios at reactor-relevant densities will be demonstrated for the first time.

As mentioned above, even in single pass regimes, one of remaining questions is the role of PDI that occur on the first pass. For example, the importance of ion sound PDI in front of the launcher [10] needs to be further investigated due to their possibly low convective losses. Moreover, the single pass absorption regime will allow confirming whether LFS PDI is excited on the first pass and, if so, allow examining quantitatively how much pump power is lost due to ion cyclotron PDI. To this end, as shown in Figure 3, a set of RF internal magnetic probes is being designed and will be installed on Alcator C-Mod to study wavenumber PDI spectra and polarization of decay waves. These probes will be located about 108 degrees toroidally away from the launcher but at a location where they are magnetically connected to the launcher. Together with existing probes, this new diagnostic will help identify how much PDI can degrade current drive efficiency on the first pass. This work is supported by USDOE awards DE-FC02-99ER54512.

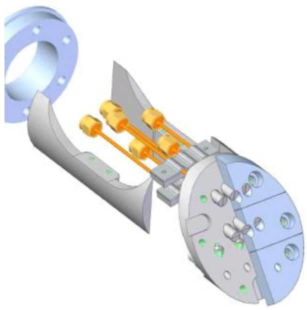

Figure 3. A prototype of a RF magnetic antenna and a drawing of the probe mount for 6 RF magnetic antennas.

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