Lower hybrid current drive at high density on Alcator C-Mod

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The lower hybrid current drive (LHCD) system on the Alcator C-Mod tokamak [1] operates with similar parameters ($B_T = 5.4$ T, $f_0 = 4.6$ GHz, $n_e > 0.5 \times 10^{20}$ m^{-3}) to ITER [2] with the aim of demonstrating advanced tokamak operation under these conditions. Full non-inductive current drive has been realized in diverted discharges at ITER-relevant densities ($\bar{n}_e \sim 5 \times 10^{19}$ m^{-3}). Equilibrium reconstructions constrained by Motional Stark Effect (MSE) measurements of the poloidal magnetic field show $q_{min} \sim 2$ at $r/a \sim 0.25$. Non-inductive discharges with plasma currents of up to 570 kA have been sustained with current drive efficiencies, $\eta \equiv n_e I_p R_0 / P_{LH}$, of $2.0 - 2.5 \times 10^{19}$ AW^{-1}m^{-2}, which is in agreement with the assumed efficiency for ITER of 2.3×10^{19} AW^{-1}m^{-2}.

Non-thermal electron bremsstrahlung, which is used as a proxy for current drive efficiency, falls exponentially as a function of line averaged density in diverted discharges [3] (see Figure 1). This drop in current drive efficiency for diverted discharges occurs at a lower density than anticipated based on earlier high density LHCD experiments in limited tokamaks [4, 5] or by conventional ray-tracing/Fokker-Planck modeling (solid line in Figure 1). Good current drive dependence is recovered for limited discharges on C-Mod above 10^{20} m^{-3} [6]; inner wall limited discharges exhibit HXR emission 2-3 orders of magnitude higher than diverted discharges at $\bar{n}_e = 1.5 \times 10^{20}$ m^{-3}. Operation in double null

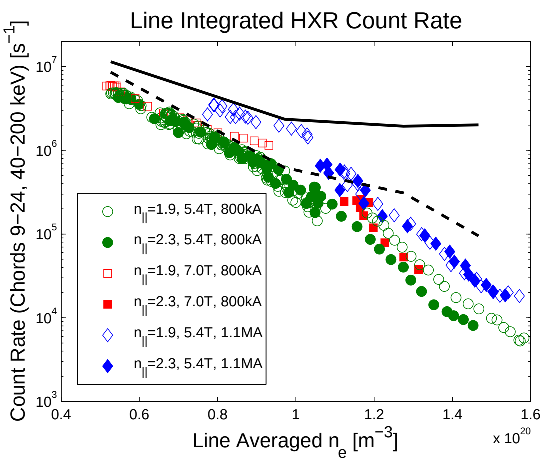

Figure 1: Hard x-rays (HXR) emitted by LH generated non-thermal electrons as a function of line averaged density for diverted discharges. Lines indicate HXR emission predicted by the CQL3D synthetic diagnostic with (dashed) and without (solid) a SOL.

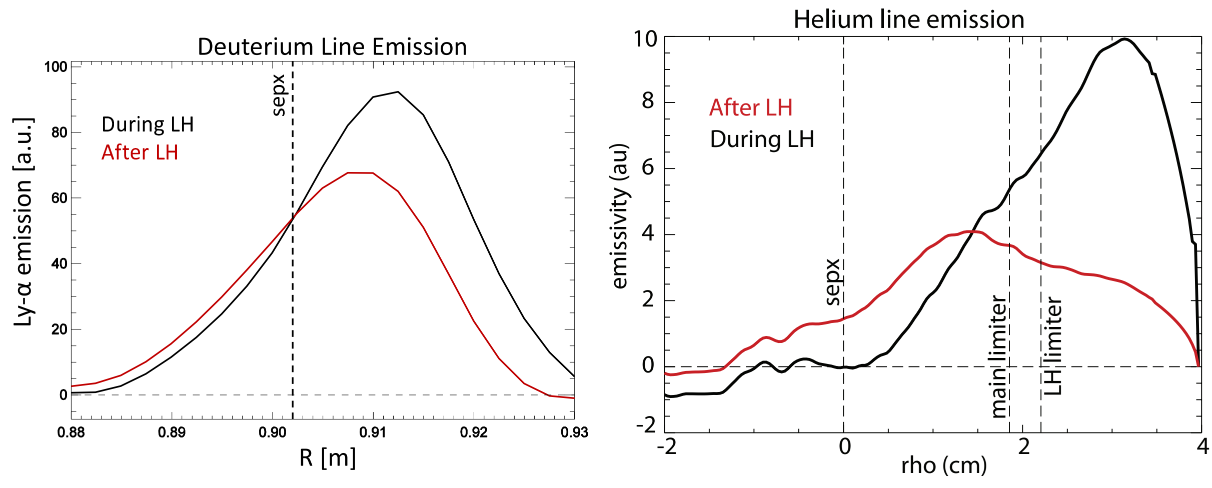

Figure 2: (left) Deuterium line emission (Ly-α) profiles in the SOL for a moderate density ($\bar{n}_e \sim 1.0 \times 10^{20}$ m^{-3}) deuterium discharge with LH. (right) Helium line emission profiles in the SOL for a high density ($\bar{n}_e \sim 1.5 \times 10^{20}$ m^{-3}) helium discharge with LH.

configuration and reducing the gap between the plasma and the inner wall have both been shown to improve current drive efficiency modestly in high density diverted discharges, but not to the level of limited discharges. Operation with hot core plasmas ($T_{e0} = 5-6$ keV) in I-mode has been shown to increase non-thermal electron emission as compared with cooler ($T_{e0} = 2-4$ keV) L-modes at the same density.

Experimental observations indicate that the LH waves are absorbed in the scrape off layer (SOL) above the density limit. Ionization of neutral particles in the SOL appears to be a significant power sink for the LH waves. Figure 2 shows the Abel inverted SOL ionization light profiles for deuterium and helium discharges at moderate to high densities. The total amount of ionization light increases when high power ($P_{LH} > 500$ kW) is on as compared to when there is no LH power. The peak of the ionization light profile also moves farther away from the last closed flux surface (LCFS) when LH is on. The shift in the ionization profile indicates that there is an increase in power dissipation in the far SOL.

The increased ionization during LH extends into the shadow of the main plasma and local LH protection limiters on the LFS. This suggests that the LH waves travel extensively through the SOL, filling the volume bounded by the slow wave cutoff layer (2.6×10^{20}m^{-3} at 4.6 GHz). The increased ionization in the far SOL is also consistent with observations of density increases in the SOL measured with Langmuir probes and an X-mode reflectometer [7]. The measurements in Figure 2 are from toroidal views near the plasma mid-plane on the low field side (LFS) of the tokamak. Assuming that the ionization is uniformly distributed toroidally and poloidally, the increased ionization power in the SOL is several hundred kW (see Figure 3), which is a significant fraction of the net LH power for these discharges. Figure 3 shows that limited and diverted discharges exhibit increased SOL ionization power loss. This may be due to poloidal asymmetries in the SOL ionization profiles which may be more pronounced in diverted configuration.

Although line averaged density and edge neutral pressure are closely correlated, the relationship between the two quantities is quite different for limited and diverted discharges. Fueling efficiency is significantly higher in limited discharges, and consequently the edge neutral pressure is lower for a limited discharge as compared to a diverted discharge at the same line averaged density. Figure 4 shows the line integrated HXR emission as a function of midplane neutral pressure for various plasma configurations. HXR count rates from limited and diverted discharges, which are significantly different when plotted as functions of line averaged density, lie on the same trend line when plotted as functions of neutral pressure. The strong dependence on neutral pressure, combined with the ionization measurements discussed above, point towards inelastic electron-neutral collisions as a probable mechanism for LH power loss in the SOL.

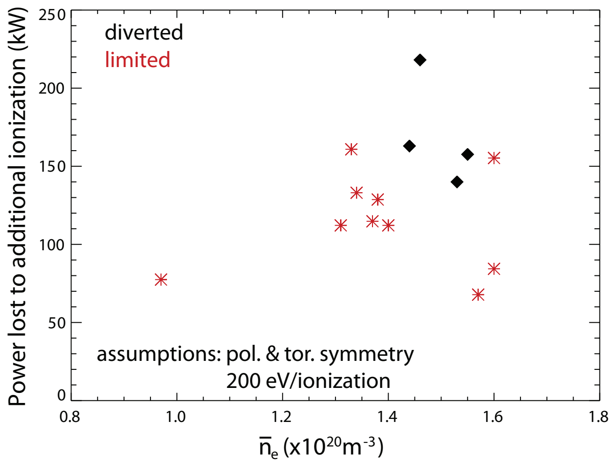

Figure 3: Estimate of additional ionization power loss during LH for helium discharges. Toroidal and poloidal symmetry of the ionization profile is assumed.

Ray-tracing/Fokker-Planck (GENRAY[8]/CQL3D[9]) simulations including collisional absorption in the SOL qualitatively predict the experimental trends for non-thermal electron emission across a wide range of densities ($\bar{n}_e = 0.5 - 1.5 \times 10^{20}$ m^{-3}). Figure 1 shows the HXR emission predicted by the CQL3D synthetic HXR diagnostic for 800 kA, 5.4 T, diverted discharges. Simulations predict higher HXR emission and more driven current for inner wall limited discharges, with good agreement in the shape of the HXR emission profile [6]. Interpretation of simulations and experimental data suggest that the

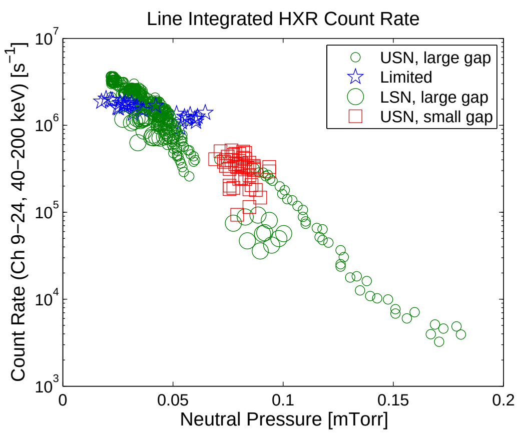

Figure 4: Line integrated HXR emission as a function of neutral pressure measured on the LFS midplane for deuterium discharges.

LHCD density limit on C-Mod is due to strong collisional absorption in the SOL as density increases combined with weak Landau absorption of the LH waves inside the last closed flux surface. Changing the SOL profiles, for instance by operating in limited configuration, can reduce the strength of parasitic absorption in the SOL. Alternatively, increasing single pass absorption may be able to reduce the impact of the parasitic losses in the SOL [10]. This second strategy is of greater interest since future plans for non-inductive operation of C-Mod are aimed at discharges with high temperatures.

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