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Measurement of LHCD edge power deposition through modulation techniques on Alcator C-Mod

I.C. Faust[1], D. Brunner[1], B. LaBombard[1], R. R. Parker[1], S.G. Baek[1], M.A. Chilenksi[1], E. Edlund[2], A. Hubbard[1], J. W. Hughes[1], J. L. Terry[1], S. Shiraiwa[1], J. R. Walk[1], G. M. Wallace[1] and D. G. Whyte[1]

[1]*MIT Plasma Science and Fusion Center, Cambridge, MA USA*
[2]*Princeton Plasma Physics Laboratory, Princeton, NJ USA*

[a)]Corresponding author: faustian@mit.edu

Abstract.
The efficiency of LHCD on Alcator C-Mod drops exponentially with line average density. At reactor relevant densities ($> 1 \cdot 10^{20}$ [m^{-3}]) no measurable current is driven. While a number of causes have been suggested, no specific mechanism has been shown to be responsible for the loss of current drive at high density. Fast modulation of the LH power was used to isolate and quantify the LHCD deposition within the plasma. Measurements from these plasmas provide unique evidence for determining a root cause. Modulation of LH power in steady plasmas exhibited no correlated change in the core temperature. A correlated, prompt response in the edge suggests that the loss in efficiency is related to a edge absorption mechanism. This follows previous results which found the generation of $n_{\|}$-independent SOL currents. Multiple Langmuir probe array measurements of the conducted heat conclude that the lost power is deposited near the last closed flux surface. The heat flux induced by LH waves onto the outer divertor is calculated. Changes in the neutral pressure, ionization and hard X-ray emission at high density highlight the importance of the active divertor in the loss of efficiency. Results of this study implicate a mechanism which may occur over multiple passes, leading to power absorption near the LCFS.

Loss of LHCD efficiency observed at high density

Lower Hybrid radio-frequency power (LHRF) has been used extensively on Alcator C-Mod for the efficient generation of current in diverted plasmas with low to moderate densities. While the system is capable of generating fully non-inductive plasmas [1], at densities of $\bar{n}_e > 1 \cdot 10^{20}$ [m^{-3}] the efficiency of LHCD drops precipitously [2]. This loss of efficiency is matched with a corresponding loss of fast electrons as measured by hard X-ray bremsstrahlung. While a number of causes have been theorized, progress has been made on identifying characteristics endemic to specific mechanisms [3] in order to identify a cause. The change in power balance due to applied LHRF can also provide characteristics for determining the spatial and temporal structure of the power deposition. Through the modulation of the LHRF power it was further validated that power is deposited in the edge plasma or scrape-off-layer (SOL) with no discernable change in the core plasma.

Modulation of LHCD extracts SOL response

Modulation of radio-frequency power has been used extensively for characterizing its deposition in tokamak plasmas [4, 5]. The nearly instantaneous change in power induces a thermal response in the plasma at finite (slower) timescales. This thermal response is dependent on the confinement properties of the plasma and is dictated by the equations of heat-transport. The increase in energy within the plasma is displayed through a local rise in the plasma temperature or particle confinement. The impulse response in temperature can be analyzed using Green's functions with profile diagnostics to provide the spatio-temporal response to the input power.

The physics of fast electrons have also been investigated through the use of power modulation with similar analysis techniques. Rather than characterize the bulk response through the plasma temperature, the effects of the

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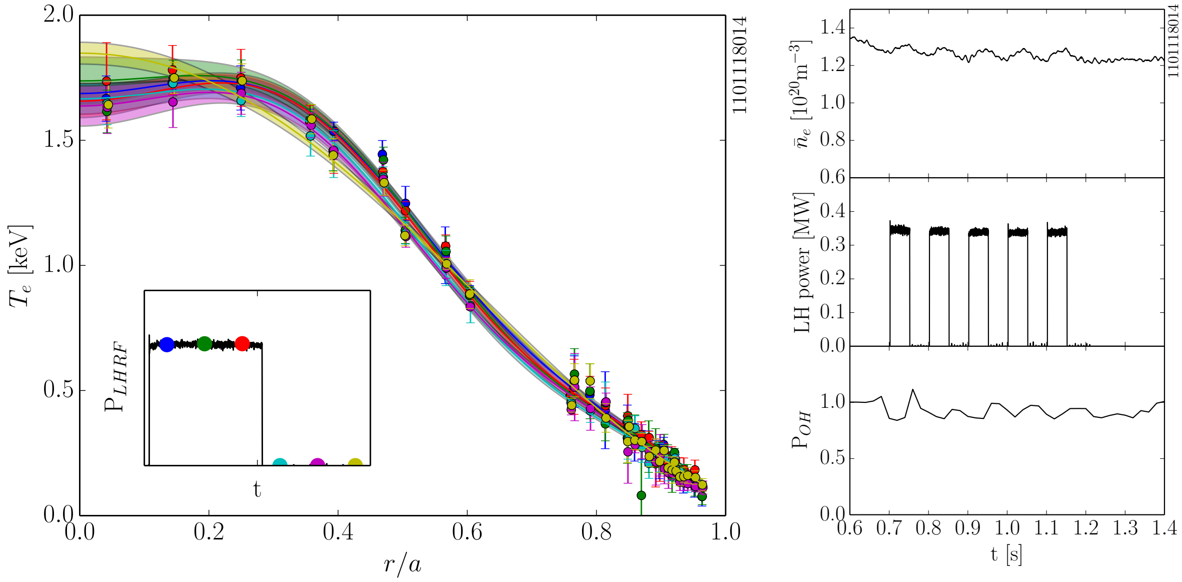

FIGURE 1: Modulation-synced Thomson scattering electron temperature profiles show little to no variation in temperature due to LHRF at high density. Profiles were generated from the average of 5 modulations at 6 times, shown on left inset figure. Weak fitting in the core is due to a small number of constraints in that region. The electron temperature profiles are within error bars of one another and the sawtooth-induced variation is ~200 eV on axis.

LHCD power on high energy electrons can be made by measuring the change in high-energy X-ray emission via bremsstrahlung [6, 7]. The timescales of interest follow the longer fast electron slowing-down, fast electron diffusion and the bulk plasma inductive timescales. At high density, the low X-ray emissivities are a result of a small fast electron population suggesting that the core electron population is thermal.

A similar modulation scheme was used to characterize the effects of LHRF on the thermal electron population near the lower hybrid density limit on Alcator C-Mod. Minimal variation in plasma density and neutron rate were observed which elimated changes in particle confinement and ion temperature as energy sinks for LHRF power. LHRF power was modulated for a range of plasma densities across the efficiency loss threshold. Ensembles of electron temperatures from the Alcator C-Mod Thomson Scattering system [8] were analyzed with Gaussian process regression [9] as a singular modulation. Electron cyclotron emission measurements of T_e were not used due to possible non-thermal contamination.

In the high density regime, as shown in figure 1, the change in the electron temperature profile due to the modulation is within the error of the measurements. The 800 kA discharge had approximately 1 MW of ohmic power with 350kW of modulated power representing a sizeable fraction of the total input power. The negligible core response in the thermal plasma to LHRF matches previous results characterizing the core fast electron content, which suggests that the power is deposited outside the core plasma ($\rho > .95$).

While the LHRF power was not seen in the core in any characteristic population, similar thermal analysis techniques can be used for analyzing the edge plasma. The open-field line nature of the SOL allows for the simplification of the power balance and heat transport equations. The confinement of heat and energy is weaker parallel to the field lines. Subsequently, the timescale of equilibration is shorter to the point of being inconsequential. Sources of power very near or in the SOL appear on various measurements instantaneously which constrasts with the longer diffusive timescales for power from the core plasma. The measurement of SOL deposition can be derived from a simple subtraction rather than from a typical plasma-dependent, time-based spectral approach.

The expected weak confinement and quick response of the edge plasma to edge-deposited LHRF was observed in high density Alcator C-Mod plasmas. As highlighted in figure 2, the edge plasma response to the LHRF became more pronounced with higher line-average densities. Power deposition in the edge greatly affected the SOL plasma and could be measured through a number of diagnostics. These measurements of radiative and conductive losses confirmed that the loss of current drive was through a mechanism which increases in magnitude but does not change

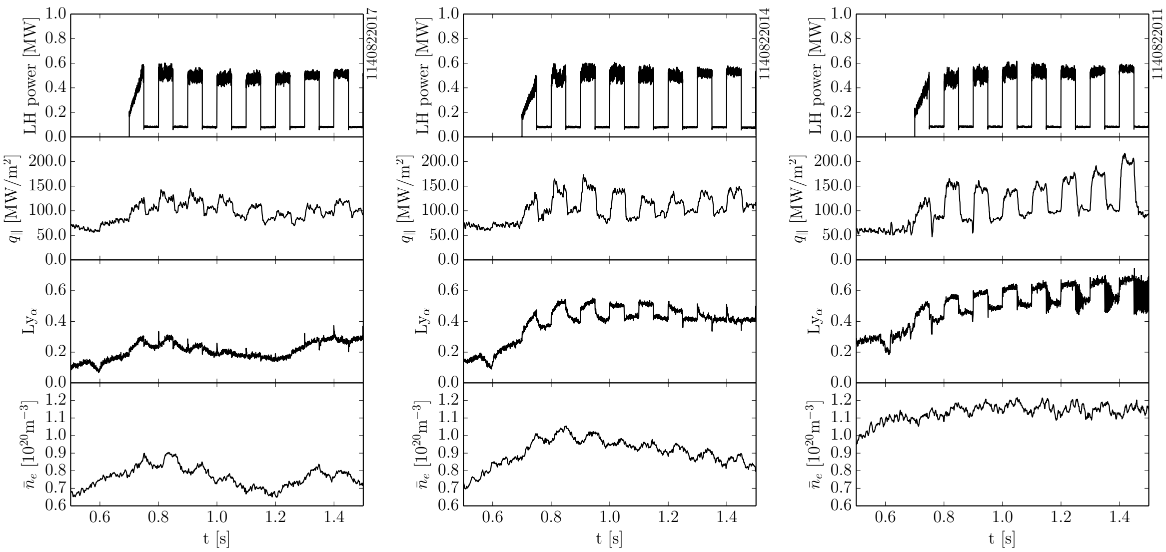

FIGURE 2: Three separate discharges at increasing densities showing the change in edge parameters due to LHRF. The parallel heat flux ($q_{\|}$) is measured near the strike point using a surface thermocouple and the Ly$_\alpha$ measurement views the active divertor. The response in the edge is fast ($t < \tau_E$) and increases in magnitude with rising density.

in response time with increasing density. This suggests that the location of LHRF power deposition was not moving outward radially from the core, but was increasing in importance near the edge. Understanding the power loss via radiation and conduction through modulation is key for determining the to the cause of the LHCD efficiency loss.

The edge radiative response was determined via a poloidally-viewing 22-channel pinhole camera measuring the Deuterium Lyman-α emission. Installed near the LHCD launcher it observes near full coverage of the plasma and both divertors. Lyman-α light is minimally reflective and is directly related to edge ionization processes of the plasma, allowing for local changes in the SOL to be identified. The emission of this light at hight density was most sensitive to LHRF in the active divertor in all diverted configurations (*e.g.* upper single null, lower single null, and double null). While the active divertor is important for fueling and recycling processes, the significant changes caused by LHRF suggests that the active divertor is important in the LHRF edge deposition.

The change in edge ionization near the active divertor measured through Ly$_\alpha$ was also observed through local measurements of the neutral pressure. Using specially designed fast time response Penning ionization gauges, the divertor pressure dropped quickly in response to LHRF power as shown in Figure 3. This pronounced change in divertor neutral pressure was only observable at high densities with low current drive efficiency and corresponded with a slow rise in the average density of the plasma (as measured by interferometry).

The edge LHRF power near the active divertor was also conducted to the divertor surfaces. Previous analysis of divertor Langmuir Probes at high density found the formation $n_{\|}$ SOL currents due to LHRF [2] power. The same Langmuir probes with nearby surface thermocouples [10] were used to analyze the character of the strike point heat flux on the outer divertor. Measurements made in plasmas with the $\vec{B}\times\nabla|\vec{B}|$ drift direction is toward the active divertor found that the change in parallel heat flux due to LHRF became larger with higher density. This trend was also observed in the closely placed Langmuir probes, abruptly stopping with the detachement of the divertor.

This linear nature of the changing heat flux is highlighted in figure 3 and was observed at two toroidally separated locations using Langmuir probes as well as in the surface thermocouple measurements. In contrast, variation in the parallel heat flux due to LHRF radially distant from the strike point was significantly weaker. The LHRF efficiency loss is not caused in the far SOL.

RF power modulation schemes on Alcator C-Mod have been used to great effect to isolate characteristics of the LHRF efficiency loss at high density. No discernable change in the bulk electron temperature was observed in the core, matching similar results for the core fast electron population. The neutral characteristics of the active divertor were found to change with modulated LHRF and significant changes were seen in the conducted power near the strike point. Further characterization of the radial structure of the conducted power to the divertor is key for isolating a root

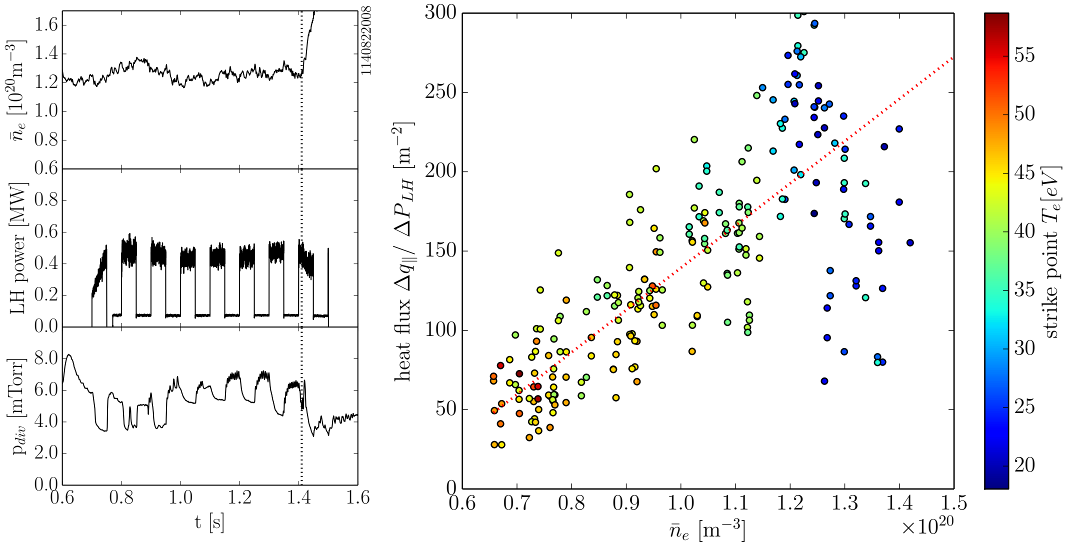

FIGURE 3: On left: Neutral pressure in the active divertor drops due to LHRF power at high density, causing a subtle (~ 10%) rise in line-average density. The rise time in density corresponds to the particle confinement time. H-modes were triggered at densities $> 1.3 \cdot 10^{20}$ [m^{-3}] near the end of pulse, shown by the dotted line. On right: The parallel heat flux due to LHRF near the strike point rises with density, as normalized to the LHRF power. This suggests that the power into the SOL is increasing linearly with higher density. This trend in the heat flux (as measured by a surface thermocouple) stops when the outer leg detaches (shown by the strike point electron temperature, as measured by a toroidally separated Langmuir probe).

cause. Integration of the heat flux can give an absolute measure of the SOL power loss of LHRF and are necessary for accounting for the changes in LHRF deposition. Finally, further work must be taken to understand the importance of the active divertor with respect to LHRF physics.

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