

Current Profile Control Using LHCD in Alcator C-Mod*

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Introduction. Lower hybrid waves are launched into Alcator C-Mod plasmas by means of a grill composed of 88 waveguides arranged in 4 toroidal rows [1]. The grill is nominally powered by 12 klystrons operating at 4.6 GHz and delivers a net power to the plasma of up to 1.2 MW. The primary purpose of lower hybrid wave experiments is to drive off-axis current which, in combination with bootstrap current, should permit access to flat or reversed shear optimized steady-state regimes. The frequency, field (5-6 T), plasma density ($\sim 1.0 \times 10^{20} \text{ m}^{-3}$) and power density ($\sim 30 \text{ MW/m}^2$) compare well with the corresponding parameters envisioned for an LHCD system for ITER. Therefore the results of these experiments, as well as accompanying model development, should be helpful in deciding whether LHCD would be useful in realizing ITER's steady-state aim.

A key aspect of these experiments is the capability to influence the driven current profile by means of varying the parallel index of refraction n_{\parallel} of the LH waves; as is well known, the latter is instrumental in determining the penetration of LH waves into the plasma, where they damp and drive current, and the overall current drive efficiency. In the C-mod experiment, n_{\parallel} can be varied from 1.6 to 3.1 within a time interval of 1 ms, thus enabling dynamic control of j_{\parallel} . In this paper we report on first results of measurements of current profiles and their time evolution following turn-on of the LH power. In addition we report on new results concerning rotation in LH-driven plasmas and LH -assisted enhanced H-modes.

Current Density Profiles. A systematic scan of current density profiles was carried out as a function of the launched n_{\parallel} over the range $1.6 < n_{\parallel} < 3.1$. Measurements of the mid-plane pitch angle of the magnetic field were made with an 8-channel MSE system which monitors emission from a nearly perpendicular diagnostic neutral beam. Traces from two typical discharges are shown in Figure 1, and the raw data showing the change in pitch angle due to the applied LH power in the case of the discharge shown in figure on the left is shown in Figure 2. The diffusion of current after the application of the LH power with a time constant of ~ 100 -200 ms is apparent from the MSE traces. As expected, the current density takes a

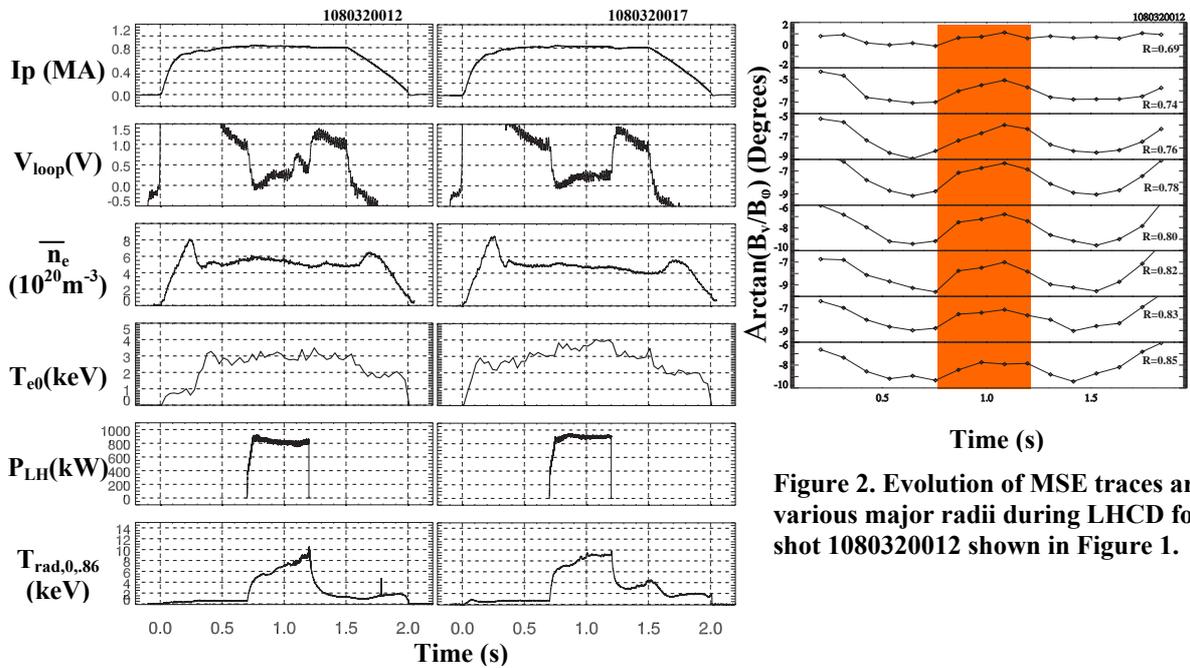


Figure 2. Evolution of MSE traces at various major radii during LHCD for shot 1080320012 shown in Figure 1.

Figure 1. Development of key parameters during LHCD

longer time to come to equilibrium in the core. MHD activity often occurs during these current drive shots. In discharge 1080320012, a 2/1 tearing mode developed and at least temporarily arrested the further development of the RF driven current as can be seen from the MSE measurements and the sudden rise in the loop voltage at ~ 1.1 s.. An indication of the MHD activity can be seen on the nonthermal ECE emission shown on the bottom trace. Although the emission frequency corresponds to that of a thermal plasma at $R=0.86$ m, the ECE signals in Figure 1 are due to relativistically downshifted nonthermal emission from fast electrons at smaller major radii.

Current profile and other equilibrium parameters have been evaluated using EFIT. The flux functions p' and FF' were respectively modeled by second and third degree polynomials in ψ , and the poloidal field on the midplane was constrained by the MSE measurements. Results for the current density, central q and internal inductance are shown in Figure 3. The increase in the central q -value above one is consistent with stabilization of the sawtooth instability, although some questions remain concerning the exact time at which this occurs. It can be seen that the lower value of $n_{||}$ was more effective in broadening the profile. Higher values, e.g., $n_{||} = 2.3$ and 2.7 had a less dramatic effect on the profile. They also tended to produce higher levels of tearing mode activity. Because the method used to analyze the equilibrium profiles is based on low-order polynomial models for j_{ϕ} , it cannot produce the structures that might be expected to occur based on simulations. An alternative approach is to reconstruct the

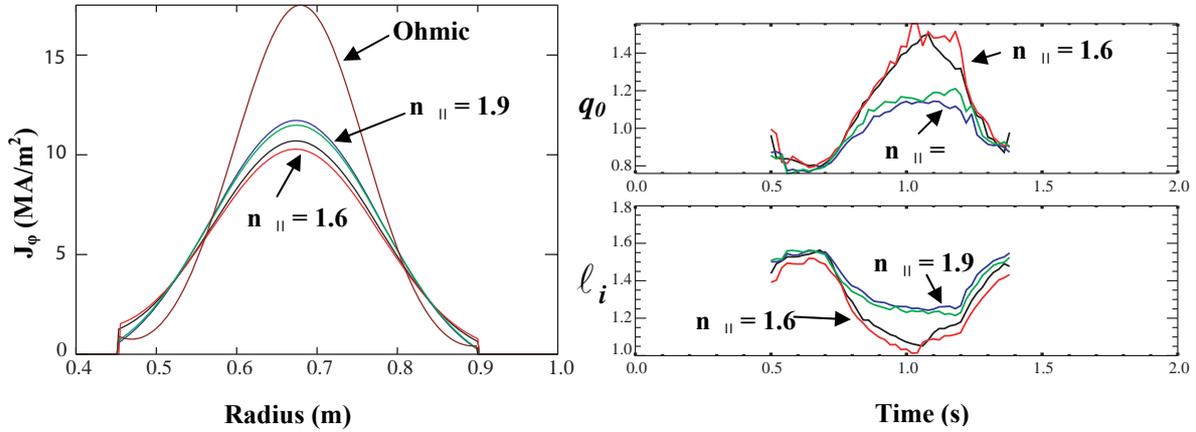


Figure 3. Current profiles for shots with $n_{\parallel} = 1.6$ and 1.9 derived from MSE constrained EFIT reconstructions (left) and time traces of central safety factor and internal inductance (right).

profiles directly from the MSE profiles [2]. Following this procedure, one does in fact recover j_ϕ profiles with more structure, but then the results are sensitive to the accuracy of the MSE profiles. This is clearly an important problem to resolve in order to validate the simulations, whether based on ray-tracing or full-wave simulations.

Rotation. When LH waves drive current in the direction of the inductive current, the plasma is observed to develop rotation in the counter-current direction. This is in contrast to the usual situation in C-Mod, in which rotation is in the co-current direction. The LH induced rotation can be substantial, with counter rotation speeds up to 40 km/s having been observed, and with net changes of rotation speed of up to 60 km/sec. The change in rotation typically develops on the resistive relaxation time scale, as can be seen in the example shown in Figure 4 where the evolution of the central rotation is compared with that of the internal inductance. The rotation tends to be localized to the plasma core, within $r/a \leq 0.5$. Some peaking of temperature and density profiles is also observed during the spin up, suggestive of formation of a weak ITB [3]. The mechanism leading to the counter rotation is under investigation. One possibility is associated with the reduction in the inductive electric field [4].

Coupling to ICRF Heated Plasmas. Lower hybrid waves have been successfully coupled to discharges with ICRH heating in both H- and L-Mode confinement regimes. There are 3 ICRF antennas in Alcator C-Mod situated in ports located 30°, 60° and 210° from the LH antenna port, where the angles are defined in the clockwise direction looking from the top of the machine. The antennas located at 30° and 60° are magnetically connected to the grill, and coupling of LH waves is generally poor when these antennas are energized. Fortunately, the third antenna is in normal discharge conditions not magnetically connected to the grill and reasonably good coupling of LH waves is achieved when that ICRH antenna is powered up to

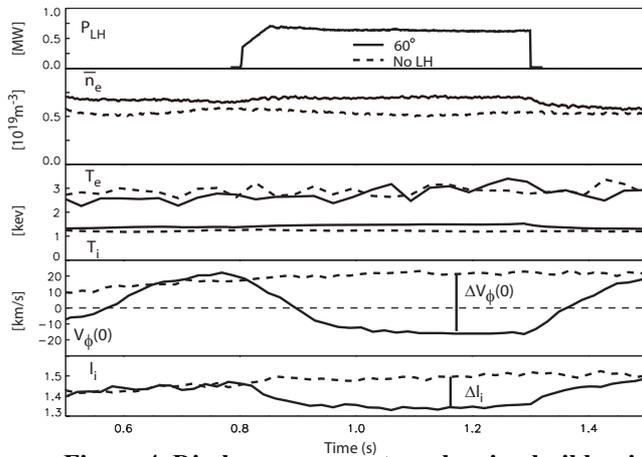


Figure 4. Discharge parameters showing buildup in central rotation during LHCD.

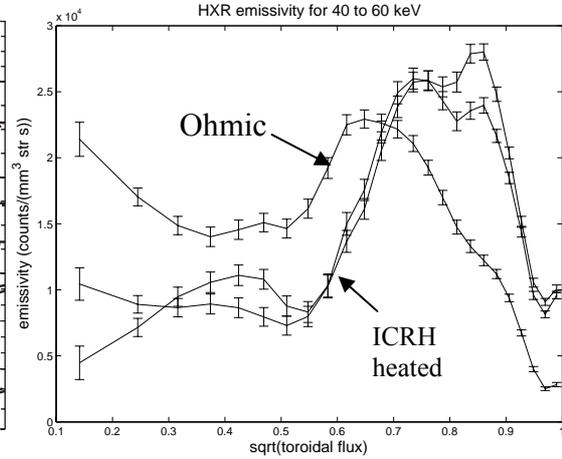


Figure 5. X-ray profiles with and without ICRH.

levels of at least 2 MW. In a plasma with Maxwellian electrons, absorption of LH waves is predicted to occur via Landau damping where the temperature is $T_e(\text{keV}) \sim 30/n_{||}^2$.

Consequently applying ICRH to raise the electron temperature should move the absorption region further toward the plasma edge. In fact this is observed as illustrated by the example shown in Figure 5 where the peak x-ray emissivity measured with an imaging spectrometer is seen to shift toward the plasma edge as a result of increasing T_e with ICRH. Thus localization of the fast electron population, and presumably the driven current is determined by the temperature profile together with the value of the parallel index of refraction.

Application of sufficiently high power ICRH in Alcator C-Mod results in a transition to H-Mode with a rise in density. At the high densities normally found in H-Modes at 5.4 T, $n_{||} > 2.3$ is required and the current drive efficiency, which in any case varies as n_e^{-1} is low.

While we have not driven significant current in H-Mode plasmas, an interesting effect in H-modes has been found, namely modification of the pedestal parameters leading to a decrease in pedestal density and an increase in pedestal (and core) temperature with increased $T_e(0)$ and W , as shown in Figure 6.

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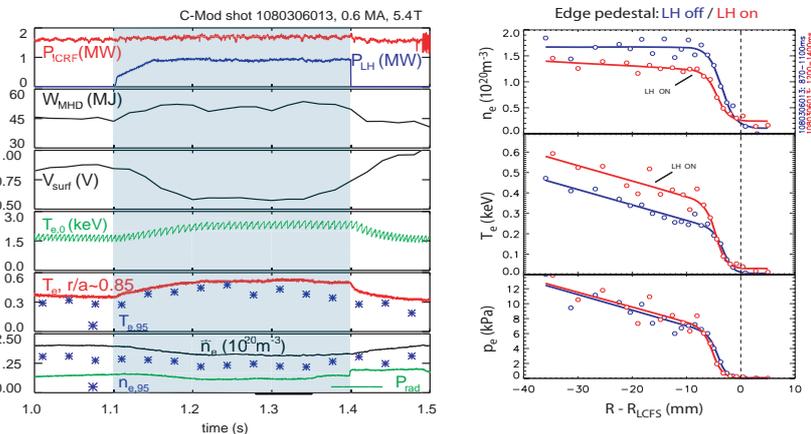


Figure 6. Traces of an LH improved H-mode (left) and effect of LH on pedestal profiles (right).