Achieving steady-state regimes with LHCD in Alcator C-Mod

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Introduction. The objective of Lower Hybrid Current Drive (LHCD) experiments on Alcator C-Mod is to develop optimized steady-state tokamak regimes in which ~ 50% of the current is due to the bootstrap effect while the remainder is driven by LH waves. The flexibility of LH waves to affect the current profile through the control of the launched index of refraction as well as the parameters of the target plasma provide an opportunity to study transport and stability of ITER-relevant steady-state regimes. C-Mod LHCD experiments are particularly relevant to ITER as they operate at essentially the same field, density and LH frequency. In the near term, studies of LH wave interactions in C-Mod are also providing a basis for using LHCD to extend the pulse length in the superconducting Asian machines, namely EAST and KSTAR.

Current profile modification. Using a 4x16 waveguide array, over 1 MW of RF power in the lower hybrid frequency range (4.6 GHz) has been injected into C-Mod plasmas. Fully non-inductive discharges have been obtained with $\bar{n} = 0.5\text{x}10^{20}\ \text{m}^{-3}$, $I_p = 0.5$ MA and $B_T = 5.4$ T. Figure 1a shows an example of such a discharge. Sawteeth are completely suppressed in these discharges and, as shown in Figure 1b, EFIT profiles constrained by Motional Stark Effect measurements of B_{pol}/B_{tor} have modestly reversed shear, with $q_0 \sim 2$ and $q_{min} \sim 1.5$. The overall engineering current drive efficiency is $\eta = 2\text{-}2.5\text{x}10^{19}\ \text{A/m}^2\cdot\text{W}$, in line with values derived in scoping studies which motivated the C-Mod LH experiments [1] and found in ITER simulations.

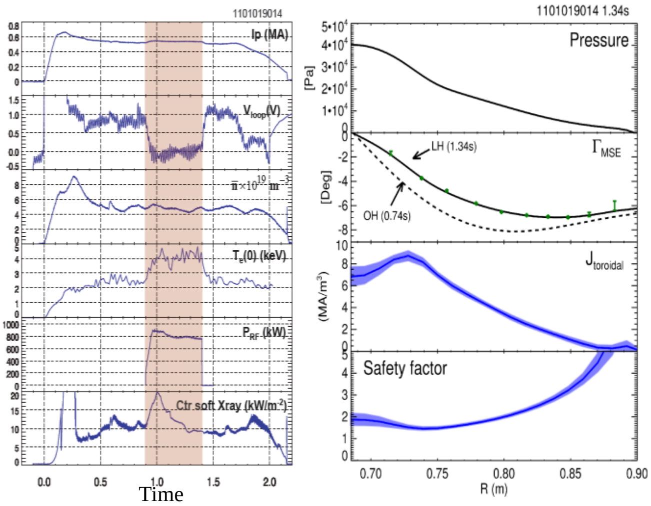

Figure 1. a) time traces showing the development of zero loop voltage duirng application of 800 kW LH pulse. b) Radial profiles of pressure, change in MSE-measured field angle, toroidal current density and safety factor.

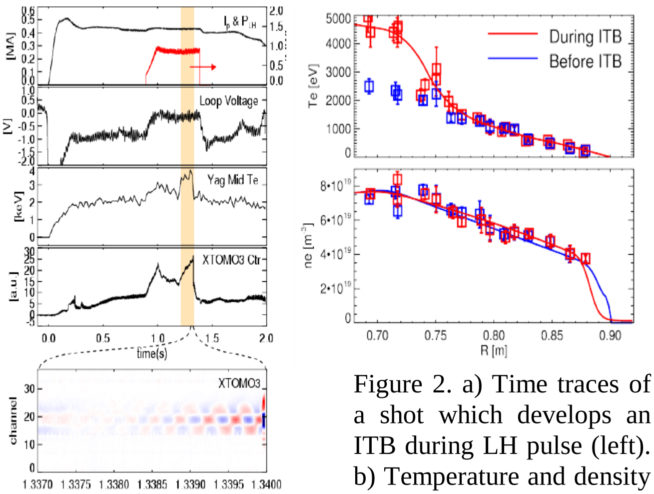

Figure 2. a) Time traces of a shot which develops an ITB during LH pulse (left). b) Temperature and density profiles before and during an ITB phase (above).

In some discharges an ITB forms in the electron temperature profile as shown in Figure 2a. However the ITB's obtained thus far terminate due to the growth of a 2/1 tearing mode. Even without the development of an ITB, control of MHD activity through optimization of the current profile is a key challenge. Near term plans call for adding a second LH launcher which will bring the coupled power to ~ 2 MW. Exploiting the ability to vary the relative power between the launchers and to launch separate spectra should provide a higher degree of control of the current profile and enhance prospects for accessing regimes with improved MHD stability.

Loss of efficiency at high density. Accessing ITER relevant steady-state regimes with f_{BS} ~ 50% in C-Mod will require increasing the density to $\bar{n}$ ~ 1.5x10^{20} m^{-3} with $T_{e0} \geq$ 5 keV. Target plasmas with these parameters have been produced in C-Mod both by mode-converted ICRF heating as well as by operating in I-Mode [2]. In Ohmically heated plasmas with T_{e0} ~ 2 keV it has been found that the LHCD efficiency drops precipitously as the density is increased above $\bar{n}$ ~ 1x10^{20} m^{-3}, even though the density remains well below the conventional limit set by either accessibility or parametric decay [3,4]. This falloff with density has been explored with two newly developed and independent simulations, one based on ray-tracing which takes into account collisional processes taking place in the SOL, the other based on an FEM full-wave model [5] which includes collisional absorption in the SOL but in addition removes uncertainties inherent in the WKB approximation [5,6]. An example of the results from the full wave code is shown in Figure 3 [7], where it can be seen that at high density power is absorbed mainly in the plasma periphery, and therefore by relatively high $n_{||}$ waves with low current drive efficiency. Notice also that especially at high density the waves extend beyond the separatrix and well into the divertor region. Both ray-tracing and full wave simulations indicate that interactions in the edge and/or SOL can lead to a loss in efficiency, either by direct collisional absorption or by causing an up-shift in the parallel index of refraction which leads to Landau damping at high $n_{||}$ near the separatrix and low efficiency. Although both ray-tracing and full-wave simulations partially explain the loss of current drive efficiency at high density, neither model exhibits the almost threshold-like way in which the efficiency, heating and fast-electron Bremsstrahlung disappear above $\bar{n}$ ~ $1\text{x}10^{20}$ m^{-3}.

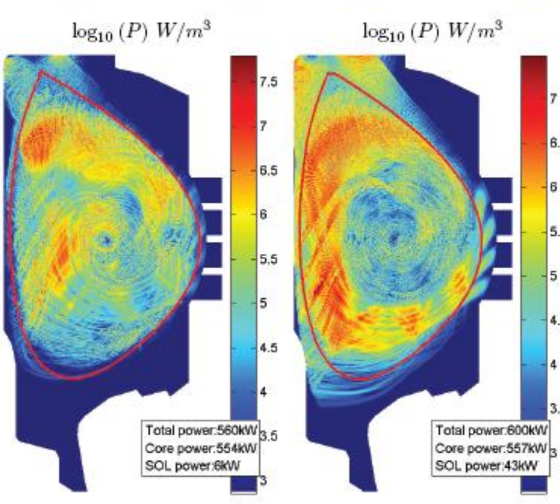

Figure 3. Contour plots of the absorbed power density resulting from full wave simulations using the LHEAF FEM code [7]. a) n = $7\text{x}10^{19}$ m^{-3} (left). b) n = $1.3\text{x}10^{20}$ m^{-3} (right).

Spectral Measurements. The strong interactions near the inner SOL and separatrix have motivated measuring wave fields there using probes mounted on the inner wall. Results obtained are shown in Figure 4 where at the higher density vigorous Parametric Decay Instability (PDI) activity is seen, i.e., the growth of sidebands (only the first downshifted sideband is shown) and simultaneous depletion of the pump, which corresponds to the LH waves applied by the launcher. The sideband frequency is displaced from the launcher frequency by approximately the ion cyclotron frequency at the *inner* separatrix. What is particularly interesting about this result is that the spectra observed at the launcher grill shows an almost undetectable sideband at the lower density and one that is still more than 40 db smaller than the launcher peak at the higher density. The peaks observed at the grill occur at the same frequency as observed on the inner wall probe. Thus it can be concluded that the PDI observed at the grill is due to local nonlinear interactions of the LH waves near the inner separatrix, and possibly in the inner SOL. These are very recent observations and more detailed measurements of SOL profiles and spectra, and theoretical interpretation [8], are in progress.

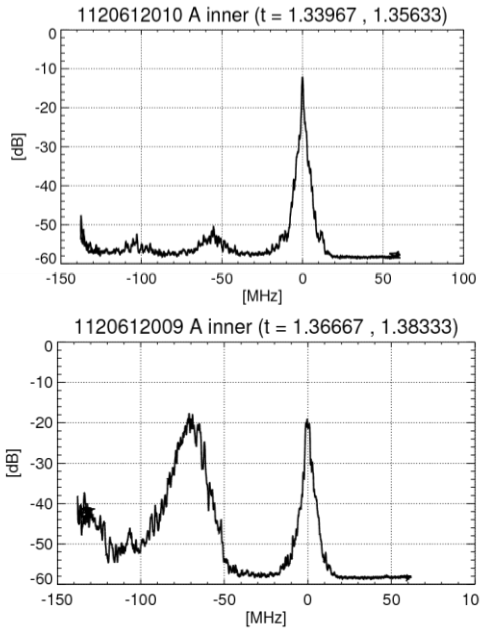

Figure 4. Wave spectra observed using a probe mounted in the inner wall. a) n = $8.5\text{x}10^{19}$ m^{-3} (top). b) n = $1.1\text{x}10^{20}$ m^{-3} (bottom).

Restoring high-n efficiency Although only the PDI process has the threshold-like behavior of the "density limit", all three mechanisms discussed above can play a role in the deterioration of LH current drive efficiency at high density in C-Mod. Multiple passes through the separatrix and SOL and divertor, where collisional absorption can take place, and reflections from the wall and divertor regions leading to significant $n_{||}$ upshifts must be avoided. Thus future experiments in C-Mod will emphasize regimes and approaches which favor strong "single-pass" damping, i.e., where the launched LH waves deposit most of their power in the core before reaching the inner separatrix as they traverse the plasma cross-section. For typical ray trajectories this requires operating in regimes in which $T_{eo} > 5$ keV. Experiments aimed at verifying the importance of enhancing single pass absorption by raising the central temperature have been carried out in mode-converted ICRF-heated He discharges with a ^{3}He minority. The production of hard x-rays from super-thermal electron Bremsstrahlung has been compared with a synthetic diagnostic embedded in the CQL-3D simulation and, as shown in Figure 5, reasonable agreement was found at densities up to $\bar{n}$ ~$1.6\text{x}10^{20}$ m^{-3}.

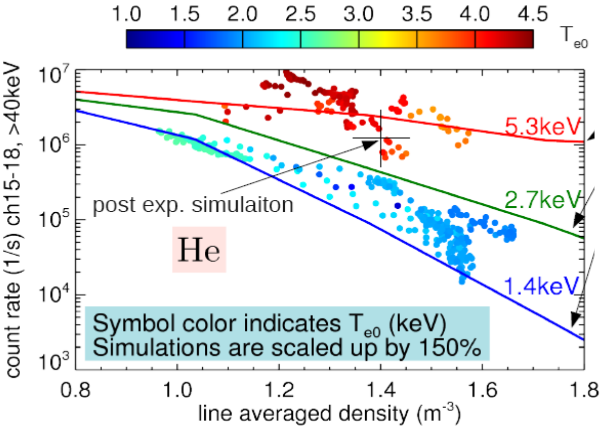

Figure 5. Fast electron Bremsstahlung vs. density with temperature as a parameter in mode-converted He discharges

As mentioned above, plans for C-Mod LH experiments call for adding a second launcher which would increase the coupled power to ~ 2 MW. This launcher, called LH3, will be located mainly above the plasma midplane in order to reduce the effect of the $n_{||}$ downshift that occurs when LH rays propagate toward the inner wall in the lower half of the plasma cross-section [9]. Modeling has shown that an important synergy can occur between waves launched by LH3 and those from the present launcher, LH2, which is approximately symmetrically located with respect to the mid-plane, as waves from LH3 create a tail in the electron distribution function which then forms a target for rays from LH2 to damp on. The flexibility of two launchers with ~ 2 MW of injected power will be vital for further development of steady-state regimes in C-Mod.

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