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Modification of Current Profile, Toroidal Rotation and Pedestal by Lower Hybrid Waves in Alcator C-Mod

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Abstract. Recent results from the lower hybrid current drive experiments on Alcator C-Mod are presented. These include i) MSE measurements of broadened LHCD current profiles; ii) development of counter rotation comparable to the rate of injected wave momentum; iii) modification of pedestals and rotation in H-mode; and iv) development of a new FEM-based code that models LH wave propagation from the RF source to absorption in the plasma. An improved antenna concept that will be used in the upcoming C-Mod campaigns is also briefly described.

Keywords: Lower hybrid current drive; rotation in toroidal plasmas; plasma wave simulations

PACS: 52.35.Hr, 52.55.Wq

Introduction

The main motivation for launching lower hybrid (LH) waves in Alcator C-Mod is to drive off-axis current in order to broaden the current profile and produce optimized low shear q-profiles with good confinement at near-steady-state (non-inductive) conditions. While the primary purpose of these experiments is to develop attractive scenarios for steady-state operation, a secondary goal has been to understand and develop detailed aspects of the physics and technology of lower hybrid current drive (LHCD), with a view toward its potential application in ITER.

Current drive efficiencies of $\eta = n_{20}IR/P \approx 0.3 \text{ A/m}^2\text{W}$, in line with those found in other LHCD experiments, have been obtained in low density L-Mode plasmas in C-Mod and have been previously reported^{1,2}. In recent campaigns several new results have been obtained and they are the main subject of this paper. They include: i) first measurements in Alcator C-Mod of poloidal-field profile modification by MSE, which are used to infer development of LH driven current profiles; ii) observation of strong counter-current rotation of the core plasma during LHCD, with buildup rate consistent with the rate of momentum injection by the LH waves; iii) LH wave modification of H-mode pedestals with a trend toward improved confinement, and iv) development of a finite element code that seamlessly treats the propagation of lower hybrid waves from the sources and waveguides feeding the grill to where they are absorbed in the plasma.

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Description of the Alcator C-Mod LH System

Lower hybrid waves are injected into Alcator C-Mod plasmas by a 4X22 wave guide grill^{3,4} shown in the photo in Figure 1. Power is supplied by a bank of 12 klystrons operating at 4.6 GHz and capable of steady-state operation at a power of 250 kW. These klystrons were manufactured by Varian 30 years ago, and have been previously used to supply power for both the Alcator C and PBX-M lower hybrid experiments. The waveguides forming the grill are 5.5 X 60 mm² in cross-section and are separated by a 1.5 mm septum. Ceramic windows are brazed into the waveguides at a position well inside the location of the ECH resonance. Dynamic phase control allows the launched $n_{||}$ spectrum to be varied from 1.5 to 4 during a pulse, with the best directivity obtained at the lower end of this range. The global reflection coefficient is typically in the range 15- 30%, depending on $n_{||}$ and the position of the grill with respect to the edge plasma. Up to 1.2 MW have been injected into Alcator C-Mod plasmas with this grill. A new grill with improved power handling capability and lower loss transmission system has been developed and will be installed and operated during the upcoming 2009 campaign. The main features of the new grill and coupling system are described in the last section of this paper.



FIGURE 1. Photo of grill used in Alcator C-Mod LHCD experiments

Modification of Poloidal Field and Current Profile by LHCD

Measurements of the poloidal field using the Motional Stark Effect have been difficult to make in Alcator C-Mod plasmas, largely owing to the machine's compact construction and poor beam penetration. However, thanks to a continued strong effort over several years the MSE diagnostic has now become operational and has produced the first measurements in C-Mod of poloidal field, current profile and electric field modification during LHCD experiments⁵. Figure 2a shows a typical Alcator C-Mod plasma with LH power applied. The raw changes in pitch-angle of \vec{B} on the mid-plane measured by MSE during a lower hybrid pulse are shown in Figure 2b. In this discharge, the sawtooth instability is stabilized as the current profile broadens and the central current density decreases, causing $q(0)$ to rise above unity. However, MHD activity identified as a 2/1 tearing mode develops late in the LH pulse as the current profile continues to broaden, consistent with Δ' becoming positive. Current density profiles have been reconstructed both by direct calculation from MSE data⁶ using Ampère's law and by using the MSE data and the location of the sawtooth inversion radius when the plasma is sawtoothing to constrain an EFIT equilibrium reconstruction. The former method generally exhibits more structure than the latter, partly due to the necessity to take derivatives of the MSE signals and partly due to the

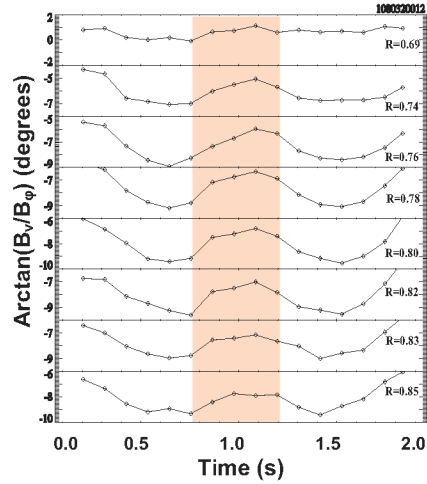
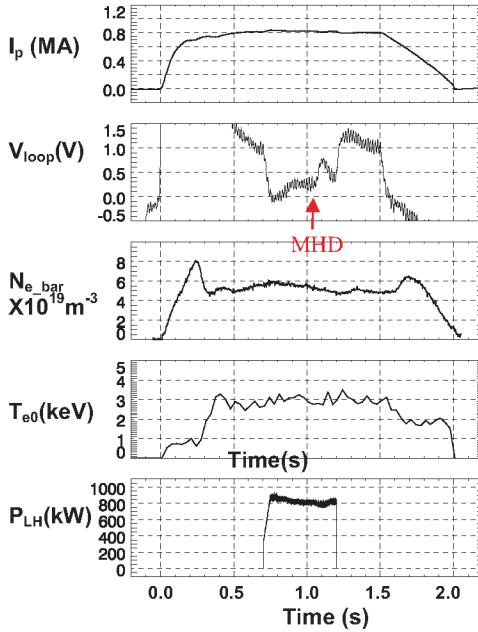


FIGURE 2. a) Traces of a typical LHCD shot (left); b) corresponding traces of pitch angle of the field on the midplane (right).

smoothing inherent in EFIT due to the use of low-order polynomials to model the p' and FF' profiles. Here we give only examples of the results using EFIT.

Figure 3 shows the EFIT-derived current profiles for two plasmas during LHCD compared with an inductive profile derived from EFIT. Clearly, LHCD is effective at broadening the current density profile for the low applied values of $n_{||}$ corresponding to the experimental conditions. At these applied values of $n_{||}$ analytic estimates as well as simulations indicate that an upshift in $n_{||}$ by a factor of ~ 2 is required for efficient

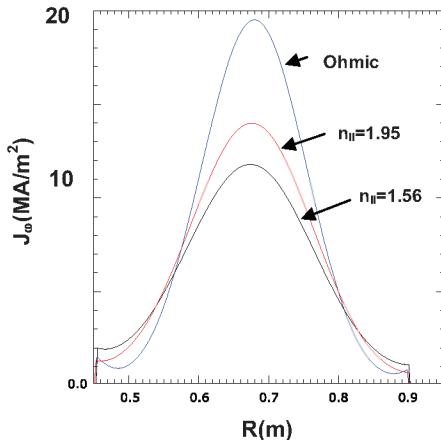


FIGURE 3. Current Profiles. The $n_{||}=1.56$ profile corresponds to the discharge in Figure 2a.

absorption; thus these discharges are likely to be in the multipass regime where the LH waves reflect from the plasma edge before being absorbed. The total current inside and outside the (arbitrarily chosen) normalized radius $r/a = 0.44$ is shown in Figure 4, from which it is seen that in this regime LHCD is effective at broadening the current profile. For higher values of $n_{||}$ full-wave simulations and ray-tracing indicate that the LH waves are absorbed in a single pass, consistent with conclusions derived from ray-tracing. Experimentally, the driven current is more peaked and located closer to the magnetic axis in the single pass regime, e.g., $n_{||} \sim 2.5$, and is less efficient at driving current and broadening the current profile as seen in Figure 5.

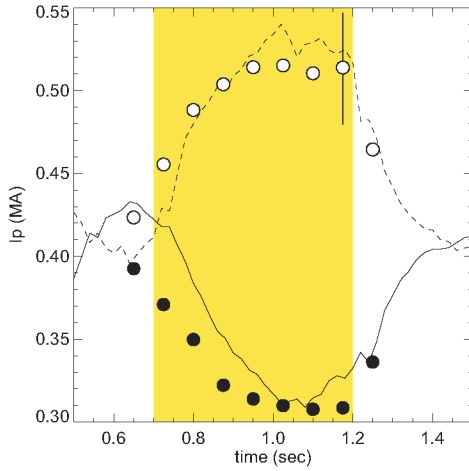


FIGURE 4. Time development of the current outside (upper curve) and inside (lower curve) the normalized radius $r/a=0.44$. The dashed and solid curves are from EFIT, the circles are from direct reduction of MSE data⁶.

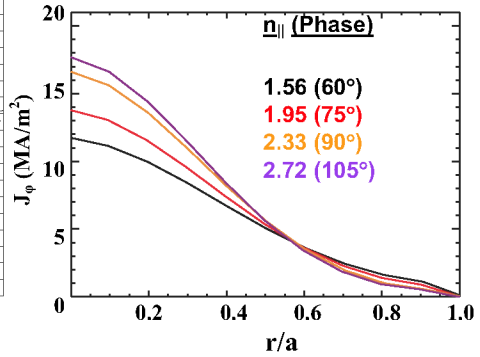


FIGURE 5. Current profiles for various values of the launched parallel index of refraction. The discharges for all cases are similar to that shown in Figure 2a.

Toroidal Rotation

Toroidal rotation in Alcator C-Mod plasmas is determined by measuring the Doppler shift of highly ionized Ar x-ray lines. Counter rotation changes of up to 60 km/s have been observed when lower hybrid current drive is applied^{7,8}. An example taken from a discharge similar to that shown in Figure 1 but with $P_{LH} = 600$ kW is shown in Figure 6. Radial force balance implies the existence of a radial electric field which in this case approaches -20 kV/m. The rotation is largely confined to the core and develops on the resistive time scale, which suggests that it may be associated with the replacement of the inductive component of current by that due to the RF drive.

The mechanism for core rotation in the presence of LHCD is not understood, but it is interesting to note that in cases with strong rotation the rate at which toroidal momentum is

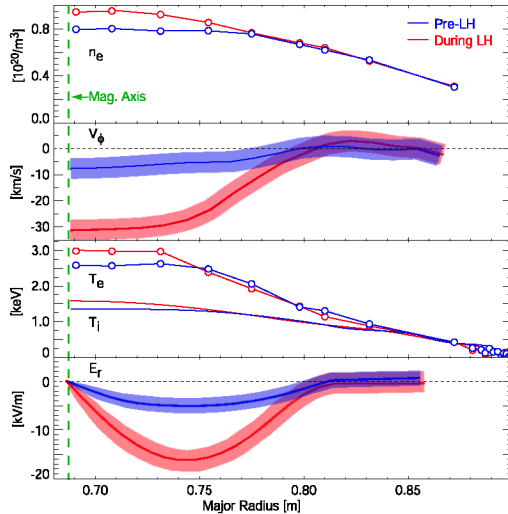


FIGURE 6. Example of LHCD-induced rotation. (Reproduced with permission from A. Ince-Cushman, et.al., PRL 102, 035002 (2009))

injected by the waves is comparable to the initial rate at which plasma toroidal momentum increases when LH waves are applied. For example, using $\dot{\vec{g}} = -\nabla \cdot \vec{\hat{t}}$ where \vec{g} is the wave momentum density and \hat{t} is the stress tensor⁹ $\frac{W}{\omega} \vec{k} \vec{v}_g$, we find by integrating over the torus cross-section

$$\dot{G}_\varphi = \oint dA \hat{\varphi} \cdot \vec{\hat{t}} \cdot \hat{\varphi} = \oint dA \hat{\varphi} \cdot \left[\frac{W}{\omega} \vec{k} \vec{v}_g \right] \cdot \hat{\varphi} = \frac{n_\varphi}{c} P_\varphi$$

where P_φ , the wave power in the φ direction, is approximately equal to the total injected power. For $P_\varphi = 1$ MW and $n_\varphi = 2$ we find $\dot{G}_\varphi = 6.7 \times 10^{-3}$ N, a value that is comparable to the rate of momentum buildup in low density L-mode plasmas with these LH parameters. This also corresponds to the rate at which the fast current carrying electrons (with energy of ~ 100 keV) lose momentum to the ions which suggests that the injected wave momentum is adequate to explain the source of the rotation drive.

A mechanism for creating a radial electric field in the plasma has been suggested by Fisch¹⁰ and involves the trapped particles. Wave momentum absorbed by the trapped electrons results in an inward pinch, similar to the Ware pinch except that the waves act only on the trapped electrons, and only over the part of their orbit where they are resonant with the wave phase velocity. Evaluating the change in canonical angular momentum over a bounce orbit, we can estimate the inward pinch velocity of a trapped electron to be $v_r \approx \langle \dot{p}_\varphi \rangle / eB_p$. Assuming roughly equal populations of trapped and untrapped particles where the RF current is generated results in an estimate of the pinch velocity of ~ 0.7 m/s. Evaluation of the transport of fast electrons by an analysis of the energetic bremsstrahlung dynamics¹¹ yields a pinch velocity of order 1 m/s, which is consistent with this estimate.

The inward pinch of the trapped electrons constitutes a radial current which must be balanced by the neoclassical polarization current, leading to a radial electric field which may play a role in the rotation. Quantitatively, this yields a build up rate of the radial electrical field that is comparable to observation. Whether the rotation is the result of direct momentum transfer of wave momentum to electrons and then ions, which requires a radial electric field by force balance, or whether it is *due to* a radial electric field caused by inward pinching electrons, the ion momentum must reach a steady-state, presumably via an effective ion viscosity.

Modification of H-Mode Pedestal

As mentioned in the introduction, good current drive efficiency has been obtained in L-mode plasmas. In Alcator C-Mod H-modes, the density rises to values typically in excess of $1.5 \times 10^{20} \text{ m}^{-3}$. While significant driven currents in excess of 100 kA would be expected at this density, no measurable current has been observed. Although the rate and energy spectrum of bremsstrahlung emission is in the range predicted by GENRAY-CQL3D simulations at lower density, fast electron bremsstrahlung

emission at $n = 1.5 \times 10^{20} \text{ m}^{-3}$ is also well below that predicted by the simulations. Thus we are led to consider a density limit, which occurs well below that expected for pump depletion by parametric decay instability¹².

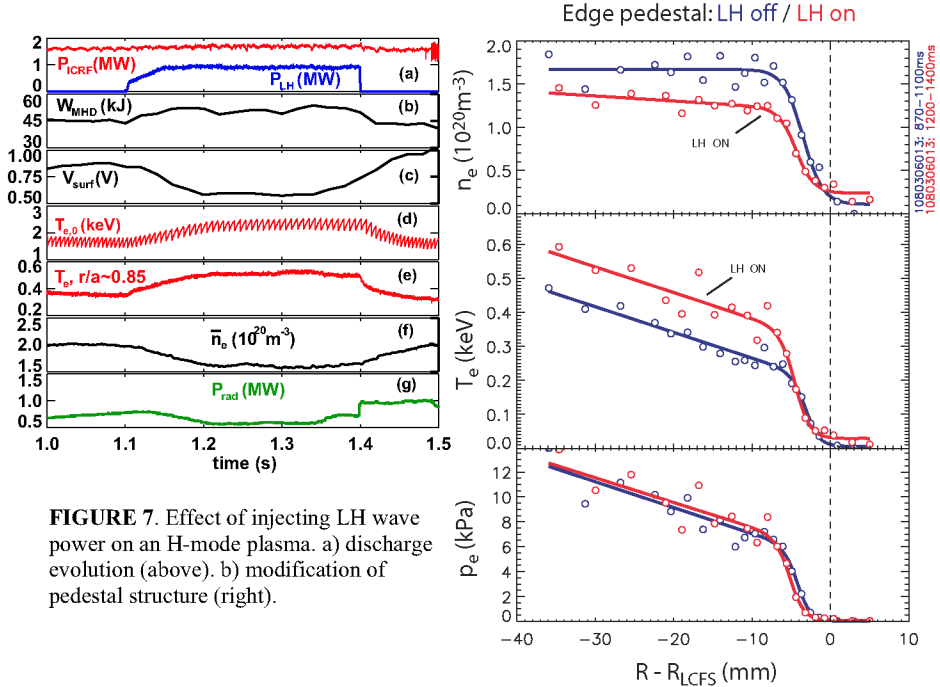


FIGURE 7. Effect of injecting LH wave power on an H-mode plasma. a) discharge evolution (above). b) modification of pedestal structure (right).

Even though the usual signs of LHCD are absent at high density, a new effect has been observed, namely a modification of the H-mode pedestal. The main effect is associated with a broadening of the pedestal density profile and a corresponding increase in the pedestal temperature as shown in the data presented in Figure 7. The pedestal pressure is nearly unchanged, or possibly slightly increased, and similarly for the confinement time. In addition to these effects, there is an increase in toroidal plasma counter rotation in the pedestal, followed by a larger counter rotation change in the core, similar to the ΔV_0 found in L-mode. The cumulative effect of LHCD counter rotation and ICRH-induced co-rotation⁸ can apparently be superimposed and together offer a path toward simultaneous optimization of confinement and rotation profile.

Simulations

The standard simulation tool used to model LH wave physics is ray tracing, e.g., GENRAY, usually combined with a Fokker-Planck code such as CQL3D. This approach has been used extensively to model and predict results of the LH experiments in C-Mod. However, ray tracing is deficient in its ability to handle reflections at cutoff layers, at caustics where the component of the wave vector perpendicular to the flux surface changes sign, and regions of steep gradient. In order to improve the accuracy of the simulations, recent emphasis in modeling C-Mod LH

experiments has been placed on the development of full wave codes which do not suffer from ray-tracing defects¹³. This is particularly important where relatively weak single pass absorption is expected.

In a new development, an FEM code based on the COMSOL Multi-physics Package has been successfully used to solve Maxwell's equations with a plasma model appropriate for LH waves¹⁴. Landau damping has been added to an otherwise cold plasma model by recognizing that the usual description of damping involving k_{\parallel} implies convolution along the field lines of the electric field with the inverse Fourier transform of ε_{zz} , the parallel-parallel component of the dielectric tensor. The model has been applied to both weak and strong single pass absorption and shown discrepancy with ray tracing only in the latter case. An example of a full wave calculation in the case of damping with a Maxwellian distribution function is shown in Figure 8. An extension to treat a self-consistent evolution of the distribution function, is under development and preliminary results have been obtained¹⁵.

An advantage of the FEM approach is that it seamlessly treats the problem of wave propagation from a convenient reference plane in the waveguides that feed the grill (or indeed starting at the microwave sources) to the region of the plasma where the waves are absorbed. Thus there is no need to use a separate coupling code to describe the launching of the LH waves from a realistic antenna, and propagation through the SOL and pedestal is self-consistently treated.

New Coupler Design

The power available for the LH experiments described here has been limited by the relatively low efficiency of the transmission system that powers the grill. Part of the loss has been attributed to the laminated plate construction of the feeding waveguides, another to the magic tees, power splitter and 3 dB coupler used to divide the power from each klystron into 8 separate waveguides. In order to improve the overall coupling efficiency, a novel power splitting system has been developed. The key element is the a 4-way H-plane slot coupler shown in Figure 9. While the principle of operation of this coupler is not new, the ability to design it with sufficient accuracy has only relatively recently been made possible thanks to accurate numerical calculations of the solutions to Maxwell's equations. In our case, the main design tools used were the RF code CST combined with TOPLHA, an extension of the TOPICA

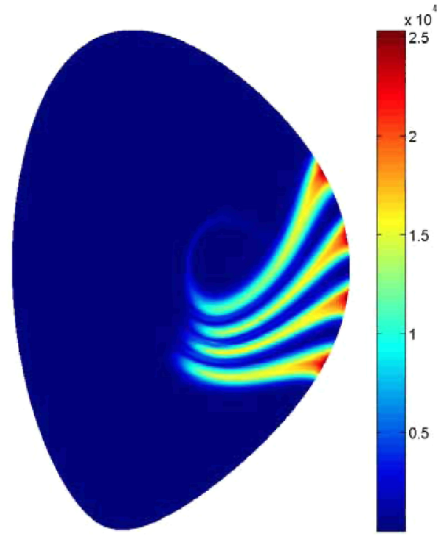


FIGURE 8. Full wave simulation of propagation of LH waves into a C-Mod plasma. Parameters are $n_0 = 5 \times 10^{19} \text{ m}^{-3}$, $T_{e0} = 2.5 \text{ keV}$, $n_{\parallel} = 2.5$. An 800 kA, 5.4 T EFIT equilibrium was used.

code for coupling LH waves^{16,17}. In the case of the new design, a transformer is used to match the sub-height waveguide at the entrance to the 4-way splitter. Each output then feeds one waveguide in a stack of four which form a single column. One nice feature is that a mismatch in any waveguide reflects only 25% of its power back to the feed guide; the rest of the reflected power is shared among the three other guides. Thus, seen from the feeding guide, the overall system is expected to be reasonably load tolerant. Other technical features of the new antenna system include individually brazed vacuum windows, and a transition to conventional C-band waveguide at the input to the splitter using a step transformer.

The schedule calls for the new coupler and grill to be installed during the 2009 run campaign. With the improvements, the maximum transmitted power should increase to ~ 1.5 MW. A second coupler of the same design and additional klystrons, will bring the LH source power to 4+ MW in 2011.

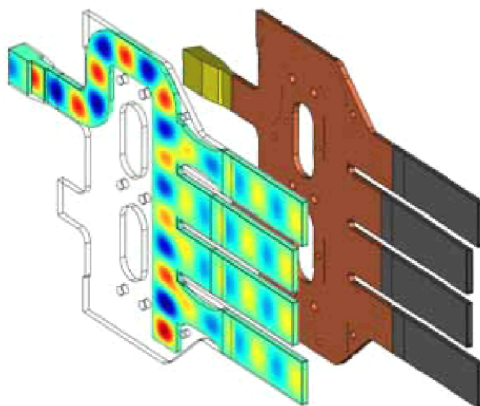


FIGURE 9. The four-way H-plane slot coupler which will be used in a new LH antenna for Alcator C-Mod.

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