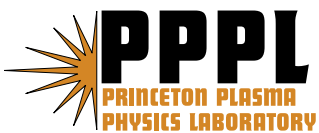# Princeton Plasma Physics Laboratory

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# Lower Hybrid Current Drive Experiments in Alcator C-Mod

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**Abstract.** A Lower Hybrid Current Drive (LHCD) system has been installed on the Alcator C-MOD tokamak at MIT. Twelve klystrons at 4.6 GHz feed a 4x22 waveguide array. This system was designed for maximum flexibility in the launched parallel wave-number spectrum. This flexibility allows tailoring of the lower hybrid deposition under a variety of plasma conditions. Power levels up to 900 kW have been injected into the tokomak. The parallel wave number has been varied over a wide range, $n_\parallel \sim 1.6\text{-}4$. Driven currents have been inferred from magnetic measurements by extrapolating to zero loop voltage and by direct comparison to Fisch-Karney theory, yielding an efficiency of $n_{20}IR/P \sim 0.3$. Modeling using the CQL3D code supports these efficiencies. Sawtooth oscillations vanish, accompanied with peaking of the electron temperature ($T_{e0}$ rises from 2.8 to 3.8 keV). Central q is inferred to rise above unity from the collapse of the sawtooth inversion radius, indicating off-axis cd as expected. Measurements of non-thermal x-ray and electron cyclotron emission confirm the presence of a significant fast electron population that varies with phase and plasma density. The x-ray emission is observed to be radialy broader than that predicted by simple ray tracing codes. Possible explanations for this broader emission include fast electron diffusion or broader deposition than simple ray tracing predictions (perhaps due to diffractive effects).

**:** Lower hybrid current drive, tokomak, rf heating.
**PACS:** 52.50.Sw, 52.55.Fa,

## INTRODUCTION

A lower hybrid current drive (LHCD) system has been installed on Alcator C-Mod in order to drive off-axis plasma current, with the eventual goal of achieving steady state current profiles suitable for advanced tokamak scenarios. The system as presently constituted consists of twelve 250 kW CW 4.6 GHz klystrons feeding a waveguide launcher composed of four rows of 24 waveguides (96 total). Each klystron feeds two columns of four waveguides. An elevation view of the launching structure is shown in figure 1. Two sections of 25 horizontally stacked plates form the feeding structure. Included in the stacked plates are the final power split and phase compensating tapers. Provision is also made for probes to measure the forward and reflected power, potentially in all waveguides. The vacuum windows (96 of them) are contained in the front coupler section. They are brazed directly into the four stainless steel couplers. All waveguide gaskets are in air. Further details can be found in refs. 1 and 2. A

manually adjustable high power phase shifter sets the phase between the two columns of waveguides. The phase between klystrons is set electronically and can be varied on a sub millisecond timescale during the rf pulse. This set-up allows a very flexible control of the launched wave spectrum, even without adjusting the manual phase shifters. Experiments have been performed primarily over an $n_{\parallel}$ range of 1.6 - 4. Power levels up to 1 MW have been injected into C-Mod plasmas. Initial experiments have concentrated on verifying that the system performs as anticipated and on learning to operate it into C-Mod plasmas.
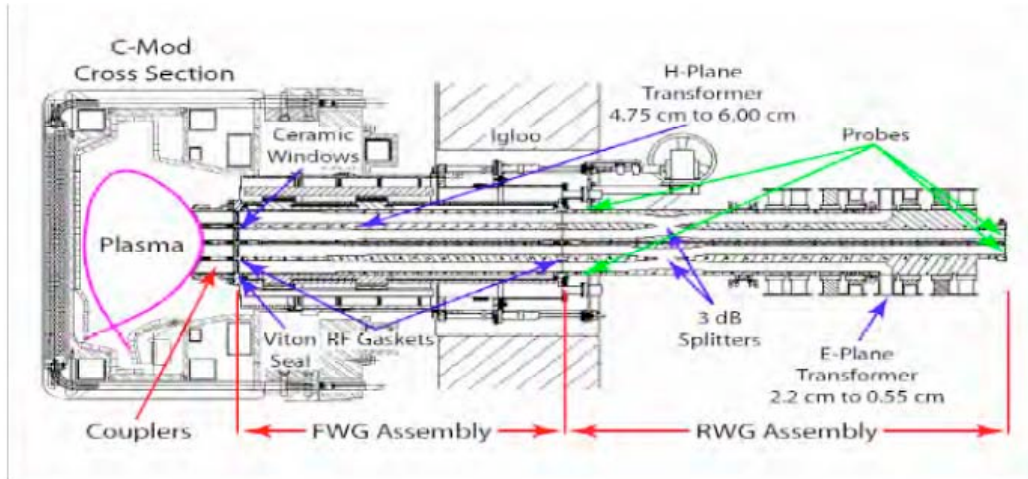


**Figure 1.** Elevation view of Lower Hybrid launcher on Alcator C-Mod

# INITIAL RESULTS

Initial experiments applied power into low density, 4-10 x $10^{19}$ m$^{-3}$, diverted L-mode plasmas looking for signs of current drive. Decreases in loop voltage and increases in electron temperature as well as non-thermal electron cyclotron emission (ECE) and x-ray s were observed, all growing larger with increased power (fig. 2).

## Current Drive Efficiency

The loop voltage is seen to decrease with increasing rf power at constant density and current. A plot of loop voltage drop versus normalized power is shown in figure 3 for a variety of shots over a range of plasma parameters. Surprisingly, a nearly linear increase in $\Delta V/V$ is seen with power. Usually a "turning-over" of the loop voltage drop is seen as full current drive is approached. It is believed that some of this straightening of the curve is due to the increase of plasma background temperature as the power is raised. This increase in temperature should push the lower hybrid deposition location further out in radius to a region of lower density, allowing more current to be driven. In order to get the best measurement of the efficiency of driven current it is necessary to have a condition of zero loop voltage for a time sufficient for
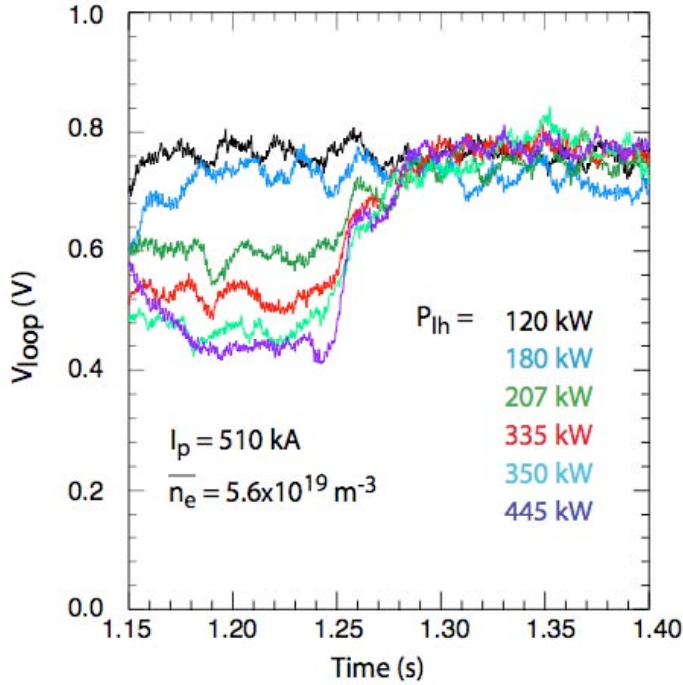
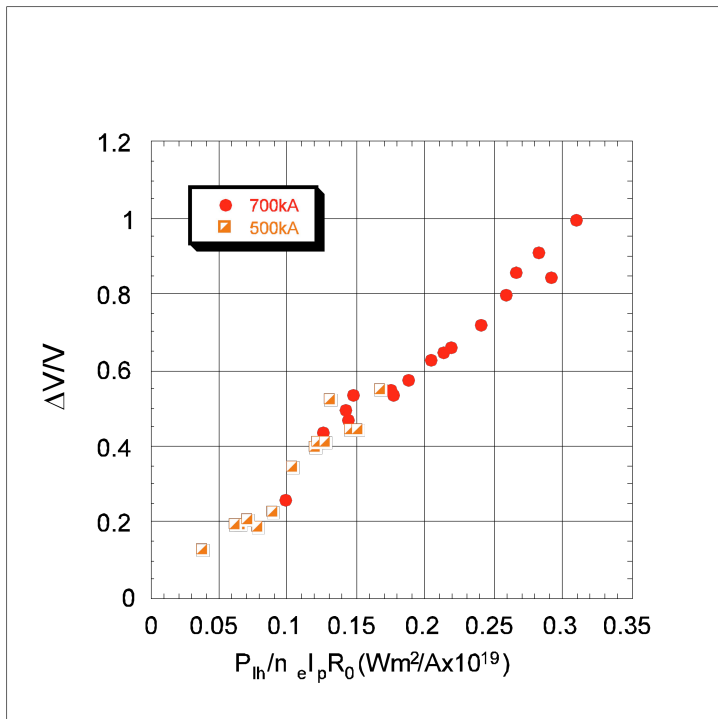**Figure 2.** Decrease of Loop Voltage with increasing LH power



**Figure 3.** Change in loop voltage versus normalized power for a range of parameters $3.5 < n_e < 7 \times 10^{19}$ m$^{-3}$, $0.5$ , $I_p < 1$ MA, $120 < P_{lh} < 830$ kW.

the current profile to relax. On C-Mod, no such condition has been achieved to date. In the absence of this data there are two methods that can be used to estimate the current drive efficiency. The first method was proposed by Giruzzi[3] and makes the assumption that the plasma current is composed of three pieces, an underlying ohmic piece proportional to the loop voltage and independent of the rf power, an rf part proportional to the lower hybrid power and independent of the loop voltage and a non-thermal component proportional to both the voltage and lower hybrid power. With these assumptions it can be shown that the change in loop voltage can be written as :

$$-\frac{\Delta V}{V} = \frac{\left(\eta_0 + \eta_1\right)x}{1 + \eta_1 x}$$

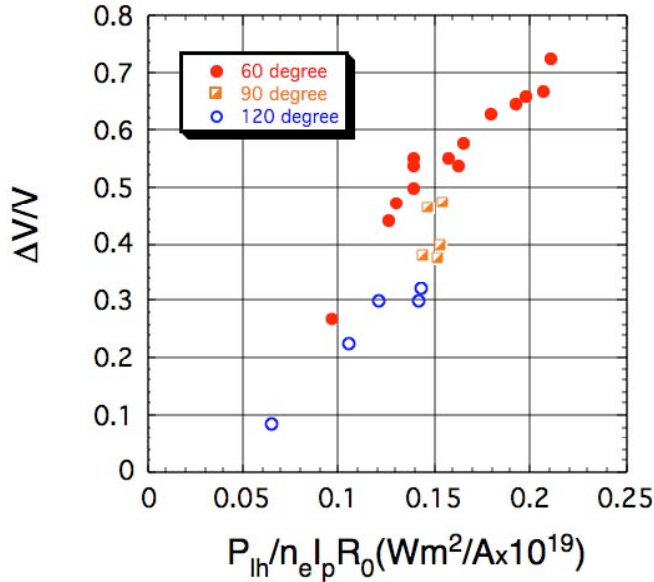where $\eta_0$ is the efficiency, $\eta_1$ is related to the non-thermal conductivity and x= $P_{lh}/n_e I_p R_0$ is the normalized power. A fit to the data is then performed and $\eta_0$ and $\eta_1$ are obtained. In order for this method to yield useful results the underlying ohmic conductivity should be a constant i.e. $n_e$, $T_e$

**Figure 4.** Loop voltage versus normalized power for three different launched $n_{||}$'s
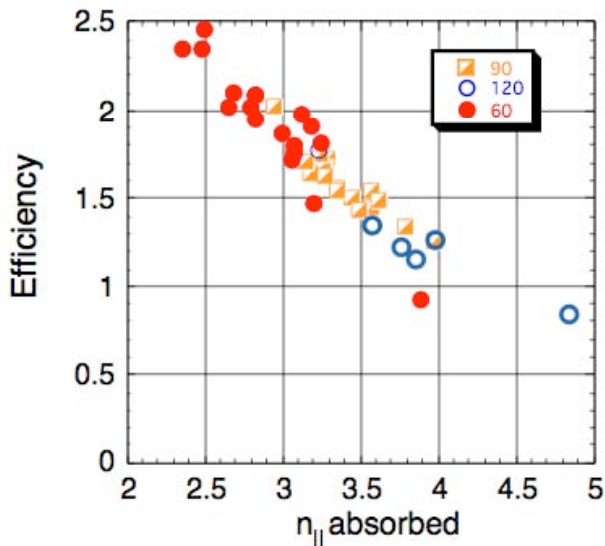


**Figure 5.** Current drive efficiency (A/Wm$^2$x10$^{19}$) versus $n_{||}$ absorbed

and $Z_{eff}$ should be held constant.. Performing this fit on a subset of the data in figure 3 that meet this criterion as close as possible, $I_p$ = 700 kA, $n_e$ = 5-6 x10$^{19}$ m$^{-3}$, $n_{||}$= 1.6 and $P_{lh}$ = 480-800 kW yields $\eta_0$ = 2.5±0.2 x10$^{19}$ A/Wm$^2$ and $\eta_1$ = 0.4±0.5, a fairly typical efficiency. The line-averaged density was used in obtaining this value as is customarily done. If the local density at the believed location of the driven current is used the fits are tighter, indicating that the location of current driven probably varies with power due to the electron heating, and the efficiency is 20% higher. If the data is separated by launched $n_{||}$, the efficiency is seen to increase with decreasing $n_{||}$ as expected (at least until the accessibility limit is reached) (fig. 4). The amplitude of non-thermal ECE and soft x-ray emission also increases at fixed power as launched $n_{||}$ is decreased. Theory would indicate that the efficiency should fall as $1/n_{||}^2$. The data in figure four indicate a much weaker dependence. A second method for estimating the current drive efficiency provides a possible explanation for this behavior. The theory of Karney and Fisch[4] gives a detailed calculation of the physics of current drive in the presence of an electric field. It relates the normalized power required to support the inductive energy in the plasma to the wave parallel velocity normalized to the Dreicer velocity. A series of numerical solutions of the appropriate Fokker-Planck equation yielded parameterized fits (depending only on $Z_{eff}$) that can be used to compare with the experiment. The assumption of the correctness of this theory is made. Each individual shot is then fit to the appropriate $Z_{eff}$ curve. The only free parameter is the $n_{||}$ of the

wave **at absorption**. (assuming all the rf power is absorbed) The same points as plotted in figure 4 can be re-plotted as (figure 5) efficiency versus $n_\parallel$ absorbed. It is immediately obvious that the points now fall together and the decrease in efficiency with $n_\parallel$ ($\sim 1/n_\parallel^{1.8}$) is nearly in agreement with theory. Further, the efficiency for the shots closest to full current drive is in agreement with the previous method of estimation.

## Current Profile Measurements and Modeling

Direct numerical modeling of a lower hybrid discharge has been performed using the GENRAY-CQL3D code[5]. This is a ray tracing – Fokker-Planck code. The results are in good agreement with the experimentally observed loop voltage and indicate off-axis current drive in agreement with the disappearance of sawteeth observed in the experiment. A more detailed description of the modeling is given in the paper by A. E. Schmidt[6] at this conference. Figure 6 shows the measured and calculated x-ray emission profiles for three different energies of x-rays. These were measured with a 32 chord perpendicularly viewing x-ray camera. The magnitude of the observed x-ray emission is in excellent agreement with the model predictions but the width is seen to be much broader experimentally than that calculated. Possible explanations for this discrepancy include first, the possibility that the fast electrons are diffusing spatially before slowing down, and second that the lower hybrid wave deposition is broader than predicted by ray tracing. These phenomenon are being investigated in this years on-going experiments by square wave modulating the rf power and looking at the formation and decay of the x-ray sig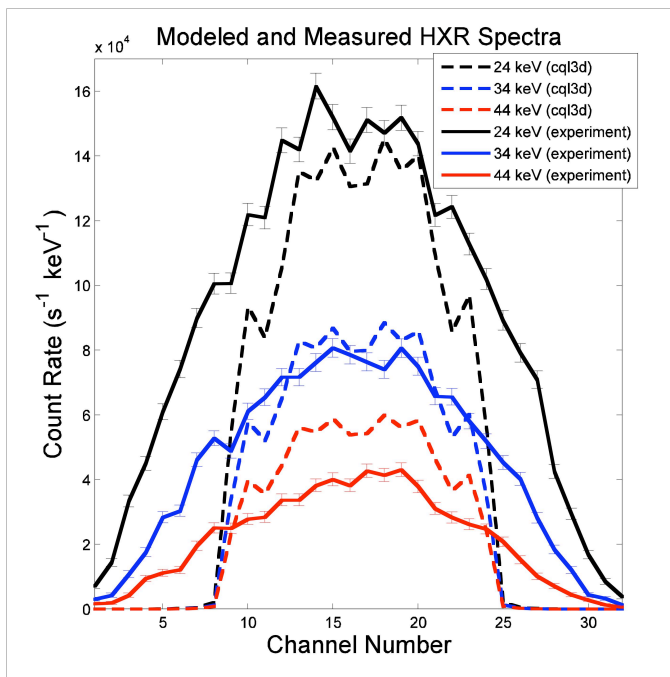nal for evidence of spatial diffusion and by using a full wave code to calculate the lower hybrid wave propagation taking into account possible diffractive effects perhaps enhanced by the large spatial extent of the launcher on C-Mod.



**Figure 6.** Measured and calculated (GENRAY-CQL3D) x-ray emission profiles

## Coupling

A topic of significant interest to the possible use of LHCD on ITER is the difficulties encountered in coupling the power from the waveguide launcher to the plasma. By using a fully active waveguide array and being able to measure the reflection coefficient directly the C-Mod experiment can contribute insight into this

problem. The density in front of the lh launcher is measured using three pairs of Langmuir probes located between the four waveguide rows. Measurements made during 2006 used long rf pulses and were compared to the Brambilla coupling model[7]. In order to get the best agreement it was found that a vacuum layer of ~0.5-1mm was required to fit the data. In 2007 the measurements were repeated using shorter (0.1 s), lower power pulses. Except at the lowest edge densities no vacuum gap was required to fit the behavior of reflection coefficient as a function of edge density and phase. See the paper by G. Wallace[8] at this conference for further details. It is postulated that for the longer high power pulses and even for the short low power pulses at low density that the lh wave is creating a vacuum gap in front of the launcher. Note, this launcher does not have close fitting protective tiles mounted on it that might create a vacuum gap, instead, a set of wall mounted tiles is in place and the launcher can be positioned radialy with respect to them. For most of these experiments the launcher was 1.5 mm outboard of the radius of these tiles. In some 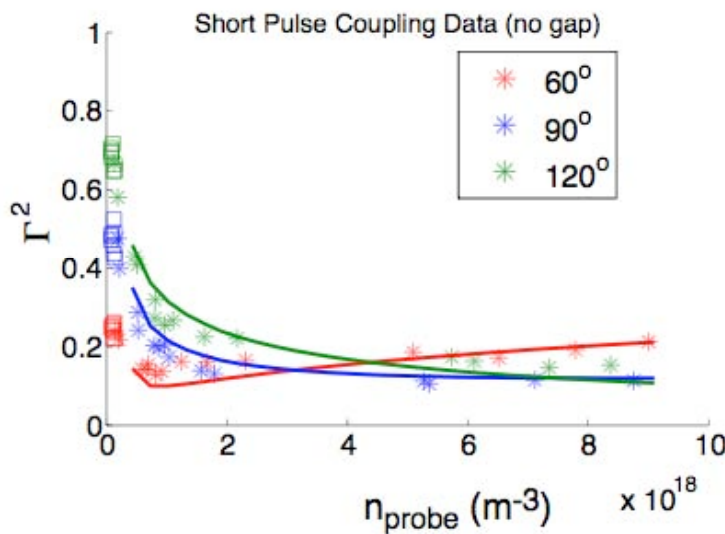of the 2006 experiments the launcher position was flush with or slightly inboard of the tile radius and a vacuum gap was still inferred. At very high densities, greater than $10^{20}$ m$^{-3}$, indications of parametric decay are found on the density probes mounted between the rows of the launcher. Only low levels of decay have been observed to date[8] in agreement with theoretical predictions that only when the density approaches a value were the local lower hybrid frequency is half the rf frequency



**Figure 7.** Reflection coefficient versus edge density for three different launcher phasing and fits from coupling code assuming no vacuum gap

is the decay particularly virulent.


# ON-GOING WORK

During the 2007 run period the C-Mod experiments will be extended to working in conjunction with ICRF and H-mode plasmas as well as higher plasma density and operation during the current ramp-up phase of the discharge. Preliminary results have already been obtained with simultaneous ICRF power. On C-Mod, ICRF power is injected via antennas located at Bays D, E and J. The lower hybrid launcher is located at Bay C.  It is found that, as in other devices[9], the application of ICRF power using

antennas that have field line connection to the LH launcher causes the density in front of the lh launcher to fall, often to unacceptably low levels. This raises further concern for the present ITER configuration where the ICRF and proposed LH launchers are in adjacent ports. Conditions with minimal field line connection were found for the J-port antenna and simultaneous operation proved feasible. Examination of achievable equilibria on C-Mod reveals other configurations that may allow operation with both the J and E port antennas. These experiments indicate that on C-Mod, as on other machines[10], gas puffing in front of the launcher will almost certainly be necessary to maintain coupling with high power simultaneous ICRF operation. Operations at higher densities and into H-mode plasmas are being explored with higher $n_\parallel$ operation being required to maintain accessibility. LH injection into the current ramp-up phase will be explored to estimate the amount of power that will be required to achieve AT target plasmas. Initial experiments with ~0.4 MW injected have postponed the appearance of sawtooth oscillations by up to 0.2 s. Edge conditions during the current ramp-up also appear favorable for lh operation. Simultaneous operation with ICRF heating in the ramp-up to raise the target electron temperature should increase the efficacy of the lh operation.

# SUMMARY

Lower Hybrid Current drive experiments have commenced on the Alcator C-Mod device. To date, power levels up to 1 MW have been injected into the machine over a wide range of $n_\parallel$'s. Nearly total current drive has been achieved in 1 MA plasmas at low density, $n_e = 5\times10^{19}$ $m^{-3}$. Estimates of the current drive efficiency are in agreement with calculations and in line with past experimental results. These indicate that the goal of maintaining long pulse AT current profiles should be achievable on Alcator C-Mod with the addition of a second launcher and the full complement of 4 MW source power. Good agreement between experimentally measured non-thermal ECE radiation chordal x-ray measurements and theoretical modeling has been found. Along with magnetic measurements these measurements show off-axis current deposition as expected. Indications that the driven current profile is somewhat broader than predicted by simple models have been seen and they are being explored further both experimentally with power modulation and theoretically through more sophisticated modeling efforts.

# ACKNOWLEDGMENTS

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