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Lower Hybrid Current Drive Experiments in Alcator C-Mod

R.R. Parker, J.R. Wilson[1], P.T. Bonoli, R. W. Harvey[2], A.E. Hubbard, M. Porkolab, A.E. Schmidt, G.M. Wallace

Plasma Science and Fusion Center, MIT, Cambridge MA USA

[1]Princeton Plasma Physics Laboratory, Princeton University, Princeton NJ USA

[2]CompX, Del Mar, CA USA

Introduction

A lower hybrid current drive system has been implemented on Alcator C-Mod [1]. The motivation is to use LHCD to supplement bootstrap current in order to access optimized regimes of tokamak operation, namely those with fully non-inductive current drive, confinement exceeding ITER-89 H-Mode scaling and normalized beta approaching the no-wall limit, $\beta_n \approx 3$ [2,3]. The LH antenna is a grill formed by 4 poloidal rows of waveguides, with each row having 24 waveguides in the toroidal direction. Power is provided by 12 klystrons, each capable of 250 kW CW operation at a frequency of 4.6 GHz. Adjacent pairs of waveguides, e.g., 1-2, 3-4, etc., are excited by the same klystron. Manually actuated high-power phase shifters set the relative phase between the two paired waveguide columns, while the overall phase progression between adjacent pairs is electronically controlled. With this system the launched parallel index of refraction can be varied over a wide range, e.g., $1.6 < n_{||} < 3.1$, in a time of ~ 1ms and with high directivity. Questions addressed in this paper include coupling efficiency in L-Mode and H-Mode plasmas, the degree to which fast-electron spatial deposition can be affected by varying $n_{||}$, current drive efficiency and comparison with predictions based on the ray-tracing code GENRAY and the Fokker-Planck code CQL3D.

Coupling Studies

Coupling studies have been carried out over a wide range of plasma conditions. The studies are aided by 6 Langmuir probes imbedded in the face of the grill and extending 1.5 mm proud of it. These probes thus measure the density averaged over a 1.5 mm distance from the grill face. The grill is moveable within fixed limiters on each side; in most conditions the grill face is kept at least 1.5 mm in back of the limiters in order to protect the probes. The best coupling is found to occur when the plasma shape conforms closely to the grill. In general, the key parameter determining the coupling efficiency is the density at the grill, and this can be varied over a wide range by varying the main plasma density, the gap between the grill and the separatrix, and the position of the grill relative to the limiters on each side of it.

Results of coupling measurements as a function of probe density and $n_{||}$ are shown in Figure 1, where they are also compared with predictions from the Brambilla grill code [4,5]. In these measurements, the coupled power was 150 kW and the pulse length was kept short (10 ms) in order to prevent modification of the density near the grill by the applied RF power. Several models of the density dependence in front of the grill have been used to compare with code predictions. The best agreement is found by setting the density at the grill face to $4x10^{17}$ m^{-3} and adjusting the density gradient (assumed spatially constant) so that the density averaged over the probe lengths conforms to measurements. Clearly, coupling is poor at low grill density as expected since LH waves are evanescent for densities less than the cutoff density, i.e., n_e<$2.6x10^{17}$ m^{-3}.

Coupling in the presence of ICRF heating and H-Modes has also been studied, although not as extensively as for L-mode as described above. It is found that the density at those areas of the grill that are connected to the ICRF antennae by flux tubes in the SOL decreases sharply during ICRF heating. This results in a loss of coupling consistent with the L-mode data shown in Figure 1. The situation regarding coupling to H-Modes is not clear. In unboronized conditions the density at the grill drops precipitously in ICRF induced H-Modes resulting in a loss of coupling. However after boronization, the precipitous drop in density is not observed and good coupling in H-mode (but so far without clear current drive effects) can be maintained. In the former case, puffing by a gas valve at the plasma periphery can be used to increase the grill density in H-Mode but not without an undesirable increase in the main plasma density. A gas valve will be installed in proximity to the grill for the next C-Mod campaign. It, together with a newly installed cryopump, will permit better control of the grill density relative to the density in the main plasma, enabling more extensive experiments related to the important issue of coupling LH power to H-mode plasmas.

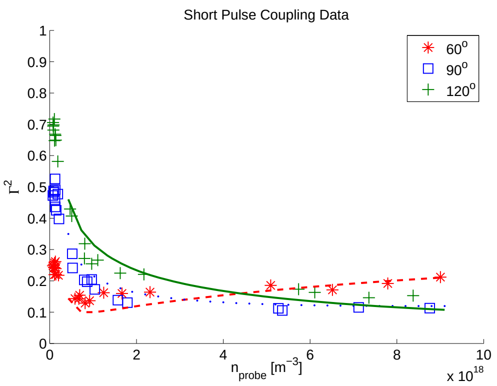

Figure 1. Density dependence of power reflection coefficient and comparison with code predictions for $n_{||}$ = 1.6 (60°), 2.3 (90°) and 3.1 (120°).

X-Ray Measurements

Perpendicular bremsstrahlung from fast electrons accelerated by the LH waves is measured by a 32 chord imaging X-Ray spectrometer [6], similar in design and construction to those developed by Y. Peysson [7]. The energetic bremsstrahlung emission provides a qualitative indication of the spatial location of the fast electrons and, by inference, where the LH waves are absorbed and current is deposited. Of particular interest is the degree of control that can be exerted over the location of the fast electrons as a function of $n_{||}$ and plasma conditions.

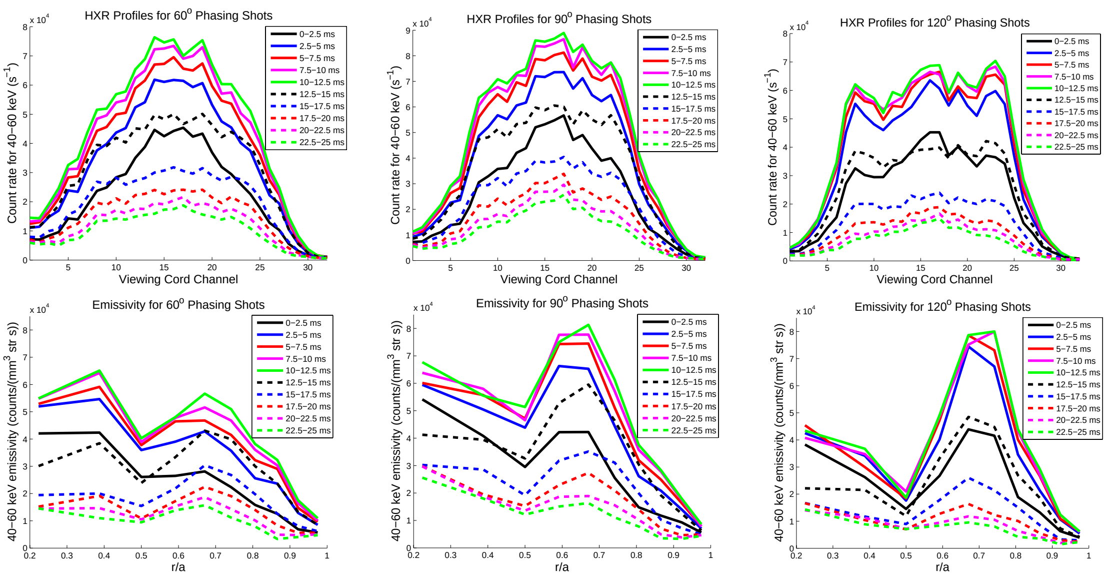

Figure 2. Bremsstrahlung profiles in the range 40 -60 keV for various $n_{||}$. Top: Raw profiles. Bottom: Emissivity profiles. From left to right, $n_{||}$ = 1.6, 2.3, 3.1.

The results of a scan in $n_{||}$ at various times with respect to the beginning of an RF pulse are shown in Figure 2. These results were obtained by square-wave modulating the RF pulse with a period of 25 ms and averaging the spectra over roughly 100 pulses in constant plasma conditions [8]. The coupled power was 400 kW and loop voltage modulation during each pulse was insignificant. As can be seen, the photon emission in the range 40-60 keV reaches steady-state after about 7.5 ms. A clear shift of the emission peak toward the outside of the plasma with increasing $n_{||}$ is observed, as expected, and is consistent with simulations leading to the development of advanced scenarios[2,3] in Alcator C-Mod. Work is progressing toward the interpretation of the dynamic evolution of the photon emission in order to assess the importance of diffusion of the fast electrons; however, the predominant effect regarding their decay after the RF turns off appears to be classical slowing down.

Current Drive

The maximum power injected in LH experiments to date is 900 kW, limited by RF breakdown in the air side of the launcher (but not at the grill). In general this power is not sufficient to fully replace the Ohmic current in relatively low density ($n(0) < 1\times10^{20}$ m^{-3}), moderate current (800 kA) Alcator C-Mod discharges. An example of a nearly full current drive shot is shown in Figure 3. In this shot , 800 kW is applied to a 1 MA discharge and the loop voltage transiently passes through 0. However, as the density rises, the RF power is insufficient to maintain the loop voltage at 0. Also, simulations using TRANSP indicate that with current driven off-axis, as expected in this case, the initial negative loop voltage is the result of rapid diffusion of the electric field in the outer half of the plasma and has not reached a steady-state.

Systematic measurement of the loop voltage reduction as a function of density, current and power yield a current drive efficiency $\eta = n_{20} I(MA) R / P(MW) \approx 0.3$ MA/MWm^{-2} with $n_{||}$ =1.6 [9] (for which the maximum accessible density is 7x10^{19} m^{-3} at 5.4 T.) The efficiency decreases with increasing $n_{||}$ although not as rapidly as $1/n_{||}^2$ as might be expected if the LH waves do not undergo changes in $n_{||}$ as they propagate to the region of plasma where they are absorbed. Stabilization of sawteeth has been observed and indicates off-axis deposition of the driven current, consistent with X-Ray emissivity and preliminary MSE measurements. Extensive modeling of the LH current drive experiments has been carried out using the ray-tracing code GENRAY and the FP code CQL3D. Two shots have been compared with experiment, namely the shot illustrated in Figure 3 and a similar shot at 530 kA. In the latter case, the codes predicted that a loop voltage of 0.2 V was necessary to sustain the discharge and this agreed well with experiment. In the case of the 1 MA discharge shown in Figure 3, the code predicted a voltage of just over 0.1 V was required for sustainment, consistent with the discussion above concerning the transient nature of the measured voltage.

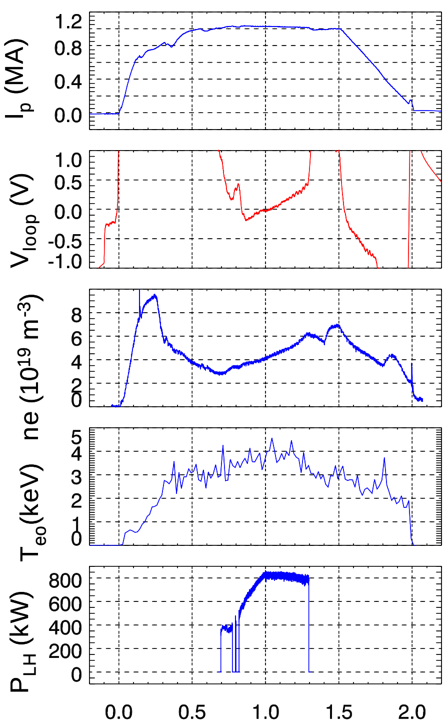

Figure 3. Example of discharge in which near full current drive is achieved.

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