Abstract. Recent progress on lower hybrid current drive (LHCD) experiment and modeling towards high performance steady-state (t > 3-5 τr) regime on Alcator C-Mod are presented. Fully non-inductive reversed shear (RS) plasmas have been obtained with spontaneous generation of internal transport barrier (ITB). LHCD pulse length has been extended up to 1 s and MHD quiescent plasmas were sustained for 0.9 s (~4 τr) by LHCD alone. LHCD efficiency at high density has been improved over prior results at high density, where unexpected degradation of LHCD efficiency was reported. LHCD simulation using LHEAF full wave code demonstrated that, in addition to collisional absorption, full wave effects can move the power deposition profile too close to the separatrix, leading to lower efficiency. Experimentally, strong parametric decay instabilities (PDI) were observed using inner wall probes, with an intensity much stronger than previously observed using low-field-side probes. Both the modeling and experimental results suggest that the key to improve LHCD efficiency is to ensure strong single pass absorption. The design of additional launcher (LH3) to achieve high (50 - 80 %) single pass absorption by velocity space synergy is presented.

1. Introduction

Lower hybrid current drive (LHCD) has a high current drive efficiency and has been widely used as the main current drive tool for realizing steady-state plasmas. The LH waves are absorbed by electron Landau damping and electrons are accelerated into the parallel direction (with respect to the magnetic field), which makes it an ideal tool for far off-axis current drive in future experiments including ITER.

Previous simulations of LHCD carried out for Alcator C-Mod envisioned fully steady-state, stable advanced tokamak (AT) regimes (f_Bs > 50%) sustained by radio-frequency (RF) heating alone. In ref [1], it was predicted that about ~ 2.5 MW of LHCD would provide the off-axis current drive required to sustain such a configuration. Realizing these regimes is the focus of efforts to achieve steady-state plasmas in C-Mod. C-Mod is equipped with a 4x16 wave guide array LHCD launcher and has been injected over 1 MW of RF power in the LH frequency range (4.6 GHz). Fully non-inductive discharges have been obtained with the line averaged density (n_e) of 0.5x10^{20} m^{-3}, plasma current (I_p) of ~ 0.5 MA, and the toroidal filed (B_T) of 5.4 T [2]. Those parameters are close to what is expected in ITER steady state operation, providing an opportunity to study transport and stability in ITER-relevant steady-state regimes as well as LH wave physics and current profile control. This paper reports recent progress of LH experiment towards realizing the envisioned regime.
Approaching this goal involves two steps. The first step is to modify the peaked current profile of a target Ohmically-heated plasma to obtain either a flat or reversed shear (RS) current profile. It is necessary to keep the density relatively low during this phase to maximize the LH driven current. Since the last FEC conference, an extensive upgrade of LHCD control system and key diagnostics that measure the current profile have been performed. These improvements extended the LHCD pulse to \( \sim 5 \tau_r \) and realized more reliable current profile measurement. The second step of our approach to generate an AT plasma regime is to increase the density so as to enhance the self-driven bootstrap current. It is important to maintain good LHCD efficiency during this phase to sustain the desired configuration. As reported previously [3, 4], the LHCD efficiency on C-Mod has been found to be unexpectedly low in diverted plasmas at high density (\( > 1 \times 10^{20} \text{m}^{-3} \)). We discuss new LHCD modelling and additional experiments to better understand and to mitigate the anomalously low efficiency.

The paper outline is: Section 2 describes the results from experiments performed in the fully non-inductive regime. Section 3 and 4 describe recent modelling and experiments to understand LHCD in high density diverted plasmas and our plan to improve LHCD in this regime. Sec 5 summarizes the present work.

2. Fully non-inductive plasmas sustained by LHCD

Fully non-inductive discharges have been obtained with \( n_e = 0.5 \times 10^{20} \text{m}^{-3} \), \( I_p \sim 0.5 \text{MA} \) and \( B_T = 5.4 \text{T} \). In this regime, sawteeth are completely suppressed and q-profile obtained by MSE-constrained EFIT profiles is modestly reversed, with \( q_0 \sim 2 \) and \( q_{\text{min}} \sim 1.5 \). Current drive efficiency is in the range \( \eta = 2.0 - 2.5 \times 10^{19} \text{A/Wm}^2 \). These results were reported in the last conference[2]. More recently, we observed a spontaneous development of an electron transport barrier in this regime. Figure 1 shows an example of such a transition. In this case, LHCD turns on at 0.9 s, and the loop voltage drops rapidly close to zero. At 1.2 s, the central temperature increased abruptly. Figure 2 compares the density and temperature profiles before and after such a transition, showing a steep gradient developed in the electron temperature profile (ITB). The transition happened 0.3 s after LHCD turn-on, which is about the same as the current relaxation time. Sawteeth were suppressed much earlier than this transition (around 1 s) and thus are not considered a direct cause of the change in \( T_e \) profile. At 1.33 s, the ITB phase ended before LH turn-off. The growth of a \( m/n=2/1 \) mode was observed in the

![FIG 1: Time trace of fully non-inductive plasma with eITB formation. (a) plasma current and LHCD power, (b) loop voltage, (c) central electron temperature, (d) soft X-ray emission (PIN diode), and (d) m-2/n-1 mode before ITB collapse observed in soft X-ray emission.](image-url)
fluctuation of magnetics and soft X-ray emission signal, suggesting this activity is responsible for the termination of ITB. A unique feature of the fully non-inductive regime on C-Mod is that the current profile of the target plasma is fully penetrated and sawtooth activity has already started. This differs from the standard recipe to produce RS plasmas on other tokamaks, in which early intense heating delays the current penetration [5, 6]. It is generally believed that reversing the current profile subject the plasma to dangerous MHD activities, and therefore it is difficult once the current penetrated. Indeed, we also observed a growth of large islands associating the degradation of LHCD efficiency in this regime. However, this discharge does not exhibit such an MHD activity except for the one which terminated ITB. We were recently able to sustain a fully non-inductive plasma without causing any harmful MHD activities for 0.9 s ( > 5τ). Although future experiments will explore the physics that controls the presence and character of MHD that develops in plasmas with q-profiles modified by LHCD, these discharges suggest that avoiding such instabilities is possible.

Since the last conference, an extensive upgrade of LHCD control system and key diagnostics for LHCD have been performed. The extension of LHCD pulse length up to 1s has been demonstrated[7]. The Motional Stark Effect (MSE) diagnostic shifted its viewing angle to provide more measurement in the central part of plasma. Additionally, MSE has a new in-vessel intershot calibration system installed, which is routinely used to improve the accuracy of pitch angle measurement and to characterize the previously-observed MSE calibration drift. A 3-cords polarimeter [8,9,10] is now routinely used to measure the change of current profile. While the polarimeter has an advantage of continuous measurement, it is more complicated to
integrate its measurements into equilibrium reconstruction codes such as EFIT [11]. The development of a robust algorithm to constrain EFIT with better flexibility of current profile is under way.

3. LHCD physics at high density

LHCD modelling using ray-tracing and full wave codes

Accessing AT regimes with $f_{\text{BS}} \sim 50\%$ in C-Mod will require increasing the density to $n_e \sim 1-1.5 \times 10^{20} \text{ m}^{-3}$ with $T_{e0} \sim 5 \text{ keV}$. 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 [12]. In Ohmically heated plasmas with $T_{e0} \sim 2 \text{ keV}$, it has been found that the LHCD efficiency inferred from LH induced super-thermal electrons drops precipitously as the density is increased above $n_e \sim 5 \times 10^{19} \text{ m}^{-3}$. This density is well below the conventional limit set by accessibility and no large parametric decay was observed [3,4]. Understanding this phenomena and finding a method to mitigate it is a major motivation of recent LHCD modelling and experiments on C-Mod.

This falloff with density has been studied with two newly developed and independent simulations, one based on ray-tracing which takes into account collisional processes taking place in the SOL (GENRAY/CQL3D [13, 14]) and the other based on an FEM full wave model which also includes collisional absorption in the SOL but removes uncertainties inherent in the WKB approximation (LHEAF) [15, 16]. The ray-tracing code predicted that collisional absorption in SOL plasma alone can reduce the current drive efficiency significantly. Especially when the collisionality in the SOL is chosen reasonably high (red dashed line in FIG. 4), the predicted hard X-ray emission from non-thermal electrons becomes more than two orders of magnitude smaller than the case without collisions in SOL (black line), more consistent with experimental trend (green circles).

More recently, a FEM based full wave LH code, LHEAF, has been applied for densities $> 1 \times 10^{20} \text{ m}^{-3}$ [17]. Interestingly, LHEAF code predicts similar magnitude of hard X-ray reduction although the power absorbed via collisional absorption is small. LHEAF can describe the spreading of wave spectrum due to diffraction more accurately, and it predicts stronger $N/\nu$ upshift as the wave propagates compared to ray-tracing. Such a difference was noticed even at relatively low density, where LHCD has good efficiency [18]. Due to high $N/\nu$ upshift, driven current diminishes significantly, explaining the observed loss in efficiency.

![FIG 4: Measured and predicted count rate of hard X-ray emission generated by LH driven fast electrons. (Green circles) experimental result using OH plasmas, (black line) the prediction by GENRAY/CQL3D without collisional absorption in SOL, (blue and red) the prediction by GENRAY/CQL3D with collisional absorption in SOL, and (leaves) the prediction by the LHEAF full wave code.](image-url)
LH spectral measurement at high field side

While these improved codes show better agreement with experiment, a discrepancy remains at \( n_e > 1 \times 10^{20} \text{ m}^{-3} \). Other mechanisms which could contribute additional loss include scattering due to density fluctuations and non-linear interactions such as parametric decay instabilities (PDI). For realizing an AT regime, in addition to understanding the mechanism behind the degradation, it is equally important to establish methods to improve the efficiency. A leading candidate for such a solution is to enhance the single pass absorption. For this scheme to work, the launched wave should be able to propagate and be absorbed during the first pass. Therefore, it is important to confirm experimentally that a significant loss of injected LH power does not occur immediately in front of the launcher.

To answer this question, we performed spectral measurements of LH waves using Langmuir probes installed in the various locations, including the inner wall and the lower divertor. A fast scanning spectrum recorder to measure the LH wave spectra near 4.6 GHz at 6 Langmuir probes simultaneously was installed for this purpose. The recorder is a heterodyne receiver using a narrow band (~ 100kHz), high rejection rate low pass filter, similar to the one used for a LH reflectometer [18], and can measure the spectrum with high repetition rate (~ 20ms).

Figure 5 compares the spectrum measured by a high field side (HFS) probe [19] to the spectrum measured by a probe installed on the LH launcher itself (low field side, LFS). A classical PDI behaviour is seen on HFS spectrum, i.e., the growth of sidebands and simultaneous depletion of the pump, which corresponds to the LH waves applied by the launcher. The behaviour is observed in the density range above \( > 1 \times 10^{20} \text{ m}^{-3} \), suggesting that PDI is the process behind the difference of experiment and modelling in FIG. 4. On the other hand, no significant activity is observed at LFS. Moreover, the frequency separation of the lower side band and the pump wave corresponds to the ion cyclotron frequency of the HFS SOL, outside the core plasma, suggesting that this is a non-linear interaction locally occurring near the inboard side separatrix.

This measurement was performed throughout the experimental campaign of this year using various target plasmas with the density up to \( \sim 1.5 \times 10^{20} \text{ m}^{-3} \). Except for one case, the PDI on LFS were either negligible or at least 20dB lower than the pump wave. Moreover, none of discharges show a significant PDI at the launcher Langmuir probe unless the density is extremely high, suggesting that, at the density interested for the AT experiment, these activities are not happening in front of the launcher even when it occurs at LFS, supporting the idea of improving the efficiency by increasing the single pass absorption.

Improvement of LHCD efficiency in high \( T_e \) plasmas

The simulations also indicate that the loss in efficiency can be recovered by increasing the first-pass absorption, which could occur by raising the temperature to \( T_{e0} > 5 \text{ keV} \).
Experiments aimed at verifying the predictions of the simulations regarding the importance of increasing the single pass absorption by raising the central temperature have been carried out in mode-converted ICRF-heated He discharges with a 3He minority. The production of hard X-rays from super-thermal electron Bremsstrahlung has been compared with a synthetic diagnostic in FIG. 6. Good agreement is found at densities up to $\approx 1.6 \times 10^{20}$ m$^{-3}$, and the current drive efficiency found in the simulation with $T_e^0 = 5.3$ keV is in line with that determined in the advanced modes of Ref. [1].

However, the high $T_e$ target plasmas used in this experiment were produced at 8T for MC heating, while the Ohmic target plasmas were produced at 5.4 - 7 T. Also, the experiment was performed using He for better diagnosis of HXR emission. Recent experiment using I-mode target plasma with D$^2$ gas suggests that the improvement by solely increasing $T_e$ may be much more modest. While further analysis is necessary for this very recent result, it emphasizes the importance of enhancing the single pass absorption to a large degree as discussed in the next section.

4. LH3 : additional launcher for high (>50%) single pass absorption

LHCD experiments reported in this paper have been performed in so-called multi-pass absorption regime, in which the LH waves undergo multiple reflection before being absorbed by the plasma via electron Landau damping. While this provides an opportunity for rigorously testing simulation codes, it differs from the wave propagation expected in future reactors, where the driven current profile will be highly localized due to the strong single pass absorption. Additionally, multiple mechanism considered contributing the degradation of LHCD at high density are most prominent in the multi-pass regime. Therefore, improving single pass absorption has a potential to improve LHCD efficiency at high density.

During the design phase of the additional launcher (LH3) to increase the total LH power to over 2MW level, which is called for in ref [1] to access the AT regimes, we explored possibilities to dramatically enhance the single pass absorption. The reason why the LH waves experience multiple reflections is that the wave parallel phase velocity needs to slow down enough to extract tail electrons from bulk electrons. Therefore, if the additional launcher can deform this part of distribution function (around 3x $v_{th}$), the LH waves from the existing launcher will be absorbed by these electrons, and the wave will be absorbed more quickly. This concept is termed velocity space synergy, and several schemes to generate such a synergy have been developed including combining of EC and LH waves [20], and using LH waves with different frequencies simultaneously [21].
The scheme employed for LH3 is to use an off-midplane launcher. The wave launched with a finite poloidal angle is known [22] to experience very different change of $N_{\parallel}$ as it propagates through the plasma from the ray launched from the mid-plane. As illustrated in FIG. 7, if the wave launch position is properly selected, the wave is quickly absorbed during the first pass. This approach was tested on JT-60U [23] and better single pass absorption was reported. For the nominal direction of current in C-Mod plasmas, this happens when moving the LH launcher above the mid-plane. In contrast, if it is placed below the mid-plane, the rays undergo a downshift.

The wide survey of design parameters of LH launcher was performed and the one selected for engineering design of LH3 [7] is shown in FIG 8. In this case, the LH3 launcher is located about 15 cm above the mid-plane. While the most of rays are not absorbed during the first pass when only LH2 is used, the significant fraction of power (>50%) is absorbed during the first pass when it is combined with LH3.

5. Summary

The LH program on Alcator C-Mod has successfully extended its fully non-inductive operation regime. Pulse length has been extended up to 1 sec and two current profile diagnostics are now routinely used. Spontaneous development of ITB was observed in this RS regime, and we obtained MHD quiescent plasmas sustained for 0.9 s ($\sim 4 \tau_r$) even though an Ohmically driven sawtoothing target plasma was used. These plasmas will provide a target plasma to access high $f_{BS}$ regime by increasing LH power to 2MW level and increasing the density. Progress has been made to better understand and to avoid the unfavorable drop of...
LHCD efficiency at high density [3, 4]. In addition to collisional absorptions, a new simulation using the LHEAF full wave code shows that full wave effects can move the power deposition profile even more off-axis very close to the separatrix degrading the LHCD efficiency. Experimentally, a careful survey of LH spectra around the separatrix has been performed and PDI activity occurring locally at HFS of torus was observed. On the other hand, PDI measured at the LH launcher was very small or undetectable, consistent with previous reports. Together, these results suggest the possibility of improving LHCD efficiency by significantly enhancing the single pass absorption. An additional off-midplane (LH3) launcher has been designed for this purpose to increase the single pass absorption to 50 - 80%. High single absorption is also expected for LHCD in ITER and exploring such a regime on an existing device will provide further information to future experiments.

Acknowledgments

This work was supported by US Department of Energy collaborative agreements DE-FC02-99ER54512 and DE-AC02-09CH11466 and SBIR grant award DE-FG02-07ER84762.

References