MODELLING OF ADVANCED TOKAMAK PHYSICS SCENARIOS IN ALCATOR C-MOD*

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Abstract

Advanced tokamak modes of operation in Alcator C-Mod have been investigated using a simulation model which combines an MHD equilibrium and current profile control calculation with an ideal MHD stability analysis. Stable access to high $\beta_{\rm t}$ operating modes with reversed shear current density profiles has been demonstrated using $2.4-3.0$ MW of off-axis lower hybrid current drive (LHCD). Here $\beta_{\rm t} = 2\mu_0\langle p\rangle/B_0^2$ is the volume averaged toroidal plasma beta. Current profile control at the β-limit and beyond has also been demonstrated. The effects of LH power level as well as changes in the profiles of density and temperature on shear reversal radius have been quantified and are discussed.

1. Introduction

Tokamak operating modes characterized by high energy confinement time, high β_N [$\beta_{\rm N} = \beta_{\rm t}/(I_{\rm p}/a\ B_0)$], and high bootstrap current fraction ($f_{\rm bs}$) can lead to more economical fusion reactors. The key tools for accessing these regimes of advanced tokamak operation are flexible pressure and current density profile control by heating and current drive. Alcator C-Mod is a unique facility for testing the physics of current profile control and access to advanced tokamak modes. The compact device size ($R_0 = 0.67$ m) allows significant off-axis current generation at reactor relevant densities and magnetic fields ($B_0 \simeq 4-5$ T and $\langle n_{\rm e}\rangle \gtrsim 1\times10^{20}\ {\rm m}^{-3}$). The highly shaped C-Mod geometry ($\kappa_{\rm x} \lesssim 1.8,\ \delta_{\rm x} \lesssim 0.8$) leads to increased β-limits relative to elliptical and circular configurations. Also, the discharge duration at $B_0 \simeq 4-5$ T and $T_{\rm e}(0) \simeq 5.0$ keV is in excess of $\tau_{\rm L/R}$, making advanced tokamak physics studies possible in plasmas with fully relaxed current density profiles. This is to be contrasted with experiments to date [1,2] where enhanced confinement modes have only been achieved transiently.

2. Current Profile Control During Start-Up

Scoping studies have been carried out using a sophisticated current drive and MHD equilibrium code (ACCOME) [3] to identify a stable path to an improved confinement regime using off-axis current profile control in the form of LHCD. These improved confinement modes are characterized by reversed shear current density profiles with $q(\psi) > 2$ everywhere, i.e. the enhanced reversed shear (ERS) [1] and negative central shear [2] modes. The time dependence of this discharge evolution is simulated by a sequence of equilibria [Figs. 1-2] starting with an ICRF heated target plasma representative of what has been achieved experimentally in C-Mod [4] and ending with a plasma near the β-limit ($\beta_{\rm N} \gtrsim 3.0$) [5]. Current profile control during start-up is shown in Fig. 1 where 3.0 MW of LHCD power at 4.6 GHz has been injected into an L-Mode target plasma characterized by $p(\psi) = p(0)(1-\psi)^2,\ n(\psi) = n(0)(1-\psi),\ T(\psi) = T(0)(1-\psi),\ n_{\rm e}(0) = 1.5\times10^{20}\ {\rm m}^{-3},\ T_{\rm e}(0) = T_{\rm d}(0) = 4.5\ {\rm keV},\ B_0 = 4.4$ T, and $n_\parallel^0 = 2.75$. The integrated currents in Fig. 1 are $I_{\rm p} = 0.69$ MA, $I_{\rm lh} = 0.39$ MA, and $f_{\rm bs} = 0.41$. The pressure profile is broad with $p(0)/\langle p\rangle = 3.17,\ \beta_{\rm t} = 0.88$ %, and $\beta_{\rm N} = 1.3\ (\% - {\rm m} - {\rm T/MA})$.

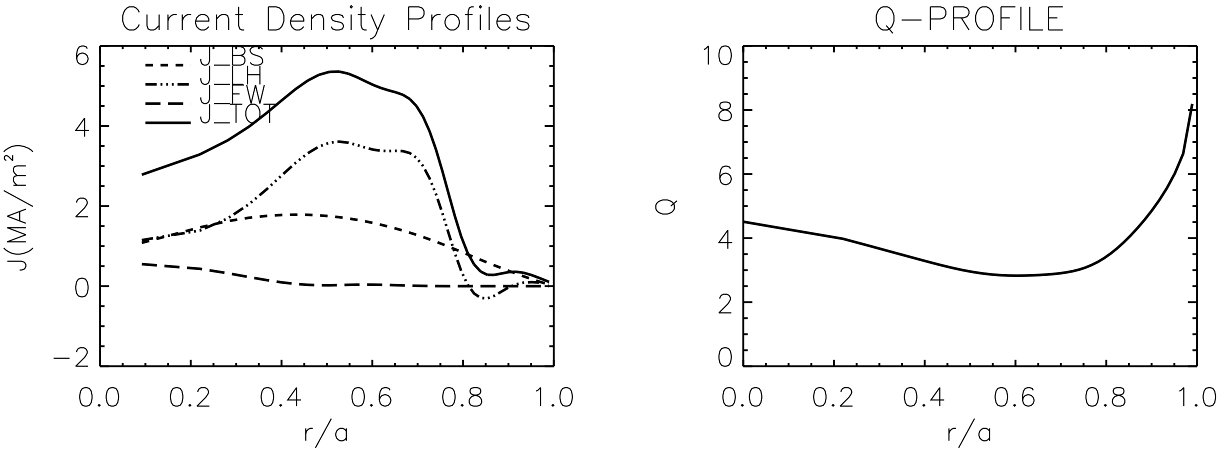

Figure 1: ACCOME simulation of C-Mod advanced tokamak mode at $B_0 = 4.4$ T, $n_e(0) = 1.5 \times 10^{20}$ m^{-3}, $I_p = 0.69$ MA, $f_{\mathrm{bs}} = 0.41$, $I_{\mathrm{LH}} = 0.39$ MA, $P_{\mathrm{LH}} = 3.0$ MW, and $\beta_{\mathrm{N}} = 1.3$.

The profile of saftey factor [Fig. 1] clearly exhibits shear reversal with $q_0 = 4.47$, $q_{\mathrm{min}} = 2.83$, and $(r/a)_{q_{\mathrm{min}}} \simeq 0.7$ Current density profiles similar to Fig. 1 are also found as T_{e}, T_{i} are increased to 6.0 keV. In this case $I_p = 0.84$ MA, $f_{\mathrm{bs}} = 0.45$, $I_{\mathrm{LH}} = 0.45$ MA, and $\beta_{\mathrm{N}} = 1.6$. The shear reversal is even more pronounced with $q_0 = 4.49$ and $q_{\mathrm{min}} = 2.23$. The class of current density profiles shown in Fig. 1 are stable to the $n = 1, 2, 3$, and ∞ modes because $q(\psi) > 2$ everywhere and β_{N} is still well below the ideal β-limit.

3. Operation at the β-Limit and Beyond

As the plasma pressure is increased to near the β - limit, it is found that 3 MW of LHCD power is still sufficient to maintain reversed shear profiles of the safety factor with about the same radius of shear reversal. An example of this is shown in Fig. 2 where now $p(\psi) = p(0)(1-\psi)^2$, $T(\psi) = T(0)[0.67(1-\psi)^{5/2} + 0.33(1-\psi^8)^{3/2}]$, $n(\psi) = p(\psi)/T(\psi)$, $n_{\mathrm{e}}(0) = 2.0 \times 10^{20}$ m^{-3}, $T_{\mathrm{e}}(0) = T_{\mathrm{d}}(0) = 7.5$ keV, $B_0 = 4.0$ T, and $n_{\parallel}^0 = 3.00$. The prescribed density profile is now exemplary of what one would expect with the formation of a transport barrier and the plasma pressure corresponds to an H-mode confinement enhancement factor of $H_{\mathrm{ITER-89}} \simeq 2.5$, assuming 6 MW of ICRF heating power. The MHD configuration is double null with $\kappa_{\mathrm{x}} = 1.8$ and $\delta_{\mathrm{x}} = 0.8$. The integrated currents in Fig. 2 are $I_{\mathrm{p}} = 0.81$ MA, $I_{\mathrm{lh}} = 0.19$ MA, and $f_{\mathrm{bs}} = 0.74$. The pressure profile is again broad with $p(0)/\langle p \rangle = 2.90$, $\beta_{\mathrm{t}} = 2.60$ %, and $\beta_{\mathrm{N}} = 3.0$. The shear reversal point in Fig. 2 is $(r/a)_{q_{\mathrm{min}}} \simeq 0.74$ with $q_0 = 3.95$ and $q_{\mathrm{min}} = 2.65$. The current density profiles and MHD equilibrium predicted by ACCOME in Fig. 2 have been tested for ideal stability by interfacing ACCOME to the JSOLVER / PEST [6] stability code. It is found that the predicted equilibrium is stable to the $n = \infty$ mode and the $n = 1, 2, 3$ external kink modes, up to values of $\beta_{\mathrm{N}} \simeq 3.7$, without a conducting shell. These stability results are summarized in Fig. 3. The marginal stability boundaries in Fig. 3 were determined using the plasma boundary, $p(\psi)$, and current density profiles given numerically by the ACCOME simulation as input to the JSOLVER. The total plasma current was then varied at constant plasma pressure and the plasma pressure was varied at constant current. If a conducting wall is placed at a radius $r_{\mathrm{wall}} = 1.3\ a$, the stability limit is found to be $\beta_{\mathrm{N}} \simeq 5.2$ and is determined by the onset of the $n = 3$ external kink mode.

The effects of changes in the density and temperature profiles on the current profile control have also been investigated. This was done by taking the ACCOME simulation in Fig. 2 and assuming that $p(\psi) = p(0)(1-\psi)^2$ (same pressure profile), $T(\psi) = T(0)[0.70(1-\psi)^{3/2} + 0.30(1-\psi^4)]$, $n(\psi) = p(\psi)/T(\psi)$, $n_{\mathrm{e}}(0) = 2.5 \times 10^{20}$ m^{-3}, $T_{\mathrm{e}}(0) = T_{\mathrm{d}}(0) = 7.5$ keV, $B_0 = 4.0$ T, $P_{\mathrm{lh}} = 2.4$ MW, and $n_{\parallel}^0 = 2.75$ It is also worth noting that the MHD equilibrium computed in this case is a single-null configuration, with $\kappa_{\rm x} = 1.78$ and $\delta_{\rm x} = 0.73$. The shear reversal radius is at $(r/a)_{q_{\rm min}} \simeq 0.78$ with $q_0 = 3.20$ and $q_{\rm min} = 2.39$. The new results are shown in Fig. 4. The integrated current is $I_{\rm p} = 0.98$ MA with $I_{\rm lh} = 0.28$ MA, and $f_{\rm bs} = 0.70$. It is interesting to see that the LH current actually increased, despite the reduction in the LH power from 3.0 to 2.4 MW. This was partly due to the increase in the current drive efficiency that resulted from lowering the parallel refractive index of the injected waves from 3.0 to 2.7. Also the local electron density at the point of rf current generation is lower with the new density profile by a

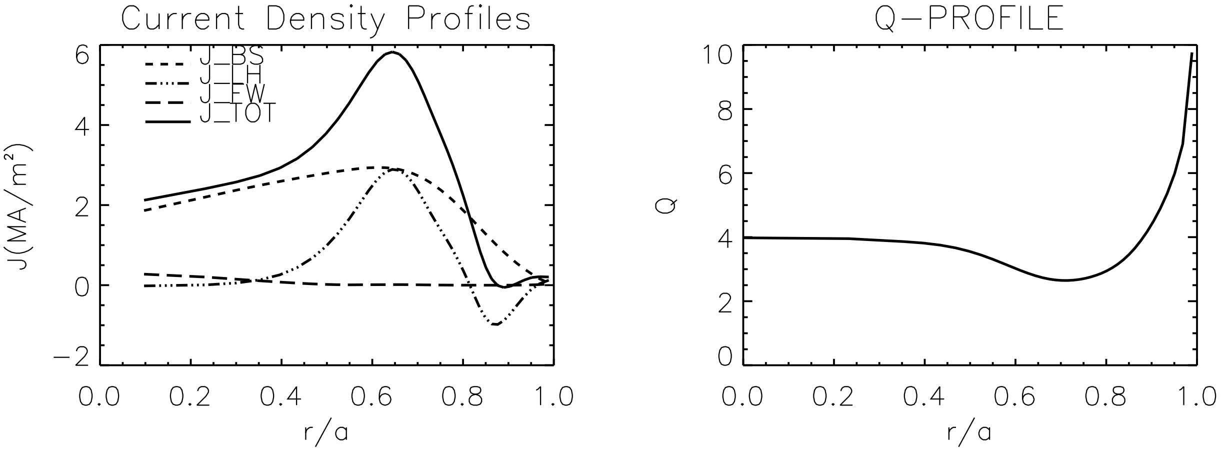

Figure 2: ACCOME simulation of C-Mod advanced tokamak mode at $B_0 = 4.0$ T, $n_e(0) = 2.0 \times 10^{20}$ m^{-3}, $I_p = 0.8$ MA, $f_{\rm bs} = 0.74$, $I_{\rm LH} = 0.19$ MA, $P_{\rm LH} = 3.0$ MW, and $\beta_{\rm N} = 3.0$.

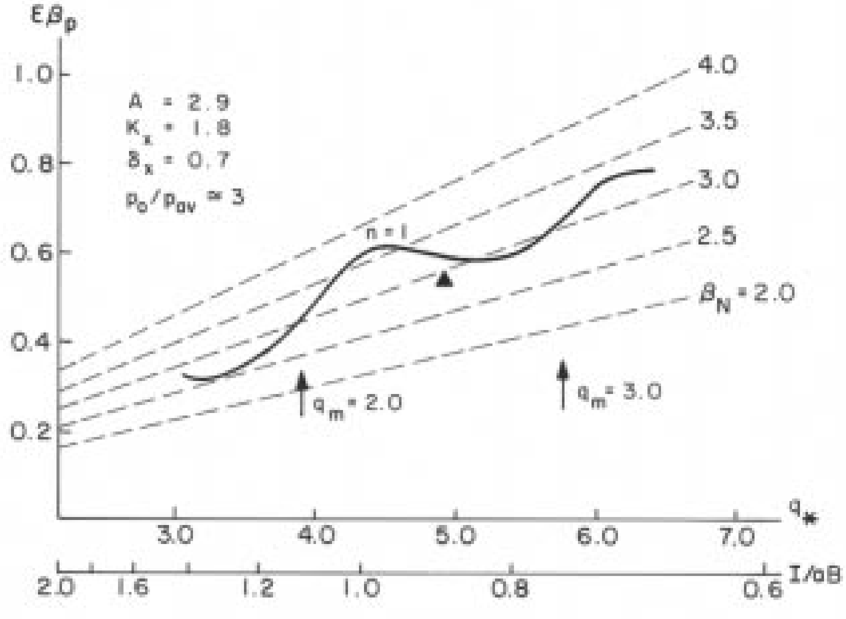

Figure 3: PEST-II stability analysis of C-Mod advanced tokamak mode shown in Fig. 2

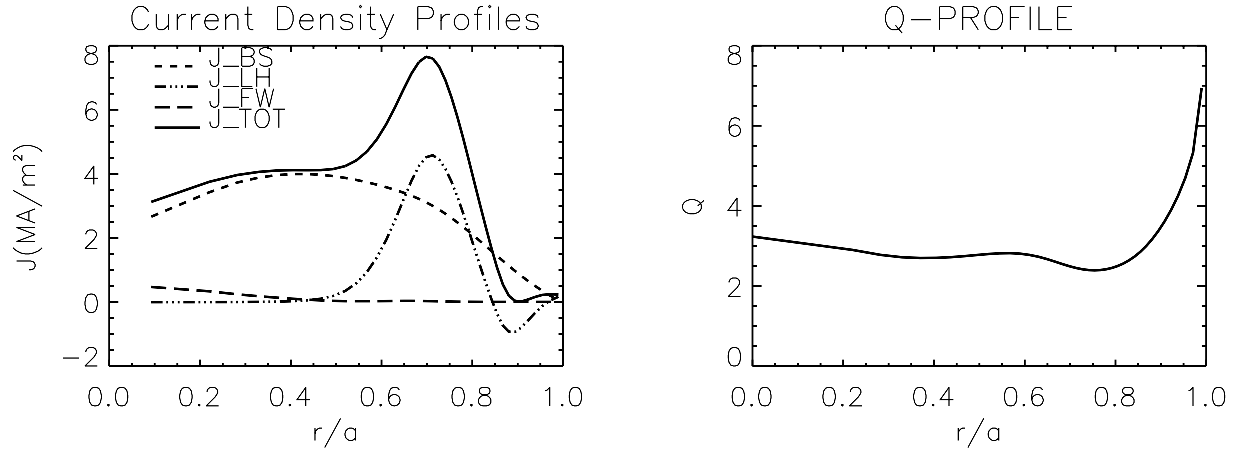

Figure 4: ACCOME simulation of C-Mod advanced tokamak mode at $B_0 = 4.0$ T, $n_e(0) = 2.5 \times 10^{20}$ m^{-3}, $I_p = 0.98$ MA, $f_{\mathrm{bs}} = 0.70$, $I_{\mathrm{LH}} = 0.28$ MA, $P_{\mathrm{LH}} = 2.4$ MW, and $\beta_{\mathrm{N}} = 2.93$.

factor of 1.45. The final $q_{\min}$ is then lower because of the higher net current density (LH plus bootstrap) at the shear reversal point. Although $\beta_{\mathrm{t}} = 3.13$ % is higher than in the previous case, $\beta_{\mathrm{N}} = 2.93$ is about the same because of the increased total current.The ideal MHD stability of this case was investigated using the CAXE / KINX [7] stability code. The equilibrium was found to be stable to the $n = 1, 2, 3$ and $n = \infty$ modes without a conducting shell. It is found that as the the LHCD power is lowered below about 1.5 MW, the degree of shear reversal becomes practically nonexistent and the shear reversal radius moves to $r/a \lesssim 0.5$, although $q(\psi) < 2$ still persists.

4. Summary

In summary, lower hybrid current drive has been shown to be a viable off-axis current profile control tool for accessing advanced tokamak modes in Alcator C-Mod. Reversed shear current density profiles with $q(\psi) > 2$ can be maintained using 2.5 - 3.0 MW of LHRF power as the plasma evolves from start up ($\beta_{\mathrm{N}} \simeq 1.0$) to the β limit ($\beta_{\mathrm{N}} \simeq 3.5$). It was also found that sufficient LHCD power is available to maintain the shear reversal radius at $r/a \gtrsim 0.6$ as the plasma evolves density and temperature profiles characteristic of an internal transport barrier [Fig. 2]. Two ICRF minority heating schemes can be used to heat these advanced tokamak discharges. There will be 4 MW of ICRF power at 80 MHz and 4 MW of tunable ICRF power (40 - 80 MHz). At $B_0 \simeq 4.0$ T, D (H) minority heating can be done on-axis with the tunable ICRF sources fixed at 60 MHz. At $B_0 \simeq 4.4$ T, D (H) minority heating can be done at $r/a \simeq 0.35 - 0.45$ with the ICRF sources set at 80 MHz and 78 MHz.

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