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# ADVANCED TOKAMAK PHYSICS SCENARIOS IN ALCATOR C-MOD\*

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## I. ABSTRACT

Several advanced tokamak modes of operation have been identified in the Alcator C-Mod tokamak. Of particular interest are (i) Reversed shear mode with high bootstrap fraction using on-axis FW current drive and off-axis mode-conversion current drive and/or lower hybrid current drive; (ii) High performance plasmas ( $Q \sim 0.1 - 1$ ) which may be accessed by the PEP (pellet enhanced performance) mode of operation with intense ICRF heating.

## II. INTRODUCTION

We have used a number of codes to model advanced tokamak (AT) modes of operation in Alcator C-Mod: (i) Since at  $B_T = 5$  Tesla the Alcator C-Mod magnet can operate at a pulse length up to 7 sec, which corresponds to 5-10 skin time at  $T_e \leq 5$  keV,  $Z_{eff} \sim 2$ , it is particularly suited for the study of the stability and beta limit of the reversed-shear mode (RS). Profile control may be achieved by on-axis fast wave current drive (FWCD) and off-axis lower-hybrid and/or fast-wave mode-conversion (IBW) current drive (LHCD or MCCD). The feasibility of this scenario is made possible by the installed 4 MW, 80 MHz ICRF power with two 2-strap antennas located in adjacent ports (i.e. current drive phasing is feasible), and the addition of 4 MW of tunable ICRF power (40-80 MHz) and a new 4-strap current drive antenna in 1996 (PPPL collaboration). Adding 2(4) MW of 4.6 GHz lower hybrid power in 1998 would complete the power sources necessary to complete these studies. The mode conversion scenario may best be achieved at  $B_0 = 4.0$  T,  $f = 46$  MHz, in 80(20)% D(<sup>3</sup>He) plasma. Owing to the long normalized pulse-length ( $t_{pulse} > \tau_{L/R}$  since  $\tau_{skin} \sim 1$  sec,  $t_{pulse} \sim 5$  sec), full current profile redistribution is expected to occur; (ii) High  $Q$  (0.1 - 1.0) PEP (Pellet Enhanced Performance) mode of operation should be feasible with 6-7 MW of net ICRF power (<sup>3</sup>He minority heating in a D plasma at  $B_T \sim 8$  T) with  $I_p \gtrsim 2$  MA, if  $H \gtrsim 2$  can be obtained. Below we shall discuss modeling of both of these scenarios.

## III. REVERSE SHEAR SCENARIO

The ACCOME current drive and MHD equilibrium code<sup>1</sup> has been used to study the feasibility of lower hybrid current drive (LHCD)assisted reversed shear current profile in C-Mod. An example of this is shown in Fig. 1, where off-axis current driven in conjunction with bootstrap current generation is used to maintain the profile with reverse shear. In this specific case  $q(0) = 4.01$ ,  $q(min) = 3.23$ , and  $q(95) = 7.91$ . The parameters used in this simulation were  $a = 0.23$  m,  $R_0 = 0.665$  m,  $B_0 = 4.0$  T,  $n_e(0) = 2.0 \times 10^{20} m^{-3}$ ,  $\langle n_e \rangle = 1.06 \times 10^{20} m^{-3}$ ,  $T_e(0) = T_D(0) = 6.2$  keV,  $n_e(\psi) = n_e(0)(1 - \psi^{\alpha_N})^{\gamma_N}$ ,  $\alpha_N = 2.541$ ,  $\gamma_N = 2.388$ , and  $T(\psi) = T(0)[2/3(1 - \psi)^{7/2} + 1/3(1 - \psi^8)^{3/2}]$ . The current drive is provided by 1.2 MW of net LHRF power at 4.6 GHz with a power spectrum characterized by  $n_{\parallel}^0 = k_{\parallel}^0 c / \omega = 3.0$ . This combination of density and temperature should be achievable in C-Mod with 6-8 MW of ICRF heating power, assuming a confinement enhancement factor over L-mode of  $H \simeq 2.0$ .

The current density profiles computed by ACCOME are shown in Fig. 1(a) and the resulting  $q$ -profile is shown in Fig. 1(b). The LH driven current is  $I_{LH} = 46$  kA, the total current is  $I_p = 577$  kA, and the bootstrap current fraction ( $f_{BS} = I_{BS}/I_p$ ) is 0.92.

The self-consistent MHD equilibrium computed by ACCOME has been analyzed for ideal MHD stability using the JSOLVER/PEST package.<sup>2</sup> The results of this analysis are shown in Table I:

	ACCOME	JSOLVER/PEST
$I_p$ (kA)	577	615
$\beta_t$ (%)	1.86	1.67
$\beta_N$ (%)	2.97	2.53
$q$ (0)	4.01	3.72
$\kappa_e$	1.852	1.765
$\delta_e$	0.495	0.438
$\ell_i(3)$	0.699	0.706

The PEST stability analysis of the ACCOME equilibrium (as reconstructed by JSOLVER) is found to be stable to the  $n = \infty$  ballooning mode and also stable to the  $n = 1, 2, 3, 4$  external kink modes, without a conducting wall. Discrepancies between the ACCOME predictions for ( $I_p$ ,  $\beta_t$ ,  $\beta_N$ ) and the reconstructed values from JSOLVER can be attributed to a lack of convergence between the current drive packages and the MHD solver in the ACCOME calculation. In summary, an MHD stable reverse shear scenario at  $\beta_N \gtrsim 2.5\%$  and  $f_{BS} \sim 0.92$  should be achievable in C-Mod through the use of LHCD for current profile control, and ICRF power for plasma heating.

#### IV. OFF-AXIS MODE CONVERSION ABSORPTION AND CURRENT DRIVE

It may be possible to drive off-axis current using mode converted ion Bernstein waves (IBW) in a D-(<sup>3</sup>He) plasma mixture in C-Mod. This TPX relevant scenario could be tested in C-Mod at  $B_0 = 4.0$  T, by using the tunable ( $f_0 = 46$  MHz) FMIT generators (MIT/PPPL-collaboration). In this case the <sup>3</sup>He cyclotron resonance would be located at 8.0 cm to the high field side (HFS) of the tokamak and the deuterium cyclotron resonance would be 22.7 cm to the HFS (outside the plasma). An IBW is excited on the HFS of the <sup>3</sup>He resonance at a location where  $n_z^2 \approx S$ . The location of this mode conversion layer will depend on the relative concentration of <sup>3</sup>He in the D majority plasma. A 1-D full-wave ICRF code (FELICE)<sup>3</sup> has been used to estimate the electron absorption of this mode converted wave. At  $n_e(0) = 1.5 \times 10^{20} \text{m}^{-3}$ ,  $T_e(0) = 2.5$  keV,  $T_D(0) = 2.5$  keV,  $n_{3\text{He}}/n_e = 0.20$ , and  $T_{3\text{He}}(0) = 5.0$  keV, it was found that about 89% of the incident fast wave power is mode converted and damped via electron absorption. The remaining 11% of the power is damped via cyclotron damping at the <sup>3</sup>He minority resonance [see Fig. 2].

In order to achieve high values of beta in the mode conversion regime, the 80 MHz (4.0 MW) FMIT sources can be used to preheat the D-(<sup>3</sup>He) plasma at  $2\omega_c$  <sup>3</sup>He. The 1-D FELICE code has been used to analyze the absorption expected in this case. At  $n_e(0) = 1.5 \times 10^{20} \text{m}^{-3}$ ,  $T_e(0) = 2.5$  keV,  $T_D(0) = 2.0$  keV,  $T_{3\text{He}}(0) = 2.0$  keV, and  $n_{3\text{He}}/n_e = (0.15 - 0.35)$ , approximately 10% of the incident fast wave power is absorbed in a single pass. About 2-4% of the power is absorbed per pass through direct electron Landau damping (core current drive). If credit is taken for

the formation of a  $^3\text{He}$  tail during second harmonic heating then increased single pass damping is found. For example, for a 10 keV  $^3\text{He}$  tail temperature the single pass absorption is increased for 20% at  $n_{^3\text{He}}/n_e \simeq 0.20$ .

#### IV. HIGH Q-MODES OF OPERATION (PEP MODE)

Under favorable assumptions, impressive high performance ( $Q \sim 0.1-1.0$ ) mode of operation may be achievable by means of ICRF heating and pellet fueling. The key ingredients to access such performance is peaked density profiles ( $n(0)/\langle n \rangle \sim 3$ ), high currents ( $I_p \gtrsim 2.0$  MA), and good H-factors ( $H \simeq 2$ ). Two examples of such scenarios are depicted in Table II, as obtained by means of the "Nevins spreadsheet."<sup>4</sup> In Table II we used  $n(0)/\langle n \rangle = 3.0$ , an H-factor of 2.5,  $I_p = 2.5$  MA,  $B = 8.2$  T,  $P_{ICRF} = 4.0$  MW. These parameters give  $\tau_E \simeq 0.14$  sec,  $\beta_N \simeq 1.1$ , a fusion power of 2.3 - 4.0 MW, or  $Q = 0.57 - 1.0$ . To obtain such a performance in a small tokamak such as C-Mod would indeed be an impressive feat.

TABLE II

	CASE A	CASE B
$\langle n_e (m^{-3}) \rangle$	$2.0 \times 10^{20}$	$1.25 \times 10^{20}$
$T_e(0)$ (keV)	9.05	10.03
$T_D(0)$ (keV)	9.86	18.94
$Q$	0.57	1.01
$P_{FUSION}$ (MW)	2.28	4.05
$P_{FW}^E/P_{FW}^I$	0.50	0.10

#### V. CONCLUSIONS

We have identified two types of advanced tokamak mode of operation in Alcator C-Mod, namely (i) the reversed shear (RS) mode and (ii) PEP high performance (high  $Q$ ) mode. We have shown that with reasonable parameters and confinement enhancement factor ( $H \approx 2$ ) C-Mod could test the beta limit in the RS mode ( $\beta_N \gtrsim 2.5$ ) and could achieve high  $Q (> 0.1)$  performance with the PEP mode.

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- <sup>2</sup> R.C. Grimm, et al., J. Comp. Physics **4**, 94 (1983).
- <sup>3</sup> M. Brambilla, Nucl. Fusion **28**, 549 (1988).
- <sup>4</sup> The Macintosh-Excel software based on the ITER formulary was developed by W. Nevins of Livermore.

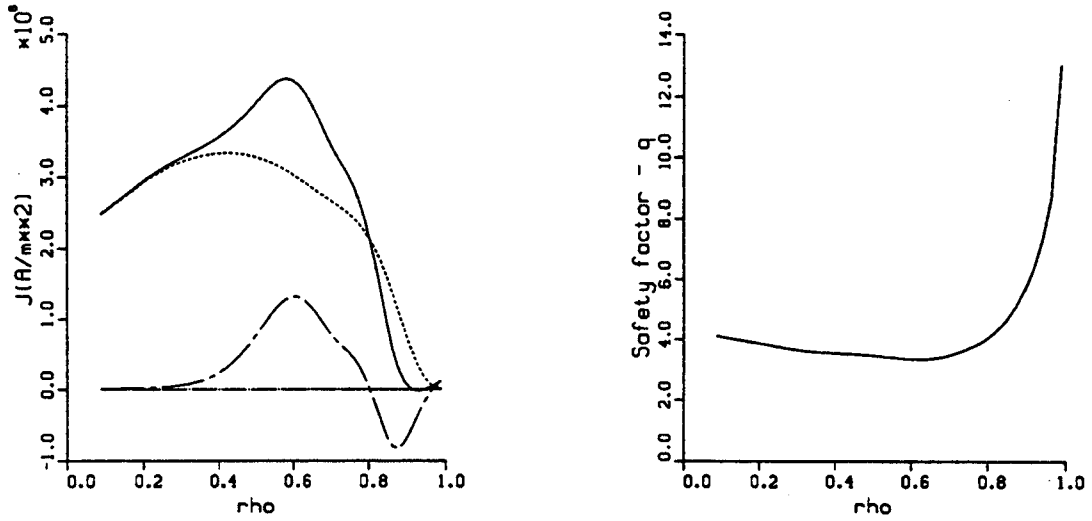


Figure 1: ACCOME Simulation of Alcator C-Mod Reverse Shear Mode [ $n_e(0) = 2.0 \times 10^{20} m^{-3}$ ,  $B_0 = 4.0T$ ,  $T_e(0) = T_D(0) = 6.2$  keV and  $P_{LH} = 1.2$  MW]. (a) Current densities (A/m<sup>2</sup>) vs. square root toroidal flux (normalized). Solid line is the total current density, chain-dash curve is the LH current density, and dashed curve is the bootstrap current density. (b) Safety factor vs. square root toroidal flux (normalized).

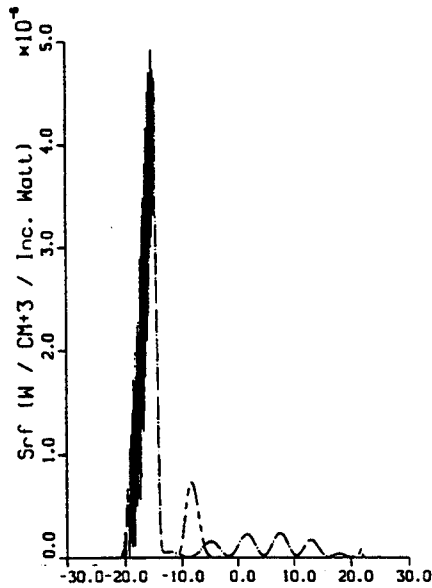


Figure 2: FELICE results for  $D-(^3He)$  mode conversion in Alcator C-Mod [ $n_e(0) = 1.5 \times 10^{20} m^{-3}$ ,  $B_0 = 4.0T$ ,  $f_0 = 46$  MHz,  $T_e(0) = 2.5$  keV,  $T_D(0) = 2.5$  keV,  $n_{^3He}/n_e = 0.20$ , and  $T_{^3He}(0) = 5.0$  keV]. Power density (W/cm<sup>3</sup> / incident W) vs. midplane distance  $x$  (cm). The chain-dot curve is the electron power density and the chain-double dash curve is the <sup>3</sup>He power dissipation.