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ELECTRON CYCLOTRON ASSISTED STARTUP AND HEATING SCENARIOS IN THE COMPACT IGNITION TOKAMAK*

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I. Introduction

The Compact Ignition Tokamak (CIT) operating scenario calls for ramping the toroidal magnetic field from B_T = 8.0 to 10.0 Tesla in a few seconds, followed by a burn cycle and a ramp-down cycle. Simultaneously, the plasma must be heated from an initial low beta equilibrium ($\bar{\beta} \simeq 0.44\%$ at 7.0 to 8.0 Tesla) to a final burn equilibrium ($\bar{\beta} = 2.5\text{-}5.5\%$) having 10.0 Tesla on the magnetic axis [1]. Here we propose ECRF heating of CIT to ignition utilizing a constant source frequency but with a time dependent, variable angle of injection. Thus, initially $N_\parallel$ is large enough so that the Doppler broadened resonance of particles on the magnetic axis with f = 280 GHz and B_T = 7.0 - 8.0 Tesla can provide adequate absorption [2]. As the resonance layer is moved toward the magnetic axis the microwave beam is swept toward perpendicular to $\vec{B}$ in order to reduce the Doppler width and avoid heating the plasma edge. At B_T = 10.0 Tesla for normal wave incidence strong absorption occurs immediately on the high field side of the resonance layer (relativistic regime) [3]. However, by reducing the angle of incidence from 90° to 60° (θ = 0 to 30°) absorption near the q = 1 surface, and concomitant sawtooth stabilization may be attained even in a burning plasma. We envisage using the ordinary mode (O-mode, $\vec{E}_{RF} \parallel \vec{B}$) of polarization which is accessible from the outside (low-field side) of the torus provided the density is such that $\omega_{pe} \leq \omega \approx \omega_{ce}$. Considering f = 280 GHz for central heating at $B(0) = 10.0T$, the maximum cutoff density is at $n_{crit} \approx 9.7 \times 10^{20}\text{m}^{-3}$ which is above the maximum central density ($n_{max} \simeq 7 \times 10^{20}\text{m}^{-3}$) in CIT. Electron heating in CIT is a viable option since equilibration of temperature between electrons and ions (τ_{EQ}) is expected to be significantly shorter than typical energy confinement times, τ_E. For example, at $n_e \approx 2.0 \times 10^{20}\text{m}^{-3}$, T_e = 5 keV, $Z_{eff} \approx 1.5$, we estimate $\tau_{EQ} \approx 30$ msec, while at $n_e(0) \approx 8 \times 10^{20}\text{m}^{-3}$, $T_e \approx T_i \approx 20$ keV, $\tau_{EQ} \approx 60$ msec, both significantly shorter than the expected energy confinement time.

II. Ray Tracing Results

To study single pass absorption of waves in equilibria representative of the CIT plasma, the temperature and density profiles are taken to be $T_e(\psi) = T_e(0)[1 - \psi]$ and $n_e(\psi) = n_e(0)[1 - \psi]$ where ψ is the normalized poloidal flux. The ray tracing and absorption simulation was performed using the Toroidal Ray Tracing, Current Drive and Heating Code (TORCH) developed by Smith and Kritz[4]. In Fig. 1 (a) we show the case of wave penetration and absorption for B_T = 8.5 T, $\theta = 20°$, $T_e(0)$ = 10 keV and $n_e(0) = 3.2 \times 10^{20}\text{m}^{-3}$. We find 100% single pass absorption with absorption peaking near r $\simeq$ 0. Notice that the half width of the absorption layer is typically $\Delta r \simeq 10$ cm. We find that relativistic effects (which are included in this code) shift the absorption toward the cyclotron resonance layer by amounts $\Delta r \gtrsim 10$ cm. Since the width of the particle resonance and the location of maximum absorption in the Doppler regime is directly proportional to $N_\parallel$, the power deposition profile can be controlled by changing the incident wave propagation angle. We find that for the 7.5 Tesla case, the optimum angle is approximately $\theta = 30^o$ to the normal [5]. In order to keep the absorption close to the magnetic axis as the beta and magnetic fields are increasing during the ramp-up, the angle must be swept toward normal incidence at $B_T = 10.0$ Tesla. This ensures wave penetration to the center at full field and beta (relativistic regime, $N_{\|} < (T_e/m_e c^2)^{\frac{1}{2}}$) [3] and central heating results for $\theta \gtrsim 10^o$ (see Fig. 1(b) for $\theta = 0$). By changing θ to 30^o away from the normal, absorption at $r/a \simeq 0.5$, near the $q = 1$ surface results which may be useful for sawtooth stabilization (see Fig. 1(c)).

The efficiency of coupling to the O-mode at the edge of the plasma as a function of the angle of incidence has been calculated, and the result is

$$\frac{P_O}{P_T} = \frac{1}{4}\left(1 + \frac{\sin^2\theta}{\eta}\right)^2 + \frac{\cos^2\theta}{\beta\eta^2}, \tag{1}$$

where $\beta = \omega_{ce}^2/\omega^2$ and $\eta = (\sin^4\theta + 4\cos^2\theta/\beta)^{\frac{1}{2}}$. For nonresonant heating ($B_T \geq 7$ T, $\theta \leq 30^o$), Eq. 1 predicts that at least 68% of the power injected will couple to the O-mode at the edge.

We have also examined the importance of scattering of EC rays by low frequency density fluctuations and find that for $< \delta n_e/n_e > \gtrsim 0.1$, scattering is not important. Monte Carlo calculations will be incorporated into the ray tracing code in the near future to further quantify these predictions.

III. Transport Code Simulations

A version of the combined equilibrium and transport code BALDUR1-1/2D originally developed by G. Bateman [6] has been used to simulate some important aspects of the ECH heating scenario for CIT. We have assumed that the electron heat flux can be written as $q_e = -\mathrm{M}\kappa_e \nabla T_e - (\mathrm{M}-1)\alpha_T \kappa_e T_e \nabla \mathrm{V}/\mathrm{V}(a)$ (conduction and inward heat pinch), with $\kappa_e = [\mathrm{CI}(\rho)\mathrm{V}^2(\mathrm{a})\mathrm{A}^{-3/2}/T_e(\rho)|\nabla V|^2][1 + \gamma_0(1 - P_{OH}/P_{TOT})^2 < \beta_p >]$ [7,8]. Here ρ is a flux surface label, I_ρ is the current within ρ, A is the total cross-sectional area, $\mathrm{V} = \mathrm{V}(\rho)$ is the volume within ρ, $\rho = \mathrm{a}$ designates the plasma boundary, and α_T describes a "canonical" profile shape $T_c \propto \exp(-\alpha_T \mathrm{V}/\mathrm{V}(a))$ which the transport model seeks to enforce. The constant C is chosen to fit low density Ohmic experiments, and $\gamma_0 \simeq 9$ reproduces L-mode experimental results with auxiliary heating, provided that ion heat transport of sufficient magnitude to reproduce ion temperature measurements is also present. This is illustrated in Fig. (2) showing the power dependence of electron stored energy and central ion temperature for 2.2 MA TFTR deuterium discharges with neutral beam injection and $\bar{n} \simeq 4.4 \times 10^{19}\mathrm{m}^{-3}$ at steady state [9,10]. Similar fits for 1.4 MA data are obtained by reducing the χ_i/χ_e values by 35%. The increase of the effective ion heat transport with input power appears consistent with an ion temperature gradient instability. The simulation points were obtained by neglecting the heat pinch [M = 1]and assuming an anomalous ion thermal conductivity with the same spatial dependence as the electron conductivity. It may be seen that while at low powers $\chi_i/\chi_e \gtrsim 0.5$, at high powers ($\mathrm{P} \lesssim 10$ MW) $\chi_i/\chi_e \simeq 1$ - 2 is required to fit the data. We have taken $\alpha_T = 3.33$ for all runs and have generally assumed that M = 3. H-mode transport is assumed to be reproduced by taking $\gamma_o \simeq 4.5$. ECH absorption per unit volume by electrons is represented by the form $\mathrm{P}(\rho) = \mathrm{P}_0\exp[-(x - x_0)^2/225]$, where $\mathrm{x}(\rho)$ is the half-width in cm of a flux surface in the meridian plane, x_0 designates the location of maximum absorption, and P_0 is proportional to the total power launched in the O-mode.

In our previous report [5], we assumed $\chi_i = 0.5\,\chi_e$, and considered both L-mode ($\gamma_o = 9$) and H-mode ($\gamma_o = 4.5$) confinement. To achieve ignition, L-mode confinement was acceptable as long as no sawteeth were present, and, depending upon density profiles, a confinement time of $\tau_E \simeq 0.60$ sec was predicted at ignition for $P_{RF} \simeq 17 - 25$ MW, $n_e(0) \simeq 6.6 \times 10^{20}\text{m}^{-3}$, $Z_{eff} = 1.5$, $\langle\beta\rangle \simeq 2.8\%$. However, under these conditions, $P_\alpha \simeq$ 70 MW, and, therefore, $\chi_i/\chi_e = 0.5$ is too optimistic.

Therefore, in the present paper we examine the importance of varying the anomalous conductivity ratio χ_i/χ_e for high density CIT discharges with parabolic density profiles. The 3 sec long ECH pulse is deposited halfway out from the magnetic axis near the $q = 1$ surface and profile consistency is assumed [8]. Assuming L-mode electron confinement and no sawteeth, 45 MW of auxiliary power is required to achieve ignition ($\tau_E = 0.5$ sec, $\langle\beta\rangle = 4.4\%$) for $\chi_i/\chi_e = 1.0$, while 75 MW ($\tau_E = 0.43$ sec, $\langle\beta\rangle = 5.8\%$) is needed for $\chi_i/\chi_e = 1.5$. Ignition does not occur for $\chi_i/\chi_e = 2.0$. It may be difficult to handle such an equilibrium and α power ($\sim$ 160 MW)and neutron flux ($\sim$ 640 MW) in CIT. Therefore, we must consider H-mode confinement, no sawteeth, and $\chi_i/\chi_e = 1.0$. In this case, 17 MW is sufficient to achieve ignition with $\tau_E = 0.73$ sec, $\langle\beta\rangle = 1.65\%$, (see Fig. 3(a)). Assuming $\chi_i/\chi_e = 2.0$, H-mode confinement ($\gamma_o = 4.5$), 36 MW of ECH power is needed for ignition with $\tau_E = 0.57$ sec, $\langle\beta\rangle = 2.7\%$ and $P_\alpha =$ 80 MW (see Fig. 3(b)).

To summarize the results of Ref. 5 and this paper, it is concluded that low to moderate values of $\chi_i/\chi_e(\lesssim 1)$ are desirable for ignition at reasonable RF and alpha powers, with confinement times of the order of $\tau_E \gtrsim 0.6$ sec. Peaked density profiles are most beneficial in this regard since in this case the η_i modes are expected to be stable, $\chi_i \simeq \chi_i^{NC}$, and ignition near the center will easily commence. Finally, sawtooth control by ECH deposited near the $q = 1$ surface may be of considerable importance.

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Figure Captions

Fig. 1. ECH ray trajectories. a) $B = 8.5$ T, $T_e = 10$ keV, $n_e(0) = 3.2 \times 10^{20}\text{m}^{-3}$, $\theta = 20^o$; b) $B = 10$ T, $T_e = 20$ keV, $n_e(0) = 8 \times 10^{20}\text{m}^{-3}$, $\theta = 0^o$; c) $B = 10$ T, $T_e = 20$ keV, $n_e(0) = 6 \times 10^{20}\text{m}^{-3}$, $\theta = 30^o$. Each solid circle represents 20% power absorption.

Fig. 2. Comparison of experimental (open squares) and simulation (circled numbers) results for TFTR, 2.2 MA deuterium discharges with neutral beam injection and $\bar{n} \simeq 4.4 \times 10^{19}\text{m}^{-3}$. a) Electron stored energy, including Thompson scattering recalibration; b) Central ion temperature.

Fig. 3. CIT discharge evolution for $n_e(0) = 6.6 \times 10^{20}\text{m}^{-3}$, ECH power deposited at $r/a = 0.5$. H-mode confinement, no sawteeth. a) $P_{RF} = 17$ MW, $\chi_i/\chi_e = 1.0$; b) $P_{RF} = 36$ MW, $\chi_i/\chi_e = 2.0$. T_e and T_i are the central, peak values.

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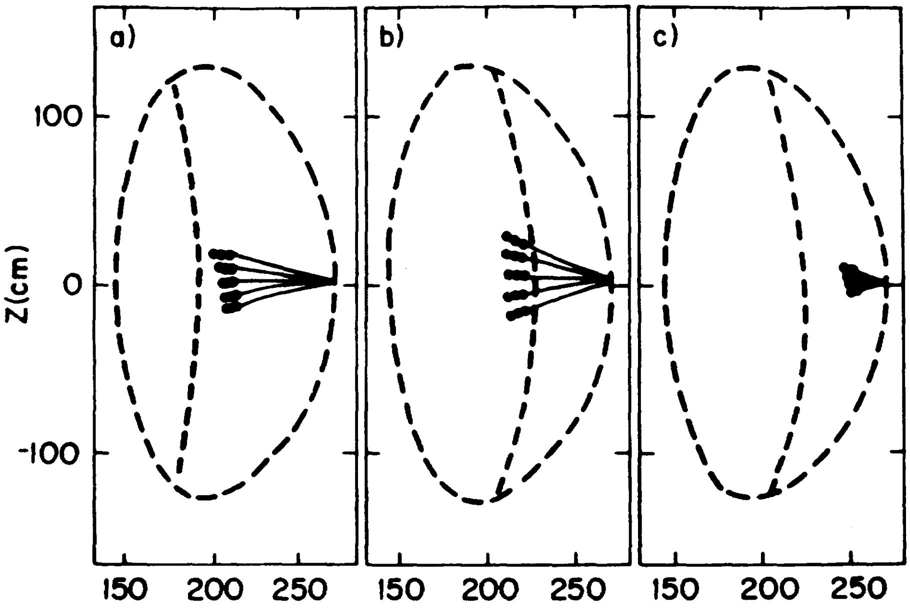

FIGURE 1

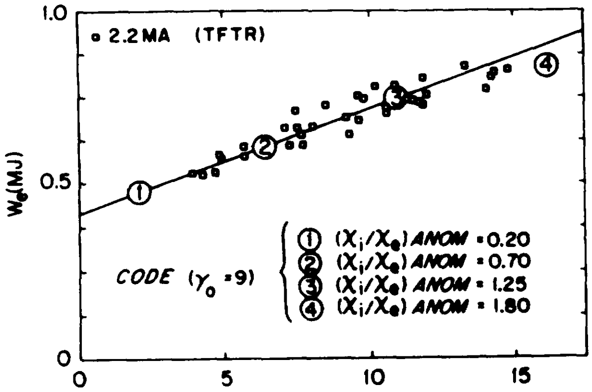

FIGURE 2(A)

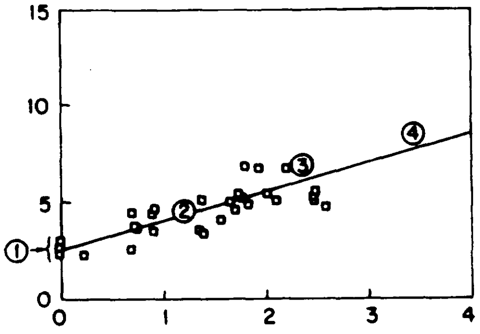

FIGURE 2(B)

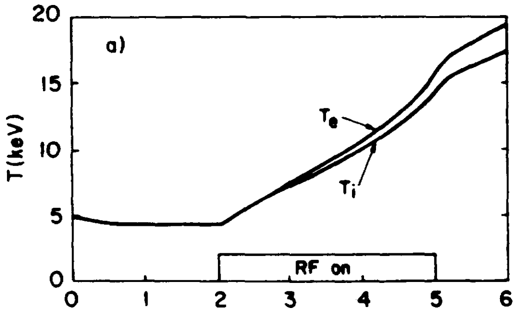

FIGURE 3(A)

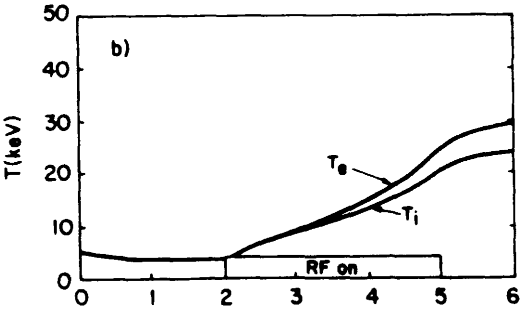

FIGURE 3(B)