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**Electron Cyclotron Heating and
Current Drive in Toroidal Geometry**

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I. Introduction

The Principal Investigator has continued to work on problems associated both with the deposition and with the emission of electron cyclotron power in toroidal plasmas.

We have investigated the use of electron cyclotron resonance heating for bringing compact tokamaks (BPX) to ignition-like parameters. This requires that we continue to refine the modeling capability of the TORCH code¹ (which evolved from the earlier TORAY code²) linked with the BALDUR 1 1/2 D transport code.³ Using this computational tool, we have examined the dependence of ignition on heating and transport employing both theoretical (multi-mode) and empirically based transport models. The work on current drive focused on the suppression of tearing modes near the $q = 2$ surface and sawteeth near the $q = 1$ surface. Electron cyclotron current drive in CIT near the $q = 2$ surface was evaluated for a launch scenario where electron cyclotron power was launched near the equatorial plane. The work on suppression of sawteeth has been oriented toward understanding the suppression that has been observed in a number of tokamaks, in particular, in the WT-3 tokamak in Kyoto. To evaluate the changes in current profile (shear) near the $q = 1$ surface, simulations have been carried out using the linked BALDUR-TORCH code. We consider effects on shear resulting both from wave-induced current as well as from changes in conductivity associated with changes in local temperature. Abstracts and a paper relating to this work is included in Appendix A.

The diagnostic potential of incremental synchrotron radiation that has been advanced in work by N. J. Fisch and the Principal Investigator⁴ is being implemented on PBX-M and is the focus of thesis work of two Princeton University Ph. D. students, K. Voss and S. Preische. A diagnostic system is being implemented on PBX-M which measures the time response of synchrotron emission to a brief pulse of lower hybrid power. It is anticipated that data obtained may yield information about the magnetic field pitch, the ion charge state, the electron density, or the deposition profile of the lower hybrid pulse. The Principal Investigator continues to contribute to this work by participating in the guidance of the theoretical aspects of the work carried out by the two doctoral students. Abstracts describing work that will be presented at the 9th Topical Conference on RF Power in Plasmas in August and the APS plasma physics meeting in November are included in Appendix A.

The Principal Investigator is also collaborating on a simulation of an electron cyclotron diagnostic designed to obtain information about the hot tail in the Tokamak de Varenne (Quebec).⁵ In that experiment, a ray will be launch vertically from the top, and TORCH will be used to calculate the transmission and reflection coefficients. The Principal Investigator is also responsible for supervising a Hunter College physics doctoral student, H. Song who is working on waves in nonuniform plasmas. In the past year, Mr. Song has worked closely with Professor Sen of Columbia University on both linear and nonlinear problems associated with the Ion Temperature Gradient mode. Work also continues in support of the various groups that are using the TORCH and TORAY codes. At present work has been started to convert these codes from the CRAY environment to the SUN and IBM workstation environment.

In the Sections that follow, we describe some of the work we carried out in the past year on electron cyclotron heating and current drive in toroidal plasmas as well as some of the results.

II. Studies of Electron Cyclotron Heating and Current Drive in CIT

We investigated scenarios in which electron cyclotron heating leads to ignition in an evolving CIT plasma.⁶ The electron cyclotron ray tracing and absorption are calculated using the toroidal ray tracing, current-drive and heating code TORCH. The absorption of the ECH power is computed using a module based on a weakly relativistic formulation developed by Shkarofsky.⁷ In the current-drive computation, relativistic effects and degradation of the current by magnetic trapping are included in an adjoint formulation.⁸ The required equilibrium information regarding density, magnetic field and temperature are obtained from the noncircular MHD equilibrium package of the BALDUR 1 1/2 D code. In particular, a noncircular MHD equilibrium calculation due to Hirshman⁹ is utilized in BALDUR code. The wave propagation and absorption are recalculated during the period of ECH injection, resulting in self-consistent profiles of RF plasma heating. An empirically based transport model¹⁰ was used in the BALDUR 1 1/2 D code to evolve the equilibrium.

In the study that was carried out, it was found that on-axis absorption can be maintained as B_0 is ramped from 8 T to 10 T by choosing $f_0 = 280$ GHz and linearly increasing the toroidal injection angle ϕ_0 of the center of the incident electron cyclotron wave energy from 60° to 80° or 85° . Similarly, off-axis electron cyclotron heating can be achieved as B_0 is ramped from 8 T to 10 T by using $f_0 = 240$ GHz and linearly sweeping ϕ_0 from 60° to 80° or 85° . This latter technique could be useful for heating near the $q = 1$ surface and perhaps stabilizing sawteeth. ECH-assisted ignition in CIT is found to have a power threshold of $P_{\text{EC}} > 15$ MW (with both on and off-axis absorption), assuming an H-mode enhancement factor ($\alpha_H = 2.0$) and a 0.3 s sawtooth period. Elimination of sawteeth was found to reduce the power threshold for ignition to $P_{\text{EC}} < 10$ MW, assuming H-mode confinement and off-axis electron cyclotron power absorption.

We also examined possible use of electron-cyclotron current drive to help prevent major disruptions in CIT. In particular, we considered the use of the current drive to suppress tearing modes near the $q = 2$ surface. With equatorial launch of the electron cyclotron power, the launch scenario envisioned for plasma heating, we found that it is difficult to drive sufficient electron cyclotron current at the $q = 2$ surface for reliable mode stabilization. In fact, current of significant magnitude and even of prescribed sign cannot be driven at the $q = 2$ surface. We concluded that if the surface were at smaller ψ (and therefore ϵ) where trapping effects were less and where the microwave absorption were stronger, then the equatorial-launch scenario might be successful. Alternatively, one could consider modification of the current profile in the presence of the inductive field by electron-cyclotron heating at larger ϕ_0 . More relevant to reactors with negligible inductive field is non-inductive current drive with a different launch scenario in which power is absorbed while propagating tangential to the desired flux surface.¹¹ Yet another type of option is heating or current drive at magnetic-island O-points¹² for which one could use either modulated gyrotron or pulsed free-electron laser sources.

III. Sensitivity of CIT Ignition to Transport Modeling

We investigated the dependence of fusion power in CIT on the type of heating employed, namely electron cyclotron or ion cyclotron, and on the transport model

employed in BALDUR. The electron cyclotron heating was computed using TORCH and the ion cyclotron heating was included in the calculation by using an assumed input power profile absorbed by the ions. We considered two transport models: 1) a multi-mode transport model and 2) an ITER scaling mode for thermal diffusivity associated with auxiliary heating. These transport models are summarized below.

The multi mode transport model involves a combination of theoretically derived transport models. Trapped electron mode and ion-temperature gradient driven modes are taken to dominate in core of the plasma and resistive ballooning modes dominate near the edge of the plasma. Coefficients are chose base on calibration of the model against L-mode, supershot and H-mode discharges.^{13,14} For the effective thermal diffusivities and for the collisionless and dissipative trapped electron modes we used forms similar to those used by Dominguez and Waltz¹⁵

$$\chi_{e,i}^{\text{DR}} = 8.33 F_{e,i}^{\text{DR}} F_{\beta} \left(\frac{r}{R} \right)^{1/2} \frac{\rho_s^2 c_s}{L_{ni}} \left[1, \frac{0.1}{\nu_e^*} \right]_{\min} [(1 + \kappa^2)/2]^{-2}$$

We took $F_e^{\text{DR}} = 0.2$ and $F_i^{\text{DR}} = 0.2$ consistent with a calibration against TFTR L-mode and supershots. Since, the trapped electron mode thermal diffusivities are such strongly nonlinear functions of temperature, the results are relatively insensitive to the choice of these coefficients. The finite beta correction, F_{β} , ranges between 1 and 1.35 and has the form¹⁶

$$F_{\beta} = \frac{1 + \beta'/\beta_c'}{1 + (\beta'/\beta_c')^3} \quad \text{where} \quad \beta_c' = \hat{s}/(1.7q^2 R)$$

For transition between dissipative and collisionless trapped electron modes we used the form¹⁷ $\left[1, \frac{0.1}{\nu_e^*} \right]_{\min}$ rather than the form¹⁵ $\left[1, \frac{\omega_*}{\nu_{\text{eff}}} \right]_{\min}$.

For the ion temperature gradient (η_i) modes we used¹⁸

$$\chi_{e,i}^{\text{IG}} = F_{e,i}^{\text{IG}} f_{\text{ith}} \frac{\rho_s^2 c_s}{L_n} (\eta_i - \eta_i^{\text{th}}) \exp(-5L_n/L_s) [(1 + \kappa^2)/2]^{-2}$$

where we took $F_e^{\text{IG}} = 3.0$ and $F_i^{\text{IG}} = 6.0$ and where

$$f_{\text{ith}} = \begin{cases} 0 & \text{for } \eta_i < \eta_i^{\text{th}} \\ 1 & \text{for } \eta_i > \eta_i^{\text{th}} \end{cases}$$

using the threshold η_i given by Dominguez-Rosenbluth

$$\eta_i^{\text{th}} = \max(1.0, 5.0 L_n/R)$$

The η_i mode typically fills in between the trapped electron modes in the core of the plasma and the resistive ballooning modes at the edge. Carreras-Diamond theory was used for resistive ballooning modes.¹⁹ The strong effect from diamagnetic stabilization of these modes typically decreases two to three orders of magnitude from the edge to the center.

Particle transport was described by simple empirical transport. Diffusivity and pinch velocity were given by

$$D = 0.5(1 - 0.5(r/a)^2) \text{ m}^2/\text{sec} \quad v = 0.3r/a^2 \text{ m/sec}$$

and produce a density profile of the form

$$n(r) = (n_0 - n_{edge})[1 - (r/a)^2]^{0.5} + n_{edge}$$

The transport coefficients were applied to all four charged particle species (D, T, He, C). A rather high edge pedestal condition $n_{edge} = 1.8 \text{ cm}^{-3}$ was used. The saw tooth period as estimated²⁰ and a fixed sawtooth period of 1.3 s was used. The Kadomtsev model was used to redistribute the temperature and density during crashes. Current density was not redistributed. Most of the calculations carried out used the multi-mode transport model outlined above. However we also considered the evolution of the rf-heated plasma when an empirical transport model is used for the auxiliary heated plasma. This model is described below.

For the auxiliary heated plasma the heat fluxes are given by

$$\begin{aligned} q_e &= -n_e \chi_e \nabla T_e & \chi_e &= \chi_e^{\text{OH}} + \chi_e^{\text{AUX}} \\ q_i &= -n_i \chi_i \nabla T_i & \chi_i &= \chi_i^{\text{NEO}} + M \chi_e^{\text{AUX}} \end{aligned}$$

where the generalized Coppi-Mazzucato-Gruber is used for ohmic heating thermal diffusivity^{10,21}

$$\chi_e^{\text{OH}} = \frac{C I(\rho) V^2(a) A^{3/2}(a)}{n_e(\rho) A_i^{2.4} T_e(\rho) |\Delta V|^2}$$

where ρ is flux surface label; a designates outer boundary; A_i is main ion mass number; $I(\rho)$ is current within ρ ; $A(\rho)$ is cross sectional area within ρ ; $V(\rho)$ is volume within ρ .

The ITER scaling for auxiliary heating is given by

$$\chi_e^{\text{AUX}} = 1.4 \frac{A(a)^2}{[A(a) - 0.9A(\rho)]4\pi(1+M)\tau_{\text{ITER}}} \times [1 - P_{\text{OH}}/P_{\text{TOT}}]^{1.5}$$

where

$$\tau_{\text{ITER}} = 0.048 \alpha_H \bar{A}_i^{0.5} I(a)^{0.85} R^{1.2} a^{0.3} \kappa^{0.5} \bar{n}_{20}^{0.1} B^{0.2} \times (P_{\text{TOT}} - P_{\text{BREM}})^{-0.5}$$

For H-Mode $\alpha_H = 2$, and we took $M = 2$ in the simulations. For the density profile evolution we include outward diffusion and an inward pinch $\propto \chi_e$. The fluxes of all the ions (D, T, light impurity and fusion thermalized alpha) were described by

$$\Gamma_i = D\nabla n_i + \gamma_N D n_i \nabla V / [V_A - V(\rho)]$$

where D was taken to be $0.35\chi_e$ and ion source profile factor $\gamma_N = 1$. We utilized Kadomtsev reconnection of density, temperature and fusion alphas at sawtooth crash.

Results for the alpha-power, P_α , and the Q factor after 8 seconds are summarized in Table 1. The effect of using various levels of electron heating and/or ion heating is illustrated. Also, the differences in the results predicted when empirical (E) transport is assumed as opposed to multi-mode (M) transport is indicated in Table 1. We found that fusion power produced with electron heating is similar to that with ion heating. However, with electron heating, the $q = 1$ surface is closer to the center of the plasma. Also, with electron cyclotron heating the sawteeth are less pronounced than with ion heating and the central electron temperature is higher. In comparing the simulations using the empirical transport model with those using the multi-mode model, we found that the empirically based model indicates larger τ_e and that the fusion power predicted by the simulation is twice what is predicted when the multi-mode model is used. We also found that with increased line-average density, there was a significant increase in τ_e and in the fusion power.

major radius R 2.6 m
 minor radius a 0.8 m
 elongation κ 2.
 triangularity δ 0.35
 toroidal field B 9.0 tesla
 toroidal current I_p 11.8 MA

1990 Compact Ignition Tokamak parameters (at the 95% flux surface):

Ion Heat. MW	El Heat. MW	Trans- port	ECH Freq. GHz	$\bar{n}_e(8s)$ 10^{14} cm^{-3}	$T_{eo}(8s)$ KeV	$\tau_e(8s)$ ITER89-P	$P_\alpha(8s)$ MW	$Q(8s)$ $P_\alpha/(P_{AUX} + P_{OH})$
25 (0.1-8 s)		M	240	3.3	17.3	1.56	40	7.1
	25 (0.1-8 s)	M	240	3.3	18.4	1.65	37	6.6
25 (4-8 s)	25 (0.1-4 s)	M	240	3.3	17.7	1.56	41	7.3
	25 (0.1-8 s)	M	245	3.3	25.4	1.68	37	6.6
	25 (0.1-8 s)	E	240	3.4	31.7	1.72	79	14.4
	25 (0.1-8 s)	M	240	4.6	25.2	1.83	98	18.0

IV. ECH Suppression of Sawtooth Oscillations

Sawtooth oscillations in a number of tokamaks have been observed to be suppressed with deposition of electron cyclotron power near the $q = 1$ surface.^{22,23} It has been proposed that this is due to current profile modification, that is changes in shear, leading to stabilization of the $m/n = 1/1$ resistive mode.²³ Electron cyclotron heating produces a change in the local current profile because associated with the power deposition 1) there is a direct wave induced current and 2) there is a change in the ohmic current because an increase in local temperature results in an increase in local resistivity.

The wave induced current is given by

$$\frac{J_{\parallel}}{B} = \left\langle \int d^3p \Gamma_w \cdot \frac{\partial}{\partial p} G \right\rangle$$

where $\langle \rangle$ denotes a flux surface average; Γ_w is the wave-induced velocity space flux; and G is modified to include mirror-trapped particles. The change in ohmic current profile results from the dependence of conductivity on temperature, that is

$$J = \sigma(T_e(r))E(r)$$

To gain further insight into these phenomena, we have used TORCH and recently TORCH combined with the BALDUR 1 1/2 D code to simulate the heating and current drive that occurs in an evolving plasma.

In our initial work on this subject, we focused on the data obtained in the WT-3 experiment. In that experiment, significant differences in stabilization occurred depending where on the $q = 1$ surface the heating occurred. In particular, with heating on the high field side, the suppression of the sawtooth oscillations were much more dramatic than with heating on the low field side.

We used TORCH (without BALDUR) to examine the effects of direct current drive on shear. The frequency of the RF power was chosen for second harmonic X-Mode power deposition near the $q = 1$ surface on both the high and low B-field sides. The tokamak equilibria into which the rf power was launched was generated using the PEST code, and a realistic description of the localization of the electron cyclotron power was obtained by describing the launched power with a gaussian beam antenna model. The total driven

current resulting from the electron power deposition was computed taking into account trapped particle and relativistic effects. The resulting modified current profile was then assessed for its stability properties using the PEST code. In our simulations, we found that the effect direct ECH current drive has on shear depends on beam pattern, beam power, launch angle, wave frequency, and plasma equilibrium (T_e , n_e). Depending on these parameters both decrease in shear near the $q = 1$ surface (resulting in stabilization) and increase in shear (resulting in destabilization) are possible consequences of electron cyclotron heating.

Our more recent work has involved determining the effect on shear associated with the change in local temperature that results from electron cyclotron heating. In particular, we simulate the evolution of the discharges using the combined BALDUR-TORCH code. Changes in shear that are a consequence of the local change in temperature are compared with changes in shear the result from wave induced current drive. While the immediate application is to interpret results obtained in the WT-3 tokamak, we are also exploring the potential use of electron cyclotron heating in the BPX tokamak for suppression of sawtooth oscillation.

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