Distribution Category:
Magnetic Fusion Energy
(UC-420)

ANL/FPP/TM-248

ANL/FPP/TM--248

DE90 013634

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439-4801

SIMULATIONS OF ICRF-FAST WAVE CURRENT DRIVE ON DIII-D

by
David A. Ehst
Fusion Power Program/Engineering Physics

June 1990

Work supported by
Office of Fusion Energy
U.S. Department of Energy
under Contract W-31-109-Eng-38

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

	<u>Page</u>
Abstract	1
1. Introduction	1
2. Experimental Conditions	2
3. Example Calculation	3
4. Survey Results	5
5. Typical Profiles - Two Examples	7
6. Conclusions	8
References	9

LIST OF FIGURES

Page

Figure 1	Typical ray trajectories in DIIID.	11
Figure 2	Evolution of index of refraction, $n_{\parallel}$, normalized parallel phase velocity, $w = \omega/k_{\parallel}v_e$, and normalized current drive efficiency [9] with and without electron trapping, plotted along a ray trajectory.	11
Figure 3	For the same ray as in Fig. 2, power density left in the wave and the flux-surface averaged parallel current density generated.	12
Figure 4	For case 53, the self-consistent MHD equilibrium showing: a) the flux-surface-averaged bootstrap current density (chain-dot), the wave driven seed current near the magnetic axis ($\Psi_{IHAT} = 1.0$), and the total current density (dotted), vs. normalized poloidal flux; b) the resulting toroidal current density profile in the midplane; c) the safety factor.	12
Figure 5	Single pass absorption vs. $n_{\parallel}$. Top curve: $T_{eo} = 6.5$ keV, $B_o = 1.0$ T, $\beta_t = 1.0$ T, $\beta_t = 2.2\%$. Middle curve: $T_{eo} = 3.5$ keV, $B_o = 1.0$ T, $\beta_t = 1.2\%$. Bottom curve: $T_{eo} = 6.5$ keV, $B_o = 1.9$ T, $\beta_t = 0.7\%$. ..	13
Figure 6	Single pass absorption vs. beta. Points clustered around upper curve have $n_{\parallel} = 5.0$; open circles are $n_{\parallel} = 2.5$. Results include both $T_{eo} = 6.5$ keV and 3.5 keV and $B_o = 1.0$ T and 1.9 T.	13

Figure 7	Influence of P_{edge} on: a) γ_{edge}^B and b) axis safety factor. Dotted curves are low beta ($\approx 0.7\%$) with $\bar{T}_e = 1.5$ keV and 2.2 keV. Solid curves are higher beta (≈ 1.4 -2.9%) with $\bar{T}_e = 1.5$ keV and 2.8 keV.	14
Figure 8	Total current vs. a) $\bar{T}_e$ and b) pressure; all with $Z_{\text{eff}} = 2.2$. Pentagons have $T_{eo} = 6.5$ keV, $n_{eo} = 0.18 \times 10^{20} \text{ m}^{-3}$, $B_o = 1.0$ T, various n_i ; open circles have $T_{eo} = 6.5$ keV, $n_{eo} = 0.30 \times 10^{20} \text{ m}^{-3}$, $B_o = 1.9$ T, various n_i ; triangles have $T_{eo} = 3.5$ keV, $n_{eo} = 0.30 \times 10^{20} \text{ m}^{-3}$, $B_o = 1.0$ T, different n_i	15
Figure 9	Current vs. average density. Top curve: $\bar{T}_e = 1.7$ keV, $Z_{\text{eff}} = 4.0$, $\beta_t \leq 0.7\%$, $P_{\text{edge}} = 1.80$ MW. Bottom curve: $\bar{T}_e = 0.8$ keV, $Z_{\text{eff}} = 2.2$, $\beta_t \geq 0.7\%$, $P_{\text{edge}} = 1.10$ MW.	16
Figure 10	Efficiency vs. Z_{eff} . Top curve: $T_{eo} = 6.5$ keV; triangles -- $\beta_t = 1.4\%$, circles -- $\beta_t = 0.7\%$. Bottom curve: $T_{eo} = 3.5$ keV, $\beta_t = 0.7\%$	16
Figure 11	Temperature profile (dashed) obtained from FWCD calculation ($\bar{T}_e = 0.69$ keV, $n_{eo} = 0.20 \times 10^{20} \text{ m}^{-3}$, $\bar{n}_e = 0.13 \times 10^{20} \text{ m}^{-3}$, $B_o = 1$ T, $Z = 4.0$, $P_{\text{edge}} = 1.80$ MW, $I_o = 176$ kA); and temperature profile (solid) measured in DIIID [12].	17
Figure 12	Calculated toroidal current density in midplane (a) with FWCD (296 kA); experimental current density (b) from NB&CD [11] (340 kA).	17

LIST OF TABLES

		Page
Table 1	Typical Results for DIIID FWCD	18

SIMULATIONS OF ICRF-FAST WAVE CURRENT DRIVE ON DIIID

David A. Ehst

ABSTRACT

Self-consistent calculations of MHD equilibria, generated by fast wave current drive and including the bootstrap effect, were done to guide and anticipate the results of upcoming experiments on the DIIID tokamak. The simulations predict that 2 MW of ICRF power is more than adequate to create several hundred kiloamperes in steady state; the total current increases with the temperature and density of the target plasma.

1. INTRODUCTION

According to theory [1-3], the fast wave polarization promises superior tokamak current drive performance at high plasma temperature and density, compared to the slow (lower hybrid) wave. A number of experimental tests have been carried out [4] to test fast wave current drive (FWCD), but these experiments have concentrated on wave frequencies at high harmonics of the fundamental deuterium cyclotron frequency ($\omega \geq 10 \Omega_D$). Recently, direct electron heating via transit-time-magnetic-pumping (TTMP) was demonstrated on JET [5] with a nondirectional antenna at frequencies ("ICRF") near the fundamental, bolstering the belief that FWCD is possible at the ICRF. The DIIID tokamak will provide the first opportunity to test this concept with a directional antenna.

As an aid to designing and interpreting the DIIID experiments a number of calculations of FWCD were done with the RIP code,[6] which self-consistently calculates 2-D tokamak equilibria with bootstrap and fast wave seed currents, and these results are presented here. Three modifications to RIP were instituted to accurately model low frequency FWCD:

1. The effect of TTMP on wave damping and FWCD [3,7] was added to the code. There is a transition from Landau damping to TTMP as the

frequency drops and the electron temperature increases [8], which is accounted for in the calculations.

2. Electron magnetic trapping at small aspect ratios can severely reduce FWCD, so care was taken to appropriately model this neoclassical effect [9].
3. Significant modifications to the bootstrap transport coefficients were found [10] when finite aspect ratio was properly factored into the neoclassical theory, and these updated coefficients are used in our work.

As will become apparent, the bootstrap current plays an important role under the DIIID conditions postulated in our calculations.

2. EXPERIMENTAL CONDITIONS

The assumed DIIID geometry is:

R_0	= 1.67 m	(major radius)
a	= 0.56 m	(midplane minor radius)
κ	= 1.6	(elongation)
d	= 0.25	(triangularity)

Wave propagation and damping is assumed in a pure deuterium plasma at a wave frequency of 60 MHz. Two values of the magnetic field on the magnetic axis are considered -- $B_0 = 1.0$ T and 1.9 T -- corresponding respectively to FWCD at the eighth and fourth cyclotron harmonics.

For simplicity the antenna spectrum is modelled by a single toroidal index of refraction, $n_{\parallel}$, and with a poloidal mode number $k_{\theta} \equiv 0$. The antenna launches power from the outboard midplane, and the total antenna radiation incident on the plasma is limited to $P_{\text{edge}} \leq 2.0$ MW. In RIP, typically five rays are launched over a poloidally distributed antenna extent (± 0.21 m, above and below the midplane) with symmetric power distribution to model the input power.

In the calculations we assume that a range of central electron densities -- $0.18 \leq (n_{eo}/10^{20} \text{ m}^{-3}) \leq 0.40$ -- should be attainable in DIIID [11,12]. It is essential to achieve a hot electron plasma to demonstrate FWCD, and we thus assume that additional heating (ECRH or neutral beams) will combine with the ICRF to provide a peak temperature in the range $3.5 \text{ keV} \leq T_{eo} \leq 6.5 \text{ keV}$ [12]. Pressure and temperature profiles influence the spatial distribution of the absorbed power and hence the resulting current density profile. We consider a variety of profiles in an attempt both to compare with previous experimental measurements and to study profile effects on FWCD. In the RIP calculation of the MHD equilibrium and ray tracing/FWCD the pressure is defined as $p(\tilde{\psi}) = p_0 \tilde{\psi}^\alpha$, where $\tilde{\psi}$ is the normalized poloidal flux; and the pressure width is varied over $1.4 \leq \alpha \leq 3.0$. The temperature and density are given by $T_e(\tilde{\psi}) = T_{eo} \tilde{\psi}^{\alpha_T}$ and $n_e(\tilde{\psi}) = n_{eo} \tilde{\psi}^{\alpha_n}$, and their volume average values, $\bar{T}_e$ and $\bar{n}_e$ are varied by adjusting the exponents such that $\alpha_T + \alpha_n = \alpha$. An additional uncertainty will be the impurity level during FWCD. Higher $\bar{n}_e$ operation should reduce Z_{eff} , but the injected power might increase Z_{eff} ; we examine two values -- $Z_{eff} = 2.2$ and 4.0 -- in this note.

An important caveat to our conclusions is that our calculations assume a true steady state with zero electric field. This will apply to the experiment only after the loop voltage vanishes and when the internal inductance becomes constant (perhaps several hundred milliseconds after applying the ICRF power [11]).

3. EXAMPLE CALCULATION

The RIP code iterates between calculations of the MHD equilibrium and solutions to the ray-tracing and current generation problem until the system converges to consistency. Figure 1 displays the ray trajectories of a typical example (Case 58 in Table I), and Fig. 2 illustrates the important parameters along the path of ray #3 (launched on the midplane with $n_{\parallel} = 5.0$). From Fig. 1 it is seen that the ray passes close to the magnetic axis before bending outward. (All calculations are stopped before the rays are reflected; thus any power not absorbed in a single pass through the plasma is assumed to be lost.) The abscissa in Fig. 2 is the normalized flux ($\tilde{\psi} = 0.0$ is the boundary; $\tilde{\psi} = 1.0$ is the magnetic axis), and the parameters are plotted for the inward-bound portion of the trajectory.

The index of refraction, n_i , increases by a factor of two, due to the small aspect ratio of DIIID, as the ray approaches the axis. A crucial variable, the ratio of parallel phase speed to the electron thermal speed -- $w \equiv (c/v_e n_i)$, affects both the damping strength and the current drive efficiency. Due to the variation of n_i and T_e along the ray path, w decreases from large values to near $w = 1.0$. When $w \gg 1$ the (normalized) efficiency of current drive is large; this efficiency, $\tilde{\eta}$, is shown in the figure as a solid line. Note that in a straight magnetic field (no trapped electrons) the efficiency $\tilde{\eta}(\epsilon=0)$ would be substantially larger. The dominant effect on FWCD, however, is that wave damping is extremely weak when $w \geq 3$ so that very little power density is absorbed for $\tilde{\psi} \leq 0.5$. This is illustrated in Fig. 3, where the ray's power is seen to diminish strongly near the axis. The generated current density -- $G(\tilde{\psi}) \equiv \langle j_i^{RF} B \rangle / \langle B^2 \rangle = (T_e/n_e) \tilde{\eta} \langle p_{rf} \rangle$ -- is proportional to the dissipated wave power $\langle p_{rf} \rangle$ and peaks strongly near the axis.

The contributions to $G(\tilde{\psi})$ from all five rays are summed and smoothed, and the bootstrap current, $H(\tilde{\psi}) = \langle j_i^{BT} B \rangle / \langle B^2 \rangle$, is also calculated. Figure 4 (from Case 53) shows that the bootstrap current typically supplies the bulk of the total current density. It is noteworthy in the fixture that even though $G+H = 0$ at the plasma boundary the diamagnetic (Pfirsch-Schlüter) current contributes to the toroidal component of the equilibrium current density.

We study the sensitivity of the expected DIIID results to:

a.	the antenna parameters	n_i
		P_{edge}
b.	the plasma parameters	T_{eo} and $\bar{T}_e$
		n_{eo} and $\bar{n}_e$
		B_o (which determines beta)
		Z_{eff}

The principal functions which we monitor include the fractional power absorbed in a single pass, $P_{\text{abs}}/P_{\text{edge}}$. Although multipass absorption may well happen in FWCD experiments we are more confident of success in DIIID if $P_{\text{abs}}/P_{\text{edge}}$ is large (≥ 0.5). We also calculate total current, I_0 , the plasma profiles, and the figure of merit for FWCD, $\gamma_{\text{edge}}^B = \bar{n}_e I_0 R_0 / P_{\text{edge}}$, these quantities being measurable from the experimental diagnostics. [The superscript "B" reminds us that bootstrap currents contribute to I_0 , although the simple MHD diagnostic loops cannot differentiate between the bootstrap and fast-wave components of I_0 . The subscript "edge" indicates that only P_{edge} is known in the experiment since the absorbed rf power is not readily inferred. If multipass absorption indeed occurs, then γ_{edge}^B would be larger than the values quoted here.

Further, we calculate both the "Troyon ratio" and the axis safety factor, q_{axis} , of the resulting equilibria. The Troyon ratio is defined as

$$g_T = \beta_t a B_0 / I_0 ,$$

where β_t is the toroidal beta; a conservative estimate would expect that g_T cannot exceed ~ 3.0 , although DIIID has done much better. Likewise, conservative planning might avoid $q_{\text{axis}} \leq 1.0$ which could lead to instability. A final constraint in this work was to limit our results to converged equilibria with essentially monotonic safety factors $q(\tilde{r})$ (which is easily achieved by supplying sufficient P_{edge} to drive adequate seed current near the magnetic axis -- see Fig. 4).

4. SURVEY RESULTS

Power absorption vs. n_i (Fig. 5)

As expected from Fig. 2, selecting $n_i \geq 5$ at the antenna results in $w = 2$ and strong damping when $T_{\text{eo}} = 6.5$ keV. Moreover, as shown in Fig. 5, selecting faster waves with $n_i \leq 3$ results in weaker absorption on the first pass. Nevertheless, at high β_t (top curve) over 50% of the power is absorbed in a single pass even for rather low n_i . Importantly, the normalized efficiency, γ_{edge}^B , is found in these calculations to be almost independent of n_i , due to the large bootstrap current contribution to the equilibria. Thus, for a given antenna power the steady state current is insensitive to the n_i launched (provided the spectrum is directional, of course).

Power absorption vs. beta (Fig. 6)

The most important factor to guarantee strong absorption is to increase beta. As the figure shows, $P_{\text{abs}}/P_{\text{edge}} \geq 50\%$ provided $\beta_t \geq 1.0\%$, regardless of n_i .

Sensitivity to P_{edge} (Fig. 7)

Due to the large bootstrap current, the effective current drive efficiency, γ_{edge}^B , is not a simple monotonic function of $\bar{T}_e$. In fact, Fig. 7a shows that γ_{edge}^B increases as P_{edge} decreases. The curves in Fig. 7a vary as $\gamma_{\text{edge}}^B = P_{\text{edge}}^{-1}$, which produces the interesting result that $I_0 (= \gamma_{\text{edge}}^B P_{\text{edge}})$ is independent of the antenna power over the range plotted. The lower limit to P_{edge} would occur when so little power is available to generate a seed current that the safety factor is non-monotonic (q_{axis} is too large). As seen in Fig. 7b, at high values of P_{edge} the axis safety factor is depressed; so for the high beta cases (solid curve) an upper limit of $P_{\text{edge}} = 0.6$ MW might be operable if instability occurs for $q_{\text{axis}} \leq 1$.

Current vs. average electron temperature (Fig. 8)

Although I_0 is insensitive to n_i and P_{edge} , it depends strongly on the average electron temperature. The points in Fig. 8 were obtained by varying the widths of the temperature and density profiles for given peak values. Thus, the pentagons, all with $T_{e0} = 6.5$ keV, show I_0 increasing as $\bar{T}_e$ varies from 0.5 keV to 3.0 keV. This underscores the relative importance of achieving high average temperatures (rather than high peak temperatures). For example, off-axis ECRH combined with central fast wave heating could be considered as a means of broadening the temperature profile and raising I_0 .

While single pass absorption was dependent on beta, it is significant that I_0 does not increase with beta. For example, the open circles in the figure correspond to I_0 as high as 480 kA, but they all have $\beta_t \leq 0.8\%$; the pentagons at the same high I_0 range all have $\beta_t \geq 2.0\%$. Since the highest beta cases graphed have Troyon ratios $g_T \approx 3.5$ there may be a tendency for these discharges to exhibit instability. Hence the (lower beta) experiments at $B_0 = 1.9$ T may generate just as much current but will be in safer operating regimes with respect to q_{axis} and g_T .

Figure 8b provides an alternative plot, of I_0 vs. the plasma pressure. It is difficult to conclude whether I_0 scales with electron temperature or with pressure.

Current vs. density (Fig. 9)

Figure 9 shows that I_0 increases with density, due to the strong bootstrap component. [This trend would not be true in the absence of the bootstrap effect, since elementary current drive theory would predict $I_0 \propto \bar{n}_e^{-1}$ at constant P_{edge} .] Note that the upper curve (with $\bar{T}_e = 1.7$ keV) represents larger current at a fixed density, even though beta is lower and Z_{eff} is higher than in the lower curve (with $\bar{T}_e = 0.8$ keV). The better fast wave coupling at high density and the large bootstrap contribution are strong motivations to pursue FWCD on DIIID at rather high $\bar{n}_e$.

Efficiency vs. Z_{eff} (Fig. 10)

At a fixed density and temperature the effective current generation efficiency decreases as the impurity content increases, as shown in Fig. 10. The points on a straight line in the figure represent about constant current. As Z_{eff} increases the required P_{edge} increases, but even at $Z_{\text{eff}} = 4.0$ there is ample power in DIIID to generate several hundred kiloamperes.

5. TYPICAL PROFILES - TWO EXAMPLES

The dashed curve in Fig. 11 is the temperature profile across the midplane for Case 59. This steady state equilibrium was calculated for an assumed temperature profile $T_e = T_{e0} \bar{\psi}^{1.7}$ and corresponds to a total current $I_0 = 176$ kA and $\beta_t = 0.6\%$ at $B_0 = 1.0$ T. The solid curve, for comparison, is the measured temperature profile in Ref. [12], obtained with ~1 MW of ECRH at the same density as for the FWCD calculation -- $\bar{n}_e = 0.13 \times 10^{20} \text{ m}^{-3}$. The congruence of the curves encourages us that the T_e profiles assumed in our calculations are typical of what may be achieved in the actual FWCD experiment.

It is interesting to compare FWCD predictions with the actual experience with neutral beam current drive (NBCD) on DIIID. Figure 12 shows the toroidal current density in the midplane for Case 58 -- 296 kA at $\bar{n}_e = 0.13 \times 10^{20} \text{ m}^{-3}$, $T_{e0} = 6.5$ keV, and $B_0 = 1.0$ T, with $\beta_t = 1.4\%$. The current density is qualitatively similar to the inferred profile (Ref. 11) in the NBCD experiment which achieved 340 kA at $\bar{n}_e = 0.20 \times 10^{20} \text{ m}^{-3}$, $T_{e0} \leq T_{i0} = 2.0$ keV, and $B_0 = 2.1$ T, with $\beta_t = 0.5\%$. A shifted magnetic axis and an inboard region of

reversed toroidal current density occur in both cases. The NBCD experiment used 10 MW of injected power, while the FWCD example requires only 1 MW of power. The higher FWCD efficiency arises primarily due to the larger bootstrap contribution -- at $T_{eo} = 6.5$ keV and $\bar{n}_e = 0.13 \times 10^{20} \text{ m}^{-3}$ the effective collisionality, ν_* , is further into the banana regime than for the NBCD experiment.

6. CONCLUSIONS

Regarding the multi-loop antenna:

- The FWCD results are insensitive to n_1 , so any value, $n_1 \sim 2-8$, will drive current, provided the power spectrum is directional.
- The available ICRF power, $P_{\text{edge}} \leq 2.0$ MW, is adequate to provide several hundred kiloamperes. Owing to the bootstrap effect, the total equilibrium current is essentially independent of P_{edge} . [At too low a power the safety factor may become double-valued, and at too high a power q_a may be driven below unity, depending on the value of B_0 .]

A successful experiment depends mostly on a well-prepared target plasma:

- The wave power absorbed in a single pass through the plasma increases with beta, and for the assumed conditions in DIIID we generally find $P_{\text{abs}}/P_{\text{edge}} \geq 50\%$; multipass absorption would improve upon the results cited in this report.
- The resulting current appears to increase with electron pressure, so the average $\bar{T}_e$ should be maximized by raising the central T_{eo} and especially by broadening the temperature profile (by off-axis ECRH, for example).
- Likewise, I_0 increases with electron density. (Antenna coupling should also improve with density.) Experiments with $\bar{n}_e \geq 0.2 \times 10^{20} \text{ m}^{-3}$ will be most successful and will be most meaningful with respect to future tokamaks such as ITER. For the best results,

sufficient heating power is needed to provide $\bar{T}_e \geq 2$ keV as the density is increased.

- Current drive efficiency, γ_{edge}^B , is highest when the impurity level is low, but even at $Z_{\text{eff}} \sim 4$ we expect $I_0 \geq 200$ kA is achievable with the available power.

In summary, DIIID should serve as an excellent test of the FWCD concept. The main challenges will be to provide good antenna-plasma coupling with a directional spectrum and a hot electron target plasma for the waves.

References

1. D.A. Ehst, in Non-inductive current drive in tokamaks, Proc. IAEA Tech. Comm. Mtg., Culham 1983, Culham Laboratory Report CLM-CD (1983), D.F.H. Start, ed., vol. ii, p. 442.
2. F.W. Perkins, in FED-A, Oak Ridge National Laboratory Report ORNL/FEDC-83/1 (1983), Y-K.M. Peng and P.H. Rutherford, eds., p. 4-28.
3. D. Moreau, J. Jacquinet, P.P. Lallia, "Fast Wave Current Drive," in JET Contributions to 13th European Conf. Contr. Fusion and Plasma Heating (Schliersee 1986), JET Report JET-P(86)15, p. 65.
4. D.A. Ehst, "Fast Wave Current Drive: Experimental Status and Reactor Prospects," Argonne National Laboratory Report ANL/FPP/TM-219 (1988).
5. L.-G. Ericksson and T. Hellsten, Nucl. Fusion 29 (1989) 875.
6. M.-Y. Hsiao, D.A. Ehst, K. Evans, Jr., Nucl. Fusion 29 (1989) 49.
7. M.J. Fisch, C.F.F. Karney, Phys. Fluids 24 (1981) 27.
8. S.C. Chiu, V.S. Chan, R.W. Harvey, M. Porkolab, Nucl. Fusion 29 (1989) 2175.

9. D.A. Ehst, C.F.F. Karney, "Neoclassical Effects on RF Current Drive," Argonne National Laboratory Report ANL/FPP/TH-247 (1990).
10. S.P. Hirshman, Phys. Fluids 31 (1988) 3150.
11. T.C. Simonen et al., Phys. Rev. Lett. 61 (1988) 1720.
12. R. Prater et al., "Electron Cyclotron Heating Experiments in the DIII-D Tokamak," in Plasma Physics and Contr. Nuclear Fusion Res. 1988, Proc. 12th Conf., Nice 1988, vol. i, p. 527.

Figure 1. Typical ray trajectories in DIIID.

Figure 2. Evolution of index of refraction, n/n_0 , normalized parallel phase velocity, $w = \omega/k_{\parallel}v_e$, and normalized current drive efficiency [9] with and without electron trapping, plotted along a ray trajectory.

Figure 3. For the same ray as in Fig. 2, power density left in the wave and the flux-surface averaged parallel current density generated.

Figure 4. For case 53, the self-consistent MHD equilibrium showing: a) the flux-surface-averaged bootstrap current density (chain-dot), the wave driven seed current near the magnetic axis (PSIHAT = 1.0), and the total current density (dotted), vs. normalized poloidal flux; b) the resulting toroidal current density profile in the midplane; c) the safety factor.

Figure 5. Single pass absorption vs. $n_{||}$. Top curve: $T_{eo} = 6.5$ keV, $B_o = 1.0$ T, $\beta_t = 1.0$ T, $\beta_t = 2.2\%$. Middle curve: $T_{eo} = 3.5$ keV, $B_o = 1.0$ T, $\beta_t = 1.2\%$. Bottom curve: $T_{eo} = 6.5$ keV, $B_o = 1.9$ T, $\beta_t = 0.7\%$.

Figure 6. Single pass absorption vs. beta. Points clustered around upper curve have $n_{||} = 5.0$; open circles are $n_{||} = 2.5$. Results include both $T_{eo} = 6.5$ keV and 3.5 keV and $B_o = 1.0$ T and 1.9 T.

Figure 7. Influence of P_{edge} on: a) γ_{edge}^B and b) axis safety factor. Dotted curves are low beta ($\approx 0.7\%$) with $T_e = 1.5$ keV and 2.2 keV. Solid curves are higher beta (≈ 1.4 -2.9%) with $T_e = 1.5$ keV and 2.8 keV.

Figure 8. Total current vs. a) $\bar{T}_e$ and b) pressure; all with $Z_{\text{eff}} = 2.2$. Pentagons have $T_{e0} = 6.5$ keV, $n_{e0} = 0.18 \times 10^{20} \text{ m}^{-3}$, $B_0 = 1.0$ T, various n_i ; open circles have $T_{e0} = 6.5$ keV, $n_{e0} = 0.30 \times 10^{20} \text{ m}^{-3}$, $B_0 = 1.9$ T, various n_i ; triangles have $T_{e0} = 3.5$ keV, $n_{e0} = 0.30 \times 10^{20} \text{ m}^{-3}$, $B_0 = 1.0$ T, different n_i .

Figure 9. Current vs. average density. Top curve: $\bar{T}_e = 1.7 \text{ keV}$, $Z_{\text{eff}} = 4.0$, $\beta_t \leq 0.7\%$, $P_{\text{edge}} = 1.80 \text{ MW}$. Bottom curve: $\bar{T}_e = 0.8 \text{ keV}$, $Z_{\text{eff}} = 2.2$, $\beta_t \geq 0.7\%$, $P_{\text{edge}} = 1.10 \text{ MW}$.

Figure 10. Efficiency vs. Z_{eff} . Top curve: $T_{e0} = 6.5 \text{ keV}$; triangles -- $\beta_t = 1.4\%$, circles -- $\beta_t = 0.7\%$. Bottom curve: $T_{e0} = 3.5 \text{ keV}$, $\beta_t = 0.7\%$.

Figure 11. Temperature profile (dashed) obtained from FWCD calculation ($T_e = 0.69$ keV, $n_{eo} = 0.20 \times 10^{20} \text{ m}^{-3}$, $\bar{n}_e = 0.13 \times 10^{20} \text{ m}^{-3}$, $B_0 = 1$ T, $Z = 4.0$, $P_{\text{edge}} = 1.80$ MW, $I_0 = 176$ kA); and temperature profile (solid) measured in DIIID [12].

Figure 12. Calculated toroidal current density in midplane (a) with FWCD (296 kA); experimental current density (b) from NBCD [11] (340 kA).

Table 1: Typical Results for DIII-D FMCD

Case #	B_o/Z_{eff} (T)	$n_{eo}/\bar{n}_e$ $10^{20} m^{-3}$	$T_{eo}/\bar{T}_e$ keV	n_i	P_{abs}/P_{edge} MW	I_o kA	$B_{Y_{edge}}$	B_T T	q_T	q_{axis}
62	1.0/2.2	.18/.13	6.5/.77	5.0	.21/.35	177	.10	0.7	2.4	.91
40	1.0/2.2	.18/.07	6.5/1.8	2.5	.40/.75	313	.05	1.2	2.2	.66
42	1.0/2.2	.18/.08	6.5/2.0	2.5	.27/.50	330	.09	1.3	2.4	.95
37	1.0/2.2	.18/.10	6.5/2.8	2.5	.43/.60	433	.12	2.0	2.8	.95
38	1.0/2.2	.18/.10	6.5/2.9	2.5	.39/.55	442	.14	2.2	2.9	1.10
41	1.0/2.2	.18/.10	6.5/2.9	3.5	.42/.55	442	.14	2.1	2.9	1.07
43	1.0/2.2	.18/.10	6.5/2.9	5.0	.47/.55	452	.14	2.2	2.9	1.20
44	1.0/2.2	.18/.11	6.5/~3	7.5	~.47/.55	459	.14	2.3	3.0	1.43
58	1.0/4.0	.20/.13	6.5/1.4	5.0	.76/.98	296	.07	1.4	2.8	.83
59	1.0/4.0	.20/.13	3.5/.69	5.0	.79/1.80	176	.02	0.6	2.2	1.05
60	1.0/2.2	.20/.13	3.5/.74	5.0	.54/1.20	194	.04	0.7	2.2	1.10
63	1.0/2.2	.30/.20	3.5/.80	5.0	.76/1.05	242	.08	1.1	2.8	1.17
64	1.0/2.2	.40/.27	3.5/.86	5.0	.86/1.05	291	.13	1.6	3.4	1.23
65	1.9/2.2	.40/.28	3.5/.95	5.0	.73/2.00	293	.07	0.5	2.0	3.8
47	1.9/2.2	.30/.13	6.5/2.1	5.0	.57/1.70	424	.06	0.6	1.7	1.44
48	1.9/2.2	.30/.24	6.5/2.4	3.5	.32/1.70	463	.07	0.8	1.9	2.6
53	1.9/4.0	.30/.21	6.5/1.7	5.0	.39/1.80	370	.07	0.7	2.1	2.29
54	1.9/4.0	.20/.14	6.5/1.7	5.0	.39/1.80	303	.04	0.4	1.7	2.57