Distribution Category:
Magnetic Fusion Energy
(UC-420)

ANL/FPP/TM-238

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DE89 009676

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**ITER EQUILIBRIUM WITH BOOTSTRAP CURRENTS,
LOWER HYBRID CURRENT DRIVE AND FAST WAVE CURRENT DRIVE**

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March 1989

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

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ITER EQUILIBRIUM WITH BOOTSTRAP CURRENTS, LOWER HYBRID CURRENT DRIVE AND FAST WAVE CURRENT DRIVE

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ABSTRACT

A current drive system is proposed for the technology phase of ITER which relies on rf power and bootstrap currents. The rf/bootstrap system permits operation at high safety factor, and we consider the axial value to be $q_a \approx 1.9$, which minimizes the need for seed current near the magnetic axis. Lower hybrid power (~ 30 MW) provides current density near the surface, ICRF (~ 65 MHz, ~ 30 MW) fast waves generate current near the axis, and high frequency fast waves (~ 250 MHz, ~ 74 MW) supply the remaining current density. The system is not yet optimized but appears to offer great flexibility (ion heating for ignition, current rampup, etc.) with relatively inexpensive and well developed technology.

I. Introduction: Current Drive Optimization for ITER

It is desirable to provide current drive (CD) for ITER with power sources which, unlike MeV neutral beams and high frequency ECRF systems, are reasonably well developed technologies. This leads us to consider the lower rf frequency ranges (~ 100 MHz, "ICRF", and ~ 1 GHz, "LHRF") for which tetrode and klystron technologies are well developed and which promise high electrical efficiencies of the driver systems. Moreover, we should endeavor to create a plasma equilibrium which requires the least absorbed rf power, while maintaining adequate total current for stability and confinement. This report concentrates on the physics aspects of rf CD in that an attempt is made to maximize the bootstrap current contribution and minimize the rf power. The equilibrium generated is characterized by a large value of the safety factor at the magnetic axis, $q_a \approx 1.9$. This scheme was studied previously,^[1] and it was shown that raising q_a removes current density from the central region where the bootstrap contribution is small; this has the effect of reducing P_{CD} , the auxiliary heating required to provide the seed current. An equivalent explanation of this strategy is that raising q_a increases poloidal beta, which allows a greater fraction of the equilibrium current to be provided for free by the bootstrap effect.^[2]

II. Equilibrium Generation under ITER Rules

We have adopted the reference ITER configuration for the steady-state technology phase of operations; the parameters are summarized in Table I. We have used an optimistic value of the Troyon ratio, $g = \beta_t R_0 B_0 / (AI) = 0.032$, which is permitted under ITER guidelines which assume that CD may permit a degree of profile control in order to maximize the value of g . There is additional latitude permissible in that CD may allow a variety of safety factors to be created. Although it appears non-intuitive, it is possible to generate a large current, $I = 18$ MA, in ITER with $q_a = 1.87$ and with a monotonic $q(\tilde{\psi})$, where $\tilde{\psi}$ is the normalized poloidal flux. This is achieved

by using a broad pressure profile, $p(\tilde{\psi}) = p_0 \tilde{\psi}^\alpha$, where $\alpha = 1.2$. The beta and safety factor in Table I result from a model of diamagnetism, $F(\psi) = RB_t = F_b [1 - \delta \tilde{\psi}^{\alpha_F}]^{1/2}$, where $\delta = 0.0474$ and $\alpha_F = 4.0$.

This target equilibrium, which we will attempt to duplicate with rf CD, is displayed in Figs. 1-3. The flux contours, Fig. 1, are used for the rf ray tracing calculation, and the resulting rf-generated and bootstrap currents are used to compute a new equilibrium.^[3] This process is iterated until the result converges. Note in Figs. 2 and 3 that the target equilibrium has substantial toroidal current density near the plasma boundary. At the magnetic axis, $R_a = 5.8$ m, the toroidal current density is only ~ 70% of its peak value.

We have chosen very simple pressure and diamagnetism functions in order to expedite the CD calculation. A detailed stability study might show that more elaborate functions are needed to achieve stability at $g = 0.032$. For example, the shear, $dq/d\psi$, is known to affect stability, but such details have not been completely addressed at present. We do not expect the CD conclusions to be greatly changed by small changes in the equilibrium, however.

III. Bootstrap Current

Plasma profiles in part determine the bootstrap current density. In the absence of detailed knowledge of the ITER profiles we have made plausible conjectures. With the density, temperature, and pressure profiles modelled by $n_e(\tilde{\psi}) = n_{e0} \tilde{\psi}^{\alpha_n}$, $T_e(\tilde{\psi}) = T_{e0} \tilde{\psi}^{\alpha_T}$, and $p(\tilde{\psi}) = p_0 \tilde{\psi}^\alpha$, we have the relation $\alpha_n + \alpha_T = \alpha = 1.2$. Considering the difficulty of fuelling near the plasma center, the density will likely be rather flat, with $\alpha_n < \alpha_T$. However, the logarithmic ratio $\eta \equiv d \ln T / d \ln n = \alpha_T / \alpha_n$, and various instabilities may limit the maximum value of η . [We assume $T_e(\tilde{\psi})/T_{e0} = T_i(\tilde{\psi})/T_{i0}$, so $\eta_e = \eta_i$.] Our choice, in Table I, of $\alpha_n = 0.4$ and $\alpha_T = 0.8$ seems reasonable.

The volume average parameters, $\bar{n} = 0.70 \times 10^{20} \text{ m}^{-3}$ and $\bar{T}_e = 18 \text{ keV}$, result in peak values $n_{e0} = 0.99 \times 10^{20} \text{ m}^{-3}$ and $T_{e0} = 32.8 \text{ KeV}$ for our equilibrium. The plasma also suffers from a high impurity content, $Z_{\text{eff}} = 2.2$, during this phase of operation.

Our CD calculation focuses on the function $G(\tilde{\psi}) = \langle j_\parallel B \rangle / \langle B^2 \rangle$ where $\langle \rangle$

denotes a flux surface average. Figure 4 shows G for our target equilibrium. The abscissa is $\tilde{\psi}$, which is zero at the boundary and unity at the magnetic axis. For well behaved equilibria $G = 0$ at the boundary, as the figure shows. The lower curve in the figure is the bootstrap contribution to G , i.e., $H(\tilde{\psi}) \equiv \langle j_{\parallel}^B \rangle / \langle B^2 \rangle$, where $\langle j_{\parallel}^B \rangle$ is given by neoclassical theory.[2,4] Roughly speaking, H provides $\sim 30\%$ of the equilibrium current density over the plasma volume. Note that H is small at the axis and near the boundary, where the plasma is not in the banana regime. The CD requirement is now clearly visualized; the rf power must provide the complementary "seed" current density to fill the gap between H and G in this figure.

IV. RF Current Generation

We propose to provide rf CD with sources at several frequencies. The added complexity of using several sources is offset by the additional flexibility in ITER operations. Moreover, the use of multiple systems will supply a measure of insurance in case one technique encounters unanticipated problems. We will study rf CD for the equilibrium of Table I with three systems: LHRF -- multi - GHz slow wave; ICRF -- fast wave near the second fuel ion cyclotron harmonic frequency; and a higher frequency fast wave (FW) near the tenth ion cyclotron harmonic.

We include LHRF because it has a large data base for CD in low density experiments. The first consideration is selecting the proper frequency. It is generally felt that $f \approx 8$ GHz is sufficiently high to avoid nonthermal alpha damping of the slow wave. In addition, engineering design studies[5] suggest that choosing a $f \gtrsim 8$ GHz permits LH grill designs with quite thin septa (which are edge-cooled), allowing well defined power spectra in n_t (the toroidal index of refraction). On the other hand, the fast alpha density is likely to be small in the outer plasma regions (due to, for example, losses from stochastic particle orbits), and a lower f may be perfectly adequate to provide CD.

Calculations of LHCD are insensitive to the actual frequency, however. This is because LH penetration is limited by density and electron temperature. Figure 5 displays LH ray trajectories at $f = 8.0$ GHz for a spectrum of n_t values. The group velocities are mostly in the toroidal direction, as the waves only slowly travel inward in minor radius. Figure 6

shows the penetration and current density, $\langle j_{\parallel} B \rangle / \langle B^2 \rangle$, generated by the ray spectrum as a function of $\tilde{\psi}$. The furthest penetration is achieved by the smallest n_t , since linear Landau damping strongly depletes a wave's energy when $(\omega/k_{\parallel} v_e) \approx 4$. For ITER we find $n_t \approx 1.65$ is the smallest allowed index, as smaller values are below the accessibility limit and such waves would be reflected at lower densities. The LH waves penetrate only to $\tilde{\psi} = 0.3$, where $T_e \approx 12$ KeV and $n_e \approx 0.6 \times 10^{20} \text{ m}^{-3}$.

If the LH wave energy density could be concentrated in n_t then strong heating could distort the electron distribution and result in weaker, quasilinear damping. Typically one might then achieve LH penetration to the region where $(\omega/k_{\parallel} v_e) \approx 3$.^[6] This corresponds to somewhat higher temperatures. However, it is questionable whether a very narrow Δn_t can be maintained as the LH waves propagate through the plasma. Density fluctuations, magnetic ripple and islands, and diffraction effects have been proposed as mechanisms which could strongly distort the power spectrum.

Figure 7 displays the contribution to G made by 20 MW of LH power spread over a broad spectrum. Appropriate spectral tailoring with an overall increase in power can reproduce the G function quite closely in the region $\tilde{\psi} \lesssim 0.3$. The same LH system could be combined with either a neutral beam or a different rf power system in order to provide the current density in the interior.

Low frequency fast waves in the ICRF are an attractive candidate to provide CD near the axis, since ion heating experiments have provided ample evidence that these waves can reach the high-density central region. We propose to directly heat electrons to provide CD, and this forces a careful selection of the wave frequency in order to avoid parasitic ion damping. If we assume the ITER plasma to retain only trace amounts of high Z impurities then the main ion damping concerns center around the fuel species and alpha ash. The best frequency seems to be $f = 65.0$ MHz for ITER, which, as shown in Fig. 8, results in only the $\omega = 2\Omega_T$, second tritium harmonic, being within the plasma. Since the deuterium and alpha resonances are outside the plasma ($R \approx 7.4\text{m}$) an ICRF antenna may be located anywhere on the outboard edge, and these waves will pass through the high central electron temperature region, depositing substantial power for electron CD before passing further inboard and encountering absorption by tritium.

At these low frequencies the fast wave propagates almost completely in the minor radius direction at the Alfvén speed; a typical ray trajectory is shown in Fig. 9. Note the strong evolution of $n_{\parallel}$, the index of refraction along the $\underline{B}$ field direction, which is due to the rather small aspect ratio, $A \approx 3$. Of importance to us is the fact that most of the ray's power is dissipated on electrons in a single pass through the plasma. This is displayed in Fig. 10; tritium absorbs $\sim 10\%$ of the power, while electrons absorb $\sim 75\%$ of the power. Thermal broadening of the $\omega = 2\omega_D$, deuterium resonance occurs, but deuterium damping rates are orders of magnitude smaller than other absorption mechanisms. About 15% of the power remains when the ray encounters the inboard edge, and this power can be absorbed in the plasma after it is reflected from the first wall. To be conservative, we do not consider multiple reflections. Rather, our CD calculation only includes power absorbed in the first pass; the remainder is assumed to be wasted power.

Figure 11 shows the ray paths ($n_t=1.5$) for power launched from a range of poloidal angles. An actual antenna will have some poloidal extent, but the present calculation does not attempt to simulate a true antenna power spectrum. Likewise, a poloidal mode number, n_θ , spectrum will be broadcast from an actual launcher, but including n_θ does not significantly alter our conclusions for ICRF CD (which assume $n_\theta=0$). One constraint which may bear on our conclusions is that ITER was assumed to have a double-null divertor with particle and power exhaust at both the top and bottom. Thus the ICRF launch position was proscribed at the very top and bottom. This may somewhat limit our ability to generate broad current density profiles with ICRF.

Although the ICRF scheme is not yet optimized we can make some general observations. As seen in Fig. 11, the ICRF fast waves easily penetrate to the magnetic axis and generate a contribution to $G(\tilde{\psi})$ which is concentrated around the central flux surfaces. These low frequency waves have a small value for the ratio $(\frac{\omega^2}{\omega_{pi}^2} \frac{mc^2}{T_e})$ which results in damping by combined Landau and transit time magnetic pumping processes. The waves' large radial group velocity leads to the strongest wave-particle energy transfer when $(\omega/k_{\parallel} v_e) \approx 1$, and, in the absence of trapped electron effects, the normalized ratio of current density to power density $\tilde{j}/\tilde{p}$, is larger than would be achieved by Landau damping alone.[3,7] Many of these observations have been made previously by other authors,[8-10] but our present results are an attempt to

rigorously include the low frequency fast wave physics in a self-consistent ray tracing, rf CD, and MHD equilibrium calculation. Care must be taken to properly account for electron trapping since the waves' parallel phase speed is comparable to the thermal speed, v_e . (See Appendix C for a detailed description of our treatment of trapped electrons.) Fortunately, the local aspect ratio is large near the axis so electron trapping does not prevent CD.

The principal conclusion, drawn from Fig. 11, is that ICRF waves do not provide a very broad current density profile, although they are an excellent source of current right near the high T_e axis region. Thus in order to provide current density in the region $0.3 \lesssim \tilde{\psi} \lesssim 0.7$ we are motivated to consider FW CD at higher frequencies.

Our search for the perfect CD wave turns to the FW at f approximately ten times the fundamental ion cyclotron frequency, $\omega \sim 10 \Omega_i$. A number of theoretical studies [11-13] of this wave have been produced, and several low-power experiments have been performed with generally good results (see Ref. 14 for a detailed analysis of experimental results). A high-power experiment is planned for DIII-D at General Atomics (see Appendix B).

Selecting the optimal frequency for this FW involves several considerations. First, increasing f results in slower radial penetration of the FW. For ITER, for example with $f = 250$ MHz as shown in Fig. 12, such ray trajectories allow absorption and CD at larger $(\omega/k_{\parallel} v_e)$ values than ICRF, resulting in absorption at larger minor radii. Moreover, operation at $\omega \gtrsim 5 \Omega_i$ permits the waves to traverse ion cyclotron harmonic resonances with negligible ion damping, even at $T_i \gtrsim 30$ keV. (See Fig. 13.) In addition, nonthermal alpha absorption may decrease as f increases to $\omega \approx 10 \Omega_\alpha$. However, selecting ω/Ω_i too large may introduce other difficulties. As shown in Appendix A, some FW CD experiments have not exceeded the LH density limit for CD at high frequencies. These experiments generally support both the slow and fast waves, and it is possible that power is accidentally coupled into the slow wave, limiting the CD effect.^[14] This limitation is surely removed by maintaining rather small values of ω/Ω_i which push the lower hybrid resonance into a very low density region in the plasma scrapeoff region. Also, operation at very large ω/Ω_i reduces the cutoff upper limit to the $n_{\parallel}$ which can propagate in ITER. Our choice of 250 MHz is a preliminary selection, subject to further tradeoff studies.

Technology issues should also be considered with regard to frequency selection. Note that 250 MHz would permit various waveguide coupler designs for ITER, as well as loop antenna options. This leeway in launcher design may ease the engineering of reactor-relevant couplers. However, operation at $f \gtrsim 100$ MHz may force the designers to use klystron power sources instead of tetrodes, and a possible decrease in electrical efficiency should be considered in selecting the optimum frequency.

For 250 MHz we have illustrated the power deposition and contribution to $G(\tilde{\psi})$ in Fig. 14 for several $n_{||}$ values and poloidal launch positions in ITER. The current profile can be quite broad and may extend to the magnetic axis. However, with the adopted constraint on poloidal launch location, enforced by the double-null configuration, it does not appear possible to generate a large current density peaked around $\tilde{\psi} \approx 0.4$.

V. Converged rf CD/MHD Equilibrium Solution

Based on surveys of ray trajectories for the three frequency regimes under consideration we chose a variety of launch positions and adjusted the power spectra in order to duplicate the target $G(\tilde{\psi})$ as much as possible. Figure 15 shows the individual ray contributions to G as well as the bootstrap term, H . The total, shown by the dotted line, does not exactly reproduce the target G (solid line) of the initial equilibrium, and consequently the converged equilibrium will be somewhat different than that described by Table I and Figs. 1 - 3. A more accurate duplication of the initial, arbitrarily chosen, equilibrium would be possible if additional current density could be localized in the vicinity of $\tilde{\psi} \approx 0.4$; this might occur, for example, if quasilinear damping permitted LH wave penetration to a slightly hotter T_e . The system envisaged by this design requires the following power spectra:

LH (8.0 GHz) $n_t = 1.7 - 5.0$	$P_{LH} = 29.5$ MW
FW (250 MHz) $n_t = 1.2 - 7.0$	$P_{FW} = 74.1$ MW
ICRF (65 MHz) $n_t \approx 1.5$	$P_{IC} = 30.5$ MW

The system of calculations converges fairly quickly, as shown in Fig. 16, which monitors the safety factor and toroidal current density in the midplane for the initial, second, third and eighth iteration of the MHD solution. Note that $q(\psi)$ is monotonic in spite of the obvious dip in j_t around $\tilde{\psi} = 0.4$. The final solution is numerically stable with parameters

$$\beta_t = 0.05^4 \quad I = 16.5 \text{ MA}$$

$$q_a \approx 2.0 \quad q_b = 3.6 \quad \bar{n}_e = 0.7 \times 10^{20} \text{ m}^{-3} \quad \bar{T}_e = 17.9 \text{ KeV.}$$

With the total launched rf power of $P_{CD} = 134 \text{ MW}$ we find that the CD figure of merit is $\gamma = \bar{n}_e I R_O / P_{CD} = 0.47$. This value of γ may increase if a refined treatment of trapped electron effects shows the current reduction to be less serious than our present crude model assumes.

The rf system proposed here offers tremendous flexibility to the operation of ITER. The LH system provides 30 MW which can be used for low density startup and/or rampup, as demonstrated on PLT. This saves transformer volt-seconds and permits a thicker, conducting vacuum vessel. The LH power might also be combined with ohmic drive in the ignition phase of ITER to stabilize MHD activity, such as sawteeth, as proposed for JET. In principle, 30 MW of LH CD could also offer the opportunity to operate in a hybrid burn cycle (ohmic drive with periodic transformer recharge at low density), which may provide significant performance advantages to larger tokamaks.[15,16]

The 30 MW ICRF system can of course be considered as the primary heating source to provide ignition. A slight change in the frequency to 54 MHz will bring the second tritium harmonic to the magnetic axis. Both harmonic heating and minority He^3 heating would be candidates for this function. Other ICRF uses appear possible. For example, Synchromak^[17] achieved gas breakdown, current startup, and current rampup with the fast wave.

The higher frequency FW, which is specified with $P_{FW} = 74 \text{ MW}$, could also be considered as a source of auxiliary heating, although in this case the electrons are selectively heated. Good wave penetration and electron heating, reported in several experiments,^[14,18] could also be used during the ignition phase of ITER to increase the conductivity and extend the burn time.

Power from rf sources has further applications to burn control. The monster sawteeth are achieved on JET with the aid of ICRH, and the ion temperature profile can be broadened by off-axis ICRH during ohmic discharges^[19]. Our calculations suggest a further intriguing possibility that the safety factor may be controlled with rf CD. If in fact $q_a \approx 2$ is achievable it may be possible to enter the second stability regime; this could lead to profound improvements in the economic outlook for tokamak reactors.^[20] Several experiments with noninductive CD have generated stable equilibria with $q_a > 1.0$ (see discussion in Ref. 1), so it appears plausible that the ICRF/FW system outlined here could be employed so as to probe for a path to higher beta.

The flexibility of the proposed rf system to accomplish several tasks is a compelling reason to consider its inclusion in the ITER design.

VI. Electrical Requirements

Little attention has been given so far to the issue of the electric-to-rf power conversion efficiency of the driver systems. However, a few generalities are possible.

An encouraging prospect for the ICRF system is that an ~ 65 MHz solid-state rf source is already under development and is projected to provide a very high efficiency, $\eta_{IC} \approx 0.90$.^[21] (The near-term application of this power supply is in fact for an RFQ accelerator of MeV ion beams.)

The higher frequency FW, at several hundred MHz, would require tubes such as klystrons or crossed field amplifiers (CFA). Development in the USSR is reported for a source with an efficiency ≈ 0.90 in the range of 500 MHz.^[22] Of course, the overall system efficiency will be lower due to transmission losses in the coax as well as insertion losses from various electrical components.

Above ~ 1 GHz the rf system efficiency may slowly decrease with frequency. The STARFIRE design^[23] utilized a CFA system with $\eta_{LH} = 0.59$ at $f = 1.7$ GHz. A design study of the LH system for JET^[24] noted increasing transmission losses as the frequency was increased from 2.45 to 4.6 GHz. Overmoded waveguides and a multijunction grill can minimize the losses. In addition, the sources drop in unit power as f increases, increasing the complexity of the hardware. A study for Tore Supra^[25] confirmed the

advantages of overmoded waveguides but also found decreasing transmission efficiencies as f increased from 4.6 GHz to 8.0 GHz. At $f \approx 8.0$ GHz other sources (gyrokystrons, for example) must be considered, but the technology may be less attractive.

VII. Alternative rf CD Combinations

The rf CD/MHD equilibrium calculations suggest that we may have considerable latitude in creating a variety of current profiles. This flexibility has not been thoroughly explored so far, but we point out that tokamak equilibria can be generated with only two source frequencies instead of the three systems advocated. This would entail a loss of system flexibility with a small gain in overall reactor simplicity.

It may be possible to dispense with the LH system, for example. The bootstrap current density at the edge (see Fig. 4, for example) may be adequate to provide equilibrium if combined with the ICRF/FW drivers in the interior of the plasma. Self-consistent rf-generated equilibria with trivial amounts of LH power have been computed previously [26-27].

It may be possible to use only the LH and ICRF systems. Generally speaking this would result in a paucity of current density over $0.3 \lesssim \tilde{\psi} \lesssim 0.7$, since only the bootstrap current would arise in this region. Preliminary studies provide some reason to believe that current profiles could nevertheless be created which have monotonic (but nonconventional) safety factors, $q(\psi)$, and which may in fact have superior stability properties.

A third alternative might be to eliminate the ICRF system, which appears to only provide a G contribution near the magnetic axis and which might also entail engineering problems associated with loop antennas and high power feedthroughs. In this case the equilibrium would be generated with either the high frequency FW alone or with a FW/LH combination, similar to the fashion outlined in Ref. 3. However, it could be a foolish mistake to eliminate the ICRF system completely; in addition to the ion heating capability which it provides there are other CD techniques which use ICRF technology. These proposed CD methods, minority heating CD [28] and mode conversion to a Bernstein wave [29], provide backup techniques to direct electron heating and also offer the opportunity to create a broad current profile.

VIII. Conclusions and Future Work

Although the ITER rf design is not fully optimized, the proposed system with ~ 30 MW of LH, ~ 75 MW of (~ 250 MHz) FW and ~ 30 MW of ICRF provides a very flexible CD option which is well suited to provide a variety of current profiles in order to maximize beta. Moreover, the ion and electron heating capability may be valuable to improve ITER performance in the ignition phase. The rf combination proposed should provide ample auxiliary heating for ignition and burn control. Finally, the ability to operate with $q_a \sim 2$ is a unique method of running steady state and exploring the possibility of entering the second stability regime.

Several issues require further study. Physics-related topics include:

- trapped electron effects -- Our model (see Appendix C) is based on an analytic treatment which has certain constants set by fitting the formula to numerical calculations. Various numerical results for the normalized $\tilde{j}/\tilde{\rho}$ are inaccurate and not in general agreement. This problem must be resolved.
- quasilinear plateau formation -- Electron trapping is less significant if electrons at $(\omega/k_{\parallel} v_e) \gg 1$ carry the current. Although our linear theory of electron damping yields current generation near $(\omega/k_{\parallel} v_e) \approx 1$ there is overwhelming experimental data showing that LH CD can create a wide plateau extending to many times the thermal speed.
- fast wave frequency -- Possible coupling of FW power into slow waves remains as an explanation of the high frequency FW density limit for CD. This mechanism (or some other explanation) must be understood if an informed choice of the FW frequency is to be made.
- alpha particle damping -- Preliminary calculations [27] have indicated that alpha damping can be small with a careful choice of the wave frequency and power spectrum. However, the question of spatial losses and the steady state alpha density complicates this issue, and further analysis is needed.

Finally, there are a number of issues related to machine constraints and the "ITER rules":

- confinement -- The enormous current, $I = 18$ MA, partly required to achieve good energy confinement, is of course forcing the CD power requirement to over 100 MW. If our understanding of energy confinement improves, we may be able to reduce I .
- $Z_{eff} = 2.2$ -- Why is the plasma so dirty? During the technology phase the only sources of heavy impurities are the first wall, wave launchers, and divertor plates; and oxygen should be absent since it will be removed by the impurity control system during a fusion burn lasting many weeks. Current drive requires less power as Z_{eff} is reduced.
- top launch position -- Additional profile control may be possible if the launchers are not restricted to the outboard region. Electron trapping effects could also be minimized.
- aspect ratio -- A larger value, $A \approx 5$, would provide several benefits. The $\omega = 2\Omega_T$ resonance could be pushed out of the plasma, and CD with ICRF would be possible without any fuel ion resonances. Also trapped electron effects would diminish. A smaller toroidal current might be possible.

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TABLE I

ITER TECHNOLOGY PHASE WITH rf CURRENT DRIVE			
<u>Parameter</u>	<u>Variable</u>	<u>Units</u>	<u>Value</u>
Aspect Ratio	A		3.0
Elongation	k		2.0
Triangularity	d		0.4
Pressure Profile Exponent	α		1.2
Diamagnetism Exponent	α_F		4.0
Well Depth	δ		0.0474
Axis Safety Factor	q_a		1.87
Boundary Safety Factor (limiter)	q_b		3.27
Volume Average Toroidal Beta	β_t		0.0598
Shafranov Poloidal Beta	β_I		1.04
"Troyon" ratio	g		0.032
Major radius	R_O	m	5.5
Vacuum Field on Axis	B_O	T	5.3
Plasma Toroidal Current	I	MA	18.0
Density Profile Exponent	α_n		0.4
Temperature Profile Exponent	α_T		0.8
Average Electron Density	$\bar{n}_e$	$10^{20} m^{-3}$	0.70
Volume Average Electron Temperature	$\bar{T}_e$	keV	18.0
Effective Ion Charge	Z_{eff}		2.2

Figure 1. PSI CONTOURS

Figure 2. TOROIDAL CURRENT CONTOURS

Figure 3. Initial equilibrium.

Figure 4. Flux surface average of parallel current density, G , and the bootstrap current contribution, H , for the parameters of Table I. The plasma boundary is at zero and the magnetic axis is at one.

Figure 5. Poloidal trajectories of lower hybrid (slow) waves with $f=8$ GHz and several $n_{||}$ values.

Figure 6. Radial penetration for LH waves; deepest penetration achieved at accessibility limit, $n_{||} \approx 1.65$.

Figure 7. Parallel current generated with eight LH wave rays, $1.7 \leq n_{||} \leq 5.0$. Total power is 20 MW, evenly distributed over $n_{||}$.

Figure 8. Location of second tritium harmonic resonance for fast wave at 65 MHz.

Figure 9. Ray trajectory and wave vector evolution for fast wave at 65 MHz, $n_{||} = 1.5$, launched just above the midplane.

Figure 10. Wave damping and amplitude for ray of Fig. 9.

Figure 11. Ray paths and parallel current generation for 65 MHz fast wave at $n_{\parallel} = 1.5$ launched from a poloidal range of angles.

Figure 12. Ray path and wave vector evolution for fast wave at higher frequency, 250 MHz, with $n_{||} = 1.2$.

Figure 13. Damping and wave amplitude for ray of Fig. 12.

Figure 14. Ray trajectories for fast waves at 250 MHz and $n_{\parallel} = 1.2-2.2$ and resulting parallel current density.

Figure 15. Multiple-wave current drive plus bootstrap current for ITER equilibrium: 30 MW of LH power; 74 MW of FW at 250 MHz; and 30 MW of ICRF fast wave @ 65 MHz. Total current density is dotted line, whereas solid line is target current density of initial equilibrium.

Figure 16. Equilibrium iteration.

APPENDIX A

EXPERIMENTAL DENSITY LIMITS FOR LOWER HYBRID AND FAST WAVE CD

In this study we first compare experimental LHCD density limits with various theoretical and empirical scalings. As a second step we compare the observed densities at which fast waves have driven toroidal currents with the LHCD density limits. The comparisons shows that at low frequencies the FW has demonstrated CD at densities several orders of magnitude higher than expected for LHCD.

Table A1 lists the density limits for LHCD taken from a large number of experiments. We note that comparisons of experimental data with theoretical formulas is frequently ambiguous for several reasons. For example, there is uncertainty regarding whether the peak or average density is quoted in the references. Likewise, published data occasionally fail to specify the ion mass or magnetic field strength. There is also an inconsistent definition of the cutoff density; possible meanings include the initial deviation of $I n_e \propto P_{rf}$, the complete loss of loop voltage drop, or the loss of a hard X-ray signal, as examples. These sources of error will cause any comparison of data and formulas to display at least a minimum amount of scatter. The table includes the quantity

$$\Omega^2 \equiv \frac{\omega^2}{\Omega_e \Omega_i} = 2.3 \times 10^{-18} \frac{f^2 A_i}{B^2 Z_i}$$

since this ratio of frequency to field strength plays a role in most theoretical attempts to understand the density limit.

Early in the history of LHCD experiments it was noted that the LH limit was frequently associated with the appearance of the LH resonance in the plasma. This lead to a theory that the frequency must exceed a few times (N) the lower hybrid frequency

$$\omega \geq N \omega_{pi} [1 + (\omega_{pe}^2 / \Omega_e^2)]^{-1/2}$$

or

$$n_e \leq \frac{23 f^2 (A_i / Z_i)}{[N^2 - \Omega^2]} .$$

Since this expression diverges as $\Omega^2 \rightarrow N^2$ it is clearly useless for large Ω^2 , for example with argon plasmas ($A_i = 40$). Even for some proton plasmas the formula does not have a predictive capability; the table shows that $N > 8$ is needed to explain the Octopole and Versator II data, whereas $N < 2$ is required to model the PLT (proton) results.

A refined theory [J-G. Wegrowe, G. Tonon, in Non-inductive Current Drive in Tokamaks, Proc. IAEA Comm. Mtg., Culham (1983), CLM-CD (1983), p. 343; also INTOR Phase Two A, Part II, IAEA, Vienna, (1986), p. 224.] attributed the loss of CD to a "switch over" from electron to ion damping at densities somewhat below the LH resonance. This cutoff density formula is

$$\bar{n}_e \leq \frac{14 f^2 (A_i / Z_i)}{[(1 + \frac{\beta}{A_i} \frac{T_i}{T_e}) - \Omega^2]}$$

This expression also diverges for large Ω^2 and is not applicable to cases with $A_i = 40$. Setting $\beta \approx 2$, as proposed for this formula, fails to yield accurate results for several experiments with $\Omega^2 > 1$. For example, $[1 + (2/A_i) T_i/T_e]$ varies from 1.3 to 1.8 for the Octopole, Versator II, and Petula B (3.7GHz), whereas Ω^2 is much larger, as seen in Table A1.

A naive fit to the data is based on the simple observation that the cutoff generally increases with frequency, f . We have fit the data in Table A1 with a power law scaling

$$\bar{n}_e \leq 1.07 \times 10^{14} \text{ m}^{-3} (f/\text{MHz})^{1.65} .$$

The data are compared with this scaling in Fig. A1. The formula appears inaccurate at the lowest densities and does not capture the A_i dependence found in experiments, such as Wega III, PLT, and ASDEX, in which both proton and deuteron plasmas were used.

The formula which best reproduces the data is based on ideas surrounding mode conversion and how the spectral gap is filled [L.H. Sverdrup, P.B. Bellan, in Applications of rf Power to Plasmas, (Proc. 7th Top. Conf., Kissimmee, 1987) AIP, New York (1987), p. 199]

$$\bar{n}_e \leq \frac{23 r^2 (A_i / Z_i)}{\{1.732 [\Omega^4 + \frac{4 T_i}{Z_i^2 T_e}]^{1/2} + [\frac{1}{Z_i} - \Omega^2]\}} .$$

This applicable to all Ω^2 values and duplicates the data quite well over three orders of magnitude, as shown in Fig. A2. Although the physics of the spectral gap as not understood and hence this formula is somewhat based on conjecture, the formula appears to be remarkably accurate and should be useful in estimating the minimum LHCD frequency needed for ITER.

Of equal importance, the spectral gap formula gives us the ability to compare FWCD results with LHCD density limits, especially in the (low frequency) range where LHCD data is sparse. Table A2 summarizes FWCD density limits. Figures A3 and A4 plot the density limits against the simple frequency scaling and the more elaborate spectral gap formula. Note that FWCD has always been possible at densities equal to or higher than expected with LHCD.

A second conclusion in the figures is that FWCD suffers about the same density limit as LHCD at high frequencies (~ 800 MHz), whereas the density limit is orders of magnitude higher at lower frequencies. Those FW experiments with the same limit as LH experiments may permit nonlinear coupling of the fast wave into a slow wave branch due to, for example, density fluctuations from drift waves near the antenna. This possible power sink is discussed in Ref. 22. One sure way to avoid this problem would be to operate at sufficiently low a frequency that only the fast wave exists at the plasma density confined in the torus. This is accomplished by placing the lower

hybrid resonance density below the edge density in the vicinity of the antenna. This resonant density is

$$n_e^{\text{LHR}} = \begin{cases} \frac{23 f^2 (A_i/Z_i)}{|1 - \Omega^2|} & \Omega^2 < 1 \\ \infty & \Omega^2 \geq 1 \end{cases}$$

Figure A5 graphically demonstrates the role played by the LH resonance on JIPP T-IIU with FWCD at two different frequencies. At 800 MHz it is seen that fast waves (the lower $n_{\perp}$ value) with $n_{\parallel} \approx 1.5$, launched into a plasma at $n_e \approx 3 \times 10^{18} \text{ m}^{-3}$, should propagate to densities $\sim 3 \times 10^{19} \text{ m}^{-3}$ unless power is channelled to the slow wave (upper $n_{\perp}$ value) at $n_{\parallel} \approx 1.5$, which suffers a propagation and CD limit at $n_e \lesssim 1 \times 10^{19} \text{ m}^{-3}$. In contrast, at 40 MHz the $n_{\parallel} = 1.5$ FW propagates at all densities; the CD result is probably limited by the Murakami limit at this point. This picture is consistent with the observations on JIPP T-IIU.

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Table A1: Data Base: Slow (Lower Hybrid) Wave

Experimental Density Limit for Current Drive

Experiment		f GHZ	B ₀ T	A _i	Z _i	Ω ²	T _i /T _e	n _e ^{CDLim} 10 ¹⁸ m ⁻³	Ref.
Octopole	(1)	.43	.083	(1)	1	62.	.3	0.3	1
CSTN-I	(2)	.29	(.13)	40	1	462.	.3	0.2	2
ACT-I	(3)	.16	.30	4	1	2.66	.1	1-2*	3
JIPPT-II	(4)	.80	1.3	1	1	.886	.3	4-10	4
Encore	(5)	.45	.15	40	1	842.	.5	1	5
JFT-2	(6)	.75	1.4	2	1	1.34	.3	6	5,6
Wega III	(7)	.80	2.25	2	1	.592	.3	14-22	7
Wega III	(8)	.80	2.25	1	1	.296	.3	10-14	7
Versator	(9)	.80	1.0	1	1	1.50	.4	6	8
Versator II	(10)	2.45	1.0	1	1	14.0	.4	10-20	9
T7	(11)	.90	1.9	2	1	1.05	.3	17-20	7
PLT	(12)	.80	3.0	2	1	.333	.4	7-12	10,11
PLT	(13)	.80	3.0	1	1	.166	.4	5-8	11
PLT245	(14)	2.45	(3.0)	(2)	1	3.12	.3	15-45	12
ASDEX	(15)	1.3	2.2	2	1	1.63	.3	30	13
ASDEX	(16)	1.3	2.2	1	1	.817	.3	10-22	13
Petula B	(17)	1.3	2.8	(2)	1	1.01	.3	15-25	14
Petula B	(18)	3.7	2.8	(2)	1	8.17	.3	30-100*	14
JT60	(19)	2.0	4.0	1	1	.585	.3	38*	15
Alcator C	(20)	4.6	10	(1)	1	.495	.3	100+	16

*Upper values near Murakami limit, n_e^M = 10²⁰B/Rq ≅ 2 × 10¹³ I/a².

Table A2: Data Base: Fast Wave

Experimental Density Limit for Current Drive

Experiment		f GHZ	B ₀ T	A _i	Z _i	Ω^2	T _i /T _e	n _e ^{CDLim} 10 ¹⁸ m ⁻³	Ref.
JIPPTIU	(A)	.800	2.64	1	1	.214	.3	2-15*	17
JIPPTIU	(B)	.040	0.2	1	1	.0935	.3	2.5*	18
ACTI	(C)	.018	.447	4	1	.0152	.3	6.7 ⁺ *	19
PLT	(D)	.800	3.1	2	1	.311	.3	7-16	20
Synchromak	(E)	.003	.0128	40	1	5.14	.3	13 ⁺ *	21
Irvine	(F)	.094	0.1	40	1	82.65	.3	4 ⁺ *	22
JFT2M	(G)	.200	1.07	1	1	.0817	.5	2.2	23,24
JFT2M	(K)	.200	1.07	2	1	.1634	.5	3.0	23
JFT2M	(H)	.75	1.07	1	1	1.148	.5	9.3	24
CCT	(I)	.080	0.1	1	1	1.496	.3	0.3*	25
CCT	(J)	.022	0.05	1	1	.453	.3	1.0*	25

*Near Murakami limit.

Figure A1.

Slow Wave Experiments

Frequency Scaling for Slow Wave Limit:
 $(\bar{n}_e/\text{m}^{-3}) = 1.07 \times 10^{14} (f/\text{MHz})^{1.65}$

Figure A2.

Slow Wave Experiments

Figure A3.

Figure A4.

JIPP T-IIU (800 MHz)

JIPP T-IIU (40 MHz)

Figure A5. Dispersion relation for fast and slow waves, $n_{\perp}$ vs. $n_{\parallel}$, at two wave frequencies on JIPP T-IIU. Dashed line is Murakami limit; solid line is lower hybrid resonance. Fast wave cutoff densities are indicated vs. $n_{\parallel}$.

APPENDIX B

FAST WAVE CD ON DIIID

Planning has started for an experiment to test fast wave CD on DIIID at General Atomics. This experiment, tentatively scheduled for 1990, would utilize ~ 2 MW of power at ~ 30-60 MHz coupled through a multiple-loop phased antenna array. The plasma target at $\bar{n}_e = 1.5 \times 10^{19} \text{ m}^{-3}$ would be preheated with ~ 2 MW of ECRH to provide a hot central $T_{eo} \sim 7 \text{ keV}$. Initial modelling assumes $B_0 = 1 \text{ T}$, deuterium fill, and $f = 60 \text{ MHz}$ (~ tenth deuterium harmonic). In order to maximize single pass absorption, considerations are centered on $n_{||} \sim 6.0$.

Our modeling results for DIIID are shown in Figs. B1-B4, where several rays with $n_{||} = 6$ are launched from the outboard region. Even though this calculation is oversimplified, we can draw relevant conclusions regarding the proposed experiment. These rays penetrate to the magnetic axis and are strongly damped at the center. Ion harmonic damping ($T_{io} \sim 3 \text{ keV}$) is very weak, and $\sim 80\%$ of the wave power is absorbed on a single pass through the plasma. Figure B4 displays $G = \langle j_{||} B \rangle / \langle B^2 \rangle$ generated by this narrow spectrum, launched into a discharge with $I = 680 \text{ kA}$. It appears possible to generate nearly all the current noninductively, although the current density may in fact be too peaked near the magnetic axis. Presumably a wider $n_{||}$ spectrum would create a broader current profile. These results indicate that a significant loop voltage drop should be possible with FWCD on DIIID with ~ 1-2 MW of power. It will be essential to control impurity release during ICRF operation, as demonstrated on the recent FW experiments of JFT-2M which used titanium gettering to limit the electron density rise [Y. Uasugi, U.S.-Japan Workshop on Current Drive, JAERI, December 1988].

Figure B1. Ray paths on DIIID at 60 MHz, $n_{||} = 6$ for fast wave current drive experiment; $B_0 = 1\text{T}$.

Figure B2. Typical ray evolution on DIIID, showing strong single-pass absorption; $T_{eo} = 7$ keV.

Figure B3. Parallel current generation on DIIID with 2 MW of FWCD at $n_{||} \approx 6$ and $f = 60$ MHz; $\bar{n}_e = 1.5 \times 10^{19} \text{ m}^{-3}$ and $T_{eo} = 17$ keV. Total rf generated current is several hundred kiloamperes.

APPENDIX C

TRAPPED ELECTRON EFFECTS ON FWCD

In calculations of rf CD it is important to account for a decrease in the normalized ratio of current density to power density, $\tilde{j}/\tilde{p}$, due to electron magnetic trapping. This effect is most serious when the wave's parallel phase speed is less than or equal to the electron thermal speed, $w = (\omega/k_{\parallel}v_e) \leq 1$, where $v_e = \sqrt{T_e/m_e}$. In order to facilitate ray tracing calculations we desire an analytic expression for $\tilde{j}/\tilde{p}$. This appendix outlines the derivation of a functional expression for $\tilde{j}/\tilde{p}$ which has been provisionally used in our ITER calculations but which will be revised as more accurate numerical studies become available.

Following Giruzzi, [1] we derive a response function for electron current drive,

$$x = x_{FB} (1 - \xi^{\alpha}) \quad , \quad (C1)$$

where the Fisch-Boozer response function is [2]

$$x_{FB} = \frac{2}{(5+Z)} w u^3 \quad .$$

Here Z is the ion charge, and $\alpha = (5+Z)/(1+Z)$. The normalized velocity space variables are $x = v_{\perp}/v_e$, $w = v_{\parallel}/v_e$, an energy $u^2 = w^2 + x^2$, and a pitch angle $\mu = w/u$. Due to the B field gradient, μ is a function of poloidal angle, and, at a given angle θ , trapped electrons are defined by

$$\mu(\theta) \leq \mu_t(\theta) \equiv \sqrt{1 - (B(\theta)/B_M)} \quad ,$$

where B_M is the maximum field strength on the flux surface. The final velocity variable is then defined as $\xi \equiv (\mu_t/\mu)$.

For a narrow spectrum we have [3]

$$\tilde{j}/\tilde{p} = \frac{\int \underline{s} \cdot \partial \chi / \partial \underline{u} \, d\underline{v}}{\int \underline{s} \cdot \underline{u} \, d\underline{v}} \quad (C2)$$

where $\underline{s} = -\underline{D} \cdot \partial f / \partial \underline{u}$, the quasilinear electron flux. For high phase speeds, $w \gg 1$, we find

$$\tilde{j}/\tilde{p} \approx (1 - \epsilon^{\alpha/2}) [\tilde{j}/\tilde{p}]_{FB} \quad , \quad (C3)$$

where $[\tilde{j}/\tilde{p}]_{FB} = 8 w^2 / (5 + Z)$, and where we evaluated our result in the limit $(x/w)^2 \ll 1$. That is, we use the local inverse aspect ratio $\epsilon \equiv 1 - (\langle B \rangle / B_M)$.

We now generalize the result of Giruzzi by extending the evaluation of $\tilde{j}/\tilde{p}$ into the range $w \lesssim 1$. This may formally violate the high energy collision assumption used to derive the response function, however CD via Alfvén wave/transit time magnetic pumping is dominated by moderately energetic electrons at $x \sim 3$. Even Landau damping results display the proper w^{-1} dependence of $\tilde{j}/\tilde{p}$ using this evaluation, although the numerical coefficient is inaccurate. The response function and its derivatives are zero for trapped electrons, so the limits of integration in Eq. (C2) are $0 < x < \sqrt{1 - \mu_t^2} w / \mu_t$. We evaluate Eq. (C2) for a narrow spectrum (i.e., $\underline{s}$ is a delta function in w) and with a maxwellian background, $f \sim e^{-(w^2 + x^2)/2}$. The magnitude of $\tilde{j}/\tilde{p}$ depends on $\underline{D}(x)$; generally AW/TTMP weights the integrand toward larger x , resulting in a larger $\tilde{j}/\tilde{p}$ than for Landau damping.

Considering first Landau damping, we set $\underline{D} = \underline{D}(x)$ and evaluate Eq. (C2). The detailed solution can be replaced by a simpler model function which we choose as

$$\tilde{j}/\tilde{p} = \frac{2}{(5+Z)} \frac{K^L}{w} (1 - e^{-cy_t}) \quad (C4)$$

where $y_t \equiv (1 - \mu_t^2) w^2/\mu_t^2$, and K^L and c are constants. This function agrees with the correct analytic function in the limits $y_t \gg 1$ ($\epsilon = 0$, or negligible trapping) and $y_t = 0$ (no circulating particles) and displays the approximate functional dependence on y_t . For Alfvén type damping we set $\underline{D} \sim (2 - x^2)^2$ and again evaluate the integrals; the function form of the result is similar to the previous result and is approximated by

$$\tilde{j}/\tilde{p} = \frac{2}{(5+Z)} \frac{K^A}{w} (1 - e^{-cy_t}) \quad (C5)$$

The constants K^L and K^A are determined by setting $\tilde{j}/\tilde{p}$ equal to its value in the $w \ll 1$ limit without trapping, as given, for example, in Ref. 4. However, a uniform approximation valid over all w values may be achieved by inspection of the three functions (C3) - (C5):

$$\tilde{j}/\tilde{p} = (1 - \epsilon^{a/2})(1 - e^{-cy_t}) \left[\frac{D}{w} + 2 + \frac{12(6+Z)}{(5+Z)(3+Z)} + \frac{8w^2}{(5+Z)} \right] \quad (C6)$$

where the quantity in brackets [4] is the value without trapping effects, with

$$D = \begin{cases} 3.76 & \text{Landau} \\ 8.09 & \text{AW/TTMP} \end{cases}$$

Finally, the constant c in Eq. (C6) is determined by comparing this expression with the numerical results of Yoshioka and Antonsen [5] for TTMP. We set $c = 0.117$ by fitting our formula to their results for the ratio of $[\tilde{j}/\tilde{p}]_{w=1.5}$ at $\epsilon = 0.1$ and $\theta = 0$ to its value at $\epsilon = 0$.

This model of electron trapping will need revision. At present it agrees roughly with numerical results of electron trapping on CD via AW/TTMP [5] and via Landau damping [6]. There are certain deficiencies in the numerical studies, however. For example, the model collision operator in Ref. 5 is not accurate for $w \ll 1$. For such reasons we are seeking more accurate Fokker-Planck results with which to fit our analytical function for $\tilde{j}/\tilde{p}$.

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