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**FAST WAVE CURRENT DRIVE:
EXPERIMENTAL STATUS AND REACTOR PROSPECTS**

by

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Fusion Power Program

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ABSTRACT

The fast wave is one of the two possible wave polarizations which propagate according to the basic theory of cold plasmas. It is distinguished from the other (slow wave) branch by having an electric field vector which is mainly orthogonal to the confining magnetic field of the plasma. The plasma and fast wave qualitatively assume different behavior depending on the frequency range of the launched wave. The high frequency fast wave (HFFW), with a frequency ($\omega/2\pi \sim \text{GHz}$) much higher than the ion cyclotron frequency (Ω_i), suffers electron Landau damping and drives current by supplying parallel momentum to superthermal electrons in a fashion similar to lower hybrid (slow wave) current drive. In the simple theory the HFFW should be superior to the slow wave and can propagate to very high density and temperature without impediment. Experiments, however, have not conclusively shown that HFFW current drive can be achieved at densities above the slow wave current drive limit, possibly due to conversion of the launched fast waves into slow waves by density fluctuations. Alternatively, the low frequency fast wave (LFFW), with frequencies ($\leq 100 \text{ MHz}$) only a few times the ion cyclotron frequency, is damped by electron Landau damping and, in a hot plasma ($\geq 10 \text{ keV}$), by electron transit time magnetic pumping; current drive is achieved by pushing superthermal electrons, and efficiency is predicted to be slightly better than for lower hybrid current drive. Most significantly, the slow wave does not propagate in high density plasma when $\omega \sim \Omega_i$, so parasitic coupling to the slow wave can be avoided, and no density and temperature limitations are foreseen. Preliminary experiments with the LFFW evidently have broken through the lower hybrid density limit. Experiments with fast wave current drive invariably find current drive efficiency as good as obtained in lower hybrid experiments at comparable, low temperatures. It is also important to note that the LFFW might be employed to drive current via means other than what we are presently considering: minority heating; mode conversion; and very low frequency ($\omega <$

Ω_i) Alfvén wave current drive. One advantage of direct coupling to electrons at superthermal parallel velocities is the avoidance of trapped particle effects.

1. EXECUTIVE SUMMARY: FAST WAVE CURRENT DRIVE PROSPECTS

In theory the fast wave [1,2,3] should drive current in the center of fusion-grade tokamaks, even at densities and temperatures too large for lower hybrid wave penetration. In Section 3 of this report we present theoretical formulas which permit an analysis of past experiments and which will be useful for predicting results for fast wave current drive in reactors like INTOR and ITER.

The experimental data base for fast waves is sparse but not nonexistent. We have studied the results over the last decade from a variety of toroidal machines: Synchromak, ACT-I, Irvine Torus, CCT, JIPP T-IIU, JFT-2M, and PLT. The data include various working gases (argon, helium, deuterium, protium), span a range of toroidal field strengths (0.01 T to 2.6 T), and include a wide range of frequencies (3 MHz to 800 MHz). Our analysis starts with the classification of the launched wave into either a high frequency fast wave (HFFW) or low frequency fast wave (LFFW); the HFFW is characterized by values of $\Omega^2 \equiv \omega^2(\Omega_e \Omega_i)^{-1}$ adequately large that both fast and slow wave branches can propagate in the plasma, while the LFFW exists in plasmas with $\Omega^2 \ll 1$, which will not support the slow wave branch. The experiments show conclusively that fast wave couplers (loops or dielectric loaded waveguides) have successfully launched the proper wave polarization. In many HFFW experiments, however, there is the appearance that mode coupling may occur such that wave energy is channeled into slow waves. Such mode mixing has been explained theoretically by wave scattering from turbulent density fluctuations in the plasma [4,5].

A variety of mechanisms compete to dissipate fast wave energy. The most efficient current drive is expected when direct electron heating occurs via Landau damping or transit time magnetic pumping (TTMP), whereas other loss mechanisms (nonresonant damping, ion heating) will reduce the current generation. Several experiments (most notably the Irvine Torus) have revealed the signature of electron Landau damping in that current drive vanishes when the wave's parallel phase speed is well above the electron tail thermal speed ($u \equiv \omega/k_{\parallel} v_e \gg 1$).

There is also unequivocal evidence that the fast wave generates current in these experiments. Startup experiments (plasma initiation and current ramp to 4 kA in JIPP TII-U) display current directionality which depends properly on the wave directionality. The efficiency, $\gamma = \bar{n}_e I R/P$, is constant with density, unless there is a critical density limit. This constancy of γ is consistent with theoretical models. The magnitude of γ is roughly the same as found with lower hybrid current drive which also agrees with our physics understanding. Current maintenance at ≥ 100 kA was achieved on JFT 2M.

Therefore, we are confident that fast wave current drive works. The main concern at this point is that the HFFW experiments have not universally generated currents at densities exceeding the lower hybrid wave limit. It seems that the LFFW may have the best prospects for current drive at high density.

Near term experiments are urgently needed if the benefits of wave current drive are to be realized for ITER. The highest priority should be assigned to experiments with large, hot plasmas in tokamaks with good confinement. The LFFW in particular should be tested using the ICRF equipment already planned for devices such as DIII. Electron coupling, via TTMP, will be enhanced if the central $T_{eo} \geq 10$ keV. However, avoidance of low harmonic ion cyclotron resonances will be necessary in order to maximize the power deposition on electrons. Careful adjustment of the source frequency can move the low harmonic resonances away from the central plasma. Implementation of LFFW current drive in DT reactors has been previously studied in some detail [6,7].

Both HFFW and LFFW options were identified during the INTOR process [8-10] as attractive innovations for current drive. During the final phase of the INTOR project these current drive options were seriously examined and compared with more conventional techniques (neutral beam injection and lower hybrid waves) to assess the expected efficiency γ in a hot reactor plasma; numerical codes from several countries were benchmarked in the process. The results, in Table I, show rough agreement in the predicted values of γ . It is noteworthy that the efficiency with fast waves is similar to that obtained with other drivers. However, unlike lower hybrid waves, the fast waves are more likely to penetrate and provide current density on the magnetic axis.

Although direct electron damping for current drive is the focus of this report, we note that the LFFW provides other current drive mechanisms [2,3], which is a measure of insurance that the fast wave will deliver its promise. Finally, it should be emphasized that the fast wave technology is fully compatible with a reactor environment, especially at low frequencies (≤ 100 MHz) for which it can double to provide ignition via ICRH [11,12]. The power train may be readily shielded from neutrons; it can have bends in the transmission line and windows to contain tritium; the electric-to-rf efficiency is high ($\geq 50\%$), and the sources do not require long term development.

In capsule, fast wave current drive is in an early stage of laboratory testing, and it appears to hold considerable potential for application to ITER.

2. EXPERIMENTAL DATA

Detailed parameters of fast wave experiments have been culled from the literature and posted to data sheets. This information, which will be digested in Section 3, is given in Appendix A.

3. REVIEW OF THEORY AND EXPERIMENTAL RESULTS

3.1 Fast Wave Propagation

In order to analyze experimental results and plan future work we present in this section a condensed set of relations which describe the fast wave characteristics; considerable useful information is obtained from the cold plasma dispersion relation.

We are concerned with wave frequencies less than the electron cyclotron frequency ($\omega \ll \Omega_e$) but which are generally above the ion cyclotron frequency

$$\frac{\omega}{\Omega_i} = 6.55 \times 10^{-8} (f A_i) / (B Z_i) , \quad (1)$$

where $f = (\omega/2\pi)$ is the frequency, B is the toroidal field strength, and A_i and Z_i are respectively the ion atomic mass (amu) and charge state. (Units are SI and keV unless otherwise noted.) The nomenclature of "high" and "low"

frequency fast wave refers to the relative ratio of frequency to field strength as given by the parameter

$$\Omega^2 = \frac{\omega^2}{\Omega_e \Omega_i} = 5.45 \times 10^{-4} \frac{Z_i}{A_i} \left(\frac{\omega}{\Omega_i} \right)^2 . \quad (2)$$

When $\Omega^2 < 1$ there exists a density, called the lower hybrid resonance, which assumes particular importance in the cold plasma model; this density is (for $\omega/\Omega_i \geq 3$)

$$n_e^{\text{LHR}} = 0.971 \times 10^{19} B^2 [\Omega^{-2} - 1]^{-1} . \quad (3)$$

When the local electron density exceeds n_e^{LHR} only one cold plasma wave polarization, the fast wave, can propagate. The term "low frequency fast wave" (LFFW) refers specifically to waves with Ω^2 sufficiently small that the value of n_e^{LHR} is well below any density encountered in the torus, i.e., $n_e^{\text{LHR}} \leq n_{\text{edge}}$, the edge electron density in the vicinity of the wave launcher.

As Ω^2 increases and approaches unity the situation becomes more complicated [13]. For a given frequency and parallel (to the magnetic field) index of refraction, $n_{\parallel}$, two independent waves may exist, with orthogonal electric field polarizations, when the local density, n_e , is less than n_e^{LHR} . The second solution to the dispersion relation, other than the "high frequency fast wave" (HFFW), is the lower hybrid wave, also known as the slow wave since it has a larger perpendicular index of refraction $n_{\perp}$ and thus a slower perpendicular phase speed. One concern with HFFW launching is that waves with small $n_{\parallel}$ (less than the value for "accessibility", $n_{\parallel}^a$) will propagate inward and, reaching a critical density, will be reflected outwards as slow waves. That is, waves with $n_{\parallel} < n_{\parallel}^a$ will not penetrate to high density when launched at the edge. The numerical value of $n_{\parallel}^a$ at a given density depends on the electron and ion plasma frequencies, ω_{pe} and ω_{pi} . The following ratios can be computed for a given n_e :

$$\frac{\omega_{pi}^2}{\omega^2} = 0.0439 \frac{n_e^2}{f^2 A_1} \quad (4)$$

$$\frac{\omega_{pe}}{\Omega_e} = 3.21 \times 10^{-10} n_e^{1/2} B^{-1} \quad (5)$$

Then, for sufficiently low densities, such that $\omega_{pi}^2/\omega^2 < \Omega^2(1 - \Omega^2)^{-1}$, we have

$$n_{||}^a = \frac{\omega_{pe}}{\Omega_e} + \left[1 + \left(\frac{\omega_{pe}}{\Omega_e} \right)^2 - \left(\frac{\omega_{pi}}{\omega} \right)^2 \right]^{1/2} , \quad (6)$$

at higher density we have

$$n_{||}^a = (1 - \Omega^{-2})^{-1/2} . \quad (7)$$

These evaluations of $n_{||}^a$ are valid for $\Omega^2 < 1$. Any fast wave with $n_{||} > n_{||}^a$ will propagate to higher density without reflection.

For even higher frequencies, such that $1 < \Omega^2$, equation (3) does not apply. Under these circumstances both slow and fast waves can propagate at any density; once again, though, the HFFW must satisfy $n_{||} > n_{||}^a$ to avoid reflection. When $1 < \Omega^2$ the value of $n_{||}^a$ at a given density is given by Eq. (6).

An additional $n_{||}$ constraint exists, related to the cutoff density for fast wave propagation. That is, for a given $n_{||}$ there is a lower limit to electron density, the cutoff density n_e^c , which permits propagation. When $n_e < n_e^c$ the perpendicular wave fields are evanescent. This density is given by

$$n_e^c = 3.47 \times 10^8 (n_{||}^2 - 1) f B , \quad (8)$$

provided $\omega/\Omega_i \gtrsim 3$. Note that the LFFW exists at higher $n_{||}$ values for a given n_e^0 than the HFFW, and therefore has a larger window of $n_{||}$ permitted between cutoff and accessibility.

A further consideration to tokamak operations should be made. In practice the machine parameters set an upper limit to electron density. Very roughly this Hugill-Murakami limit is $\bar{n}_e^M \approx 1 \times 10^{20}$ (B/Rq), where R is the major radius, q is the edge safety factor, and a bar denotes a volume average. If this expression is combined with the usual relations for q in a circular large aspect ratio tokamak, this limit becomes

$$\bar{n}_e^M = 2 \times 10^{13} I/a^2 . \quad (9)$$

If there is insufficient fast wave power or a low current drive efficiency the I may be so low as to significantly restrict $\bar{n}_e^M$ by Eq. (9). In some experiments this is overcome by generating a large ohmic current first and using this as the target plasma for the fast wave.

The perpendicular wavelength is a function of $n_{||}$ and density, given by the dispersion relation. For the fast wave polarization at high harmonics ($\omega/\Omega_i \gg 1$) we use the approximate form [14]

$$n_{\perp}^2 = \frac{1836 A_i}{n_{||}^2} \left(\frac{\omega_{pi}}{\omega} \right)^2 \left(\frac{\omega_{pe}}{\Omega_e} \right)^2 - n_{||}^2 . \quad (10)$$

For planning future LFFW experiments (ICRF) we would calculate $n_{\perp}^2$ by the following procedure. First, the Alfvén speed is computed,

$$v_A = 7 \times 10^6 A_i^{-1/2} (\Omega_e/\omega_{pe}) , \quad (11)$$

then [15]

$$n_{\perp}^2 = \frac{c^2}{v_A^2} \left[\alpha + \frac{\alpha (1 - \alpha)}{\alpha - N_{\parallel}^2} \right] - n_{\parallel}^2, \quad (12)$$

where $N_{\parallel} \equiv v_A n_{\parallel}/c$ and $\alpha \equiv [1 - (\omega/\Omega_{\perp})^2]^{-1}$ and where $\omega/\Omega_{\perp} \lesssim 5$. The perpendicular wave number combines the radial and poloidal mode structure as $n_{\perp}^2 = c^2 (k_r^2 + k_{\theta}^2)/\omega^2 \equiv (c k_{\perp}/\omega)^2$. Denoting the minor radius as a , we see that the machine will support normal modes when a is adequately large, very roughly when $a \gtrsim 2\pi k_{\perp}^{-1}$, that is, for $n_{\perp} \gtrsim (c/af)$. For very large values of $n_{\perp} af/c$ the perpendicular mode density becomes very large, and WKB (ray tracing) analysis is a useful tool for more detailed studies.

3.2 Fast Wave Damping

The energy density of travelling fast waves consists of kinetic energy of the plasma particles plus the energy density of the associated electric and magnetic field oscillations. Since this energy is depleted in a tokamak by a variety of loss mechanisms, every energy sink must be considered in order to arrange for an efficient transfer of energy to the electrons for current drive.

In very low temperature plasma wave energy is lost by collisions of the nonresonant electrons with neutrals and ionized plasma. In analyzing such experiments we can estimate the neutral density as

$$n_0 = 3.6 \times 10^{22} p_0, \quad (13)$$

where p_0 is the filling pressure (in Torr). If the measured $n_e \gtrsim n_0$ we may ignore electron-neutral collisions; otherwise we have a collision frequency

$$\nu_{eo} = 2.39 \times 10^{11} p_0 T_e^{1/2} \left[1 - \frac{n_e}{n_0} \right]. \quad (14)$$

The electron-plasma collision frequency is typically

$$\nu_{ep} = 6.9 \times 10^{-16} \ln \Lambda \frac{n_e}{T_e^{1/2}} \frac{(2 + Z_i)}{2}, \quad (15)$$

where the Coulomb logarithm is approximately $\ln \Lambda = 37.82 - \ln \{n_e^{1/2} T_e^{-1}\}$. The relative strength of the nonresonant power dissipation, P_{nr} , depends on the ratio of electron collision frequency to the wave frequency, $\nu_e/\omega \equiv (\nu_{eo} + \nu_{ep})/(2\pi f)$, and current drive is most efficient when this nonresonant dissipation is small compared to electron Landau damping power absorption, P_{eLd} . The Landau damping strength is a function of the wave's normalized phase speed parallel to the magnetic field:

$$u = (\omega/k_{\parallel} v_e) = c/(n_{\parallel} v_e) \quad (16)$$

where v_e is the thermal speed of the electrons, $v_e = 1.326 \times 10^7 T_e^{1/2}$. In some cases an electron tail is present which couples to the wave, and it is then appropriate to evaluate Eq. (16) with an effective tail electron temperature, T_h . The ratio of nonresonant to electron Landau damping is then

$$\frac{P_{nr}}{P_{eLd}} = \frac{0.798 (\nu_e/\omega)}{u^3 e^{-u^2/2}} \left[1 + \frac{2.97 \times 10^{-7}}{A_i^2} \left(\frac{\omega}{\Omega_i}\right)^2 \left(\frac{n_i}{n_{\parallel}}\right)^2 \right]. \quad (17)$$

As T_e increases other collisionless dissipation processes start to compete with electron Landau damping. Ion damping is a concern, of course, since it might not be a channel for efficient current drive. At high harmonics of the ion cyclotron frequency the ion damping is principally perpendicular Landau damping, which is a function of the ratio

$$x = \omega/(\sqrt{2} k_{\perp} v_i) = 2.122 \times 10^8 / (n_{\perp} v_i), \quad (18)$$

where the ion thermal speed is $v_i = 3.1 \times 10^5 \sqrt{T_i/A_i}$. The ions behave as if they were unmagnetized in the limit $\omega/\Omega_i \gg 1$, and the relative strength of ion to electron Landau damping [16] is

$$\frac{P_{iLd}}{P_{eLd}} = 42.8 A_i^{1/2} \left(\frac{T_e}{T_i}\right)^{3/2} \frac{n_i}{n_e} e^{\frac{u^2}{2}} - x^2, \quad (19)$$

where again T_e may be replaced with T_h if the waves damp on a high energy electron tail. Additional damping mechanisms (related to parametric instabilities, mode conversion to ion quasi-modes, etc.) are associated with fast waves if they couple to slow waves near the lower hybrid resonance. Such losses will not be explicitly treated here, but care should be taken to avoid such problems.

The LFFW can couple well to the ions when ω/Ω_i is of order unity. This ICRH via fast waves has had ample experimental verification. Whereas minority heating has been proposed as a current drive technique in its own right [2] and has even had preliminary experimental study [17], it may be somewhat less efficient than direct electron damping for current drive [6,11]. Likewise, mode conversion at a cyclotron harmonic resonance to a strongly damped ion Bernstein wave has the potential for current drive [3] but has received little theoretical study. If it is desired to damp the LFFW energy directly on electrons it is necessary to assure that the relation $(\omega - \Omega_i)/(k_{\parallel} v_i) \gg 1$ holds throughout the plasma for low harmonics. In practice this is achievable by selecting frequencies which remove the cold ion resonances ($\omega = \Omega_i$) from the central regions [6,7].

Still another power sink, of concern only in an ignited tokamak, is alpha particle damping. The alphas are so energetic that this must be considered as a special case of ion damping. This loss mechanism is treated elsewhere [7,18] and will be of no further concern in the report.

As T_e increases even further towards reactor relevant values the electron Landau damping is overcome by electron transit time magnetic pumping (TTMP). This damping mechanism is very attractive for current drive but has not been

substantiated in experiments. Relative to electron Landau damping its magnitude is [19]

$$\frac{P_{TTMP}}{P_{eLd}} = \left[\frac{T_e}{m_e c^2} \left(\frac{\omega_{pi}}{\omega} \right)^2 \right]^2 . \quad (20)$$

Notice that for a fixed T_e and density this TTMP is larger for the LFFW than for the HFFW.

We can express the strength of electron Landau damping in terms of a wave damping rate Γ , where, for a wave energy density U , we define the steady state relationship $P_{eLd} = 2\Gamma U$. Then the inverse quality factor with electron Landau damping is

$$Q_{eLd}^{-1} = \frac{2\Gamma}{\omega} = \frac{3.41 \times 10^{-4}}{A_1 Z_1} n_{\parallel}^2 \left(\frac{\omega}{\Omega_1} \right)^2 \left(\frac{\omega}{\omega_{pi}} \right)^2 u^3 e^{-u^2/2} . \quad (21)$$

A final loss mechanism is power dissipation in the walls of the tokamak vacuum chamber. Assuming a typical metallic resistivity for the chamber the skin depth is

$$\delta = 0.225 f^{-1/2} ,$$

and the inverse quality factor for wall heating is

$$Q_{wall}^{-1} = 2 \delta / a . \quad (22)$$

The total cavity Q is found by summing over all the dissipative mechanisms, and electron current drive will be most efficient when the electron damping dominates. Notice that if $Q \gg 1$ then eigenmodes exist in the torus.

3.3 Fast Wave Current Drive

In the studies of rf current drive [1] by Fisch and Karney it is theorized that the physics of fast wave and slow wave particle diffusion is similar. Both waves push electrons parallel to the magnetic field, the main differences being in the magnitude and perpendicular velocity dependence of the quasilinear diffusion tensor. In the linear limit (small deviations of the electron distribution from Maxwellian) both waves have similar current drive efficiency at high phase speeds ($u \equiv \omega/k_{\parallel} v_e \gg 1$), but the fast wave performs significantly better at low phase speeds. In normalized units the ratio of current density to absorbed power density is [20]

$$\tilde{j}/\tilde{p} = \frac{8 u^2}{5 + Z_i} + 2 + \frac{12(6 + Z_i)}{(5 + Z_i)(3 + Z_i)} + \frac{2D}{Z_i u} \quad (23)$$

This formula matches results found in various limits and is accurate within 10% for $1 < Z_i \leq 2$, $T_e \leq 50$ keV, and $n_{\parallel} \geq 1.1$. (Relativistic corrections are small under these circumstances [20].) The term D depends on whether electrons experience Landau damping or transit time magnetic pumping:

$$D = \begin{cases} 3.76 & \text{Landau damping} \\ 8.09 & \text{TTMP} \end{cases} \quad (24)$$

In SI units the actual local current density to power density ratio is given by

$$j/p = \frac{19.19 \times 10^{18}}{\ln \Lambda} \frac{T_e}{n_e} \tilde{j}/\tilde{p} \quad , \quad (25)$$

where $\ln \Lambda$ is the Coulomb logarithm.

A more useful figure of merit for reactor considerations and a parameter more easily determined in experiments is the ratio of total toroidal current to total rf heating power, I/P . A simplified extension of Eq. (25), assuming

uniform j and p across the plasma cross section, yields the result $I_{rf}/P \sim [T_e \tilde{j}/\tilde{p}] \times 10^{18}/[2\pi R n_e]$, or

$$\gamma \equiv (n_e/10^{20} \text{ m}^{-3}) I_{rf} R/P \approx 1.6 \times 10^{-3} T_e \tilde{j}/\tilde{p} . \quad (26)$$

This quantity, γ , is theoretically a function of T_e , Z_{eff} , and wave phase speed through the factors $T_e \tilde{j}/\tilde{p}$; it is not directly dependent on density and the major radius, R . The main motivation for studying fast waves is that γ in fact has an unacceptable deterioration for slow waves above a certain critical density. Lower hybrid experiments generally find $\gamma \approx \text{constant}$ with density, but $\gamma \rightarrow 0$ rapidly above the critical density. This cessation of slow wave current drive is empirically associated with the appearance of the lower hybrid resonance in the plasma as density is increased, $n_e \rightarrow n_e^{LHR}$. A number of criteria have been proposed in order to model this critical density. An early suggestion was that the wave frequency must be a few times the lower hybrid frequency:

$$\omega > N \omega_{pi} [1 + \omega_{pe}^2/\omega_e^2]^{-1/2}$$

where this is evaluated at the average electron density $\bar{n}_e$. By this model the critical density limit for the slow wave is

$$\bar{n}_e \leq \frac{1.24 \times 10^{-2} f^2}{[5.45 \times 10^{-4} (N/A_1)^2 - 1.276 \times 10^{-21} (f/B)^2]} , \quad (27)$$

where $N = 2.5$. More recently [21] the following scaling was suggested:

$$\bar{n}_e \leq .971 \times 10^{19} B^2 \left\{ 1.732 \left[1 + \frac{4}{\Omega} \frac{T_i}{Z_i^2 T_e} \right]^{1/2} + \left[\frac{\Omega^2}{Z_i^2} - 1 \right]^{-1} \right\} . \quad (28)$$

A purely empirical scaling shows the critical density may equally well be a simple function of frequency

$$\bar{n}_e \leq 1.07 \times 10^{14} (\text{f/MHz})^\beta, \quad (29)$$

where $\beta = 1.65$. Our experimental analysis (below) shows that LFFW current drive occurs at densities much larger than the critical lower hybrid boundary given by these formulas.

On the other hand, current drive with the HFFW has not performed much better than the slow wave at densities close to the lower hybrid resonance. One plausible reason that the HFFW current drive is impeded ($\gamma \rightarrow 0$) near n_e^{LHR} is that density fluctuations (e.g., due to drift wave turbulence) may scatter the launched fast wave and in so doing change the $n_{\parallel}$ and $n_{\perp}$ spectrum of the power density [4,5]. Since the $n_{\perp}$ values of fast and slow waves are similar near n_e^{LHR} this scattering can mix the modes, channeling wave power density into slow waves. These slow waves would then experience the same parasitic power sink which destroys conventional lower hybrid current drive at these densities. According to theory [4] the fast wave scatters in a distance L_s , which should be compared with the tokamak dimensions to gauge the significance of this effect. One plasma parameter needed to estimate L_s is the correlation length of the turbulence, L_T . If this is not measured in an experiment it might be estimated from experience with drift waves to be of order the ion Larmor radius (which characterizes perpendicular wavelengths of drift waves), so

$$L_T = 3.23 \times 10^{-3} T_i^{1/2} A_i^{1/2}/B. \quad (30)$$

The correlation length can be normalized to the free space wavelength of the launched fast wave:

$$\bar{L}_T \equiv \omega L_T/c. \quad (31)$$

The second plasma property of importance is the level of density fluctuations. If not measured this might be estimated from drift wave theory to be

$$\epsilon = \langle (\delta n_e / n_e)^2 \rangle^{1/2} = L_T / L_n \quad (32)$$

where L_n is the density scale length, $(d \ln n_e / dr)^{-1}$, which is very roughly on the order of the minor radius. When the fast wave wavelength is long compared to the correlation length, $s^2 \equiv (n_{\perp} \bar{L}_T)^2 \ll 1$, the scattering distance is predicted to be

$$L_s = \frac{3.36 \times 10^6}{\sqrt{n_e}} \frac{n_e}{\omega_{pe}} \frac{1}{\epsilon} \frac{c^2}{\bar{L}_T \sqrt{1 + 4C^2 + C^4}} \quad (33)$$

where $C \equiv n_{\parallel} / \sqrt{n_{\parallel}^2 + n_{\perp}^2}$.

Another crucial issue for current drive is of course how large the efficiency γ will be. For lower hybrid current drive a large number of experiments fall within the scaling of Eq. (26) with $\tilde{j}/\tilde{p} \approx 20-50$; that is, γ increases roughly linearly with T_e . We expect a similar temperature dependence for fast waves. Moreover, reference to Eq. (23) indicates that $\tilde{j}/\tilde{p} \approx 20-50$ corresponds to $u \approx 2-4$, which means the phase speeds responsible for lower hybrid current drive are exactly those values of u which maximize electron Landau damping. Again, the same behavior is expected with fast wave current drive, since TTMP also maximizes for $u \approx 2-4$. Higher phase speeds ($u \gg 3$) are expected to result in negligible damping and current drive. We note that in some tokamaks two different electron "temperatures" may be created, for example by injecting a high energy (few hundred volts) electron beam into a much colder background plasma. In this case the fast waves may couple only to the hot electrons and care must be taken when analyzing such situations with standard theories which assume a single maxwellian distribution.

Another consideration when comparing theory and experiment is that our Eq. (26) assumes complete absorption of the launched wave power by electrons. This is questionable especially in collisional plasmas or where ion absorption or vacuum chamber losses compete with electron wave damping.

Finally, the least ambiguous evidence of current drive obtains when there is no electric field in the plasma. Ideally this requires a zero loop voltage, $V_L = 0$, and long pulse operation with constant current, $\dot{I} = 0$, and constant plasma inductance (stationary current profile), $\dot{L} = 0$. In practice

these conditions are rarely obtained, and in order to estimate γ we must try to subtract the effect of inductively driven currents from the experimental data. For experiments in which $\dot{I} \neq 0$ we can estimate the rf driven portion of the current as

$$I_{rf} = I - [V_L - L\dot{I}]/R_S, \quad (34)$$

where the expressions for inductance and the toroidal (Spitzer) resistance are, respectively,

$$L = 4\pi \times 10^{-7} R [\ln(8A/\sqrt{\kappa}) - 1.75] \quad (35)$$

and

$$R_S = 4.79 \times 10^{-8} \frac{A^2}{\kappa R} \frac{Z_i}{T_e^{3/2}}. \quad (36)$$

The geometric factors of elongation, κ , and aspect ratio, A , enter these formulas. When feedback control holds the total current constant, Eq. (34) is replaced with

$$I_{rf} = \left(-\frac{\Delta V_L}{V_L} \right) I, \quad (37)$$

where ΔV_L is the change in the loop voltage when rf is applied. Again care must be used when interpreting experiments; some decrease in loop voltage may be due to heating and increased Spitzer conductivity.

Lastly, to qualify as a demonstration of fast wave current drive an experiment must as a minimum have an asymmetry. Thus, in a maxwellian the current should reverse direction as the wave phasing is adjusted to change direction. Alternatively, an asymmetric electron distribution (e.g., from beam injection) could be maintained with a symmetric wave spectrum.

3.4 Analysis of Individual Experiments

Experimental conditions and derived quantities relevant to wave driven currents are summarized in Appendix A. Standard conditions and typical parameters are listed there which serve as a reference for the qualitative discussions below. Detailed current drive results are likewise given in the appendix by tables which document the current drive efficiency under specific conditions.

3.4.1 Synchrotron

This device, which reported the earliest results with a fast wave antenna [22], provided a clear demonstration of current drive at low frequency (3 MHz) and high density ($> 10^{19} \text{ m}^{-3}$). Because the toroidal field was so low we find $\Omega^2 = 5.14$, and thus both fast and slow waves can be supported by the plasma (see Fig. 1) at any density. Tests were performed with three phase speeds, $n_{\parallel} = 160, 300$ and 700 , established by adjustments in the delay line wrapped around the torus. Reference to Fig. A1 shows that the fast wave is operating near cutoff for $n_{\parallel}$ in this range and $n_e \lesssim 1 \times 10^{19} \text{ m}^{-3}$. In fact, typically $n_{\perp} \lesssim c/af$ so it is difficult to fit an eigenmode in this small torus. However, electron Landau damping and nonresonant wave dissipation are so strong that cavity modes would not arise in any event.

Neutral gas ionization and current startup were achieved with rf alone, with about 50 kW of absorbed power. The current could reach a few hundred amperes, providing good confinement ($q_{\text{edge}} = 2$). The current was observed to flow opposite the direction of the travelling waves, demonstrating wave coupling to the electrons. The current drive mechanism is plausibly electron Landau damping since the best results occurred with $u \approx 1-2$; current drive decreased as u was increased, possibly due to weaker Landau damping.

No sharp density cutoff for current drive was found. At the highest reported density, $\bar{n}_e = 1.3 \times 10^{19} \text{ m}^{-3}$, the efficiency was still fairly constant, $\gamma = 4 \times 10^{-5}$. In practice it was difficult to generate plasma at higher filling pressures with the limited power available [23]. Likewise, the decrease in toroidal current with increasing n_e prevented the achievement of a good equilibrium, the density well exceeding the Murakami value.

The current drive efficiency is in accord with Fisch-Karney predictions. If we note that the nonresonant power dissipation exceeds the collisionless damping by the factor of 15, then at most only 6.5% of the power was dissipated on the resonant electrons. This would increase the typical measured $\gamma = 5 \times 10^{-5}$ to an effective value of $(5 \times 10^{-5})/(0.065) = 7.7 \times 10^{-4}$. If this value and the reported peak temperature, $T_{eo} = .01$ keV, are substituted into Eq. (26) we find $\tilde{j}/\tilde{p} = 48$, in excellent agreement with lower hybrid current drive experiments.

3.4.2 ACT-I

In many ways this experiment [24] improved over the conditions provided by Synchrotron. By operating at only 18 MHz but a relatively high field it was possible to push the lower hybrid resonance to very low density -- $\Omega^2 = 0.015$ and $n_e^{LHR} = 3 \times 10^{16} \text{ m}^{-3}$. Hence the plasma would only support the fast wave under typical experimental conditions ($\bar{n}_e = 3 \times 10^{18} \text{ m}^{-3}$), and this provides a classic illustration of LFFW current drive. The single, electrostatically shielded loop antenna was presumed to broadcast a broad spectrum with power in the range $n_{\parallel} = 10$ -20. Reference to Fig. A2 shows that this corresponds to $n_{\perp} \approx 200$ when n_e is sufficiently above cutoff ($\geq 3 \times 10^{18} \text{ m}^{-3}$), and eigenmodes should fit in the ACT-I chamber. It was observed that waves were cutoff and current ceased when $n_e \leq 1 \times 10^{18} \text{ m}^{-3}$, in good agreement with Eq. (8). Moreover, for $n_{\parallel} \geq 10$ we observe that Eq. (8) predicts $n_e^c \propto f^{-1}$ for a fixed $k_{\parallel}$, and this dependence was likewise found in the experiment. Such tests provide unequivocal evidence that the LFFW was successfully excited.

Since the single element antenna launched a symmetric spectrum it was necessary to provide an asymmetry by introducing a unidirectional beam, a 40 A, pulsed current injected at 400 V from an emitting cathode. Numerical simulations suggested this beam provides $\sim 1\%$ of the electron density and included energies in a range extending well above $T_h = 0.4$ keV. Waves typical of the launched spectrum, with $n_{\parallel} = 12$ for example, would be strongly damped by the beam since they had $u \approx 3$. Compared to Synchrotron this device also was in a more collisionless regime so power was more effectively channeled into the resonant electrons. The ratio of nonresonant to resonant power dissipation is difficult to know accurately without detailed knowledge of the power spectrum, but we estimate $p_{nr} \approx p_{eLd}$. Wall dissipation is also the same order

of magnitude as the resonant absorption. Cavity modes with $Q \approx 250$ would be expected; near cutoff individual eigenmodes were in fact detected.

A total decrease of γ above a critical density was not found, although at the highest reported $\bar{n}_e$ a large drop may have been setting in. Machine operation was impractical at higher density since breakdown was harder to achieve [25], so upper limits to n_e for LFFW current drive were never fully tested. In this regard we note that the toroidal current was so low that good flux surfaces were not created and true tokamak confinement was not possible.

An absolute comparison of the experimental current drive efficiency, γ , with theory is difficult since it is unclear whether to use the bulk or hot tail temperature in Eq. (26). Assuming 30% of the rf power is resonantly absorbed by electrons the efficiency increases from $\gamma = 3.5 \times 10^{-4}$ to an effective value of $3.5 \times 10^{-4}/(0.30)$. From Eq. (26) this implies $\tilde{j}/\tilde{\rho} \approx 2-48$, for T_e in the range 0.015-0.400 keV.

3.4.3 Irvine Torus

Like Synchrotron, this experiment [26] operated with a relatively low field, so $\Omega^2 \approx 83 \gg 1$, and both wave polarizations could exist in the plasma. The 16-element fast wave antenna was designed to be one wavelength long both toroidally and poloidally. The principal index of refraction was $n_{||} = 10.6$, and $f = 94$ MHz. The investigators found unambiguous evidence that the fast wave was excited. For example, at densities less than $\sim 5 \times 10^{17} \text{ m}^{-3}$ no current generation was possible, and this agrees with the fast wave cutoff for $n_{||} = 11$ (see Fig. A3). In contrast, the slow wave cutoff is much lower ($\sim 10^{14} \text{ m}^{-3}$), so the slow wave was definitely not responsible for current drive. Moreover, an examination of Eq. (10) reveals that $k_{\perp} \propto \omega$ at fixed density, field, and $k_{||}$ for the fast wave; and measurements confirmed that the radial wavelength in the torus agreed with the equation and had the correct frequency dependence. Additional tests also confirmed the identity of the fast wave.

As with ACT-I, the Irvine torus operated with a hot electron tail, provided by thermionically emitting filaments which injected electrons at ≤ 350 V in both toroidal directions. This permitted strong electron Landau damping ($u \approx 3-4$ with $T_h = 0.350$) using the available $n_{||} = 10.6$. We calculate from Eq.

(17) that the electron Landau absorption and nonresonant damping were comparable, $P_{eLd} \approx P_{nr}$, while other losses were negligible.

Current drive could be convincingly attributed to the travelling wave. The emitting filaments created plasma but no current, as the emission was in both directions. Then current was created in the toroidal direction opposite to the phase velocity of the travelling waves, and with symmetric phasing of the antenna elements no current arose. The Landau mechanism was apparently at work, for if the filament voltage was reduced (< 300 V) then current generation dropped, which would correspond to weaker wave Landau damping as u increased above ~ 4 . A hard upper density limit for current drive was not reported, and it is encouraging that the working density, $\bar{n}_e = 4 \times 10^{18} \text{ m}^{-3}$, is an order of magnitude higher than expected from slow wave experience [cf. Eq. (28) and (29)]. On the other hand, the dispersion relation in Fig. A3 shows that power with $n_{||} \lesssim 20$ will not be accessible to density higher than $1 \times 10^{19} \text{ m}^{-3}$.

Even though the lower hybrid resonance did not occur within the plasma, the Irvine Torus provided valuable measurements of the attenuation of wave amplitude with distance from the antenna, which suggested that wave scattering was happening. Probe measurements found attenuation lengths several orders of magnitude shorter than could be accounted for by dissipative processes such as electron Landau damping. In fact, drift wave turbulence with $\langle (\delta n_e / n_e)^2 \rangle^{1/2} \approx 0.06$ was present, and, if we use Eq. (33) we can calculate an attenuation length which is quite close to the observed value (~ 0.10 m). Such scattering of wave energy could be a serious detriment to HFFW current drive if slow waves near the lower hybrid resonance are the energy recipients.

A comparison of the actual current drive efficiency with the prediction of Eq. (26) is hampered by the presence of two electron distributions. If we select $T_h = 0.35$ as the relevant temperature and increase γ by a factor of two to an effective value $\gamma = 0.010$, accounting for the nonresonant wave heating, we infer $\bar{j}/\bar{p} \approx 20$. Hence the current drive efficiency is comparable to lower hybrid current drive.

3.4.4 CCT

This machine was built with the intention operating as a steady state tokamak. It features a large area cooled antenna with Faraday screens. The

antenna consists of eight helical coils (5/4 turns poloidally), equally spaced toroidally; each coil has three separate conductors in parallel. Antenna phase control is provided such that two or more integral wavelengths will be established around the torus. Probe measurements show, however, that the plasma typically upshifts $n_{||}$ by a large factor from the imposed spectrum [27]. Thus, for example, $n_{||} = 2.9$ corresponds to $\pi/2$ phasing of the eight antenna elements, but typically $n_{||} = 20-50$ appears in the plasma. The plasma filters out the fundamental wavelengths and transmits the short wavelength components. The discreteness and helical nature of the antenna would be expected to provide an edge spectrum rich in short wavelength harmonics.

The antenna operates over a frequency range, $f = 7, 22$, and 80 MHz. Our analysis is devoted to the case $f = 22$ MHz with $B = 0.05$ T, for which $\Omega^2 = 0.453$ (proton plasma) and $n_e^{\text{LHR}} = 3 \times 10^{16} \text{ m}^{-3}$. For typical operation the average density $\bar{n}_e = 3 \times 10^{17} \text{ m}^{-3}$, so the lower hybrid resonance resides in the low density edge region. The dispersion relation is shown in Fig. A4, where we find the fast wave cutoff density is $n_e^c \gtrsim 1 \times 10^{17} \text{ m}^{-3}$ for $n_{||} \gtrsim 20$. This in fact corresponds with the cutoff density as measured by the antenna loading resistance. Additional measurements of energy propagation confirmed that the wave characteristics were those of fast waves, not slow waves.

Observations of wave damping in CCT are hard to compare with theory since the expected strength of Landau damping is difficult to estimate. At these low densities the electron temperature is variously estimated between 0.020 keV and 0.150 keV; as discussed, the values of $n_{||}$ in the plasma are upshifted and broadened. Hence the ratio $u = (\omega/k_{||}v_e)$ is somewhat uncertain and lies in the range ~ 2 to ~ 5 . For $u \sim 4-5$ the electron Landau damping is relatively weak ($Q_{\text{eLd}}^{-1} \leq 10^{-2}$), which would account for the observed presence of cavity modes in the experiment [28]. Without an accurate knowledge of u it is difficult to know the actual amount of power dissipated collisionlessly, but it is likely that the nonresonant wave damping may exceed the Landau damping.

Current generation depends on the antenna directionality and varies linearly with applied rf power [28]. The results are consistent with fast wave current drive. In particular, there does not appear to be an upper density limit. Experiments were not carried out above $\sim 1 \times 10^{18} \text{ m}^{-3}$ because the limited power available (20 kW) provided such a small current (< 1 kA) for the large tokamak volume [28]. As with the Irvine Torus it was found that

wave attenuation occurred over distances too short to be explained by collisional and resonant damping, and this was attributed to wave scattering. Such scattering could help explain the large n_i upshift observed. More importantly, the signature of slow waves (short wavelength, electrostatic modes) was detected near the plasma edge, suggesting that some power was indeed channeled into the slow wave near the lower hybrid resonance.

The actual current drive efficiency should be compared with the prediction of Eq. (26). This is made difficult by not knowing the fraction of power going to Landau damping. If we set $T_e = T_h = 0.15$ keV and assume $\tilde{j}/\tilde{p} = 30$, for example, the formula would predict $\gamma = 7.2 \times 10^{-3}$, roughly ten times larger than the best γ reported. This would imply that only 10% of the wave power was absorbed by Landau damping while 90% was uselessly dissipated as nonresonant heating. Such an inference falls within the wide range of P_{nr}/P_{eLd} values which are plausible for CCT.

3.4.5 JIPP T-IIU (40 MHz)

By selecting a low frequency, 40 MHz, the researchers on JIPP T-IIU intentionally pushed the lower hybrid resonance to a very low density [9,29]; for the LFFW experiment $\Omega^2 = 0.094$ and $n_e^{LHR} = 4 \times 10^{16} \text{ m}^{-3}$, while the wave was typically launched into a much higher density, $\bar{n}_e = 2 \times 10^{18} \text{ m}^{-3}$. A substantial current (3.5 kA) could be started up, without a transformer, in a fairly large volume tokamak by providing high power to the antenna (several hundred kilowatts). Although closed flux surfaces were generated, this rf power was insufficient to raise T_e above the radiation barrier.

The fast wave antenna was a five-loop array with variable phasing between elements. The dispersion relation (Fig. A5) shows that fast wave cutoff requires densities approaching 10^{18} m^{-3} for $n_i \geq 10$, which corresponds to the experimental conditions.

This particular experiment shares a peculiarity common to lower hybrid current drive experience, namely the apparent upshift of the n_i spectrum. There is no attempt to create a nonthermal tail on the electron distribution, and the calculated spectrum spans $n_i = 4-8$. Such phase speeds are far too high to interact via linear Landau damping, and it seems evident that some mechanism operates to provide slower phase speeds in the plasma interior.

The analysis of current drive is complicated by the strong influence exerted by the vertical (equilibrium) magnetic field. The direction of toroidal current is tied to vertical field polarity (as required for equilibrium), and toroidal current arises even with a symmetric spectrum (π phasing). However, the current increases with forward travelling waves and is reduced with reversed polarity, which could indicate a current drive effect. Moreover, $\pi/4$ phasing, which results in higher phase speeds ($n_{||} = 2-6$) than $\pi/2$ phasing, is seen to result in larger efficiency, γ . Such an increase of γ with phase speed is predicted by current drive theory [cf. Eq. (23)].

The highest density achieved with current drive was $\sim 2.5 \times 10^{18} \text{ m}^{-3}$, roughly two orders of magnitude higher than would be expected for lower hybrid current drive. Attempts to operate at still higher $\bar{n}_e$ were foiled by the growth of MHD instabilities, which may be related to a violation of the Murakami limit. It was also not possible to circumvent this problem by using a higher field, as gas breakdown became difficult above $B = 0.2 \text{ T}$ [23].

A naive assessment of the current drive efficiency, $\gamma = 1.6 \times 10^{-4}$ at $T_e = 0.01 \text{ keV}$, would suggest $\bar{j}/\bar{p} = 10$ in Eq. (26), in approximate agreement with lower hybrid experience. Such a conclusion has questionable validity since we are uncertain what fraction of launched power is actually delivered to the resonant electrons.

3.4.6 JIPP TII-U (800 MHz)

In a series of experiments at higher frequency and magnetic field [30] the HFFW alternative was also tested on JIPP TII-U. This sequence of tests provided better confinement and higher target plasma temperatures by starting from an ohmic discharge ($\geq 40 \text{ kA}$). However, in many ways it illustrated the difficulties of HFFW current drive since there was evidence that some phenomenon (e.g., coupling to slow waves) prevented current drive above the lower hybrid limit.

The dispersion relation with $q^2 = 0.214$ is shown in Fig. A6 where it is seen that $n_e^{\text{LHR}} = 1.9 \times 10^{19} \text{ m}^{-3}$. Although current drive ceased as n_e was increased towards n_e^{LHR} , there were indications that the fast wave was excited at lower densities. Thus, for example, when the four-loop antenna was phased at $\pm \pi/2$ the calculated $n_{||}$ peaked at $|n_{||}| \approx 2.3$. These slow phase speeds are near cutoff when $n_e \leq 3 \times 10^{18}$, and this correlates with an absence of fast

wave effects seen at that phasing. In accordance with fast wave theory (Fig. A6) antenna loading and wave effects increased with higher $\bar{n}_e$ values, shorter antenna/plasma gap, or shallower phase ($\Delta\phi = \text{zero}$, corresponding to lower $n_{\parallel}$ values). Detailed diagnostics revealed the wave-plasma interactions at different densities. At $\bar{n}_e = 3 \times 10^{18} \text{ m}^{-3}$, for which current drive was possible, the electron tail extended from the thermal range (typically 100 eV) out to 300 keV. Significantly, this upper electron energy limit corresponds to $n_{\parallel} = 1.3$, which is very close to the accessibility limit, $n_{\parallel}^a = 1.2$. Any fast wave spectral components with $n_{\parallel} \leq 1.2$ are expected to be reflected as slow waves and cannot penetrate to the high density interior of the plasma. At the other end of the spectrum, we see that values of $n_{\parallel} \geq 2.5$ are cutoff for typical operating densities on JIPP T-IIU. (This cutoff phase speed is a particular concern mainly for the HFFW, as $n_{\parallel}$ can become larger at lower frequencies, such as on the 40 MHz experiments on JIPP TII-U.) This forms a puzzle as to how the spectral gap is filled in to provide electron interactions down to energies at ~ 100 eV. Reference to Fig. A6 shows that only slow waves exist with adequately large $n_{\parallel}$ values when $n_e \leq 1 \times 10^{19} \text{ m}^{-3}$. This provides indirect evidence of mode coupling from the launched HFFW to slow waves. As $\bar{n}_e$ is increased, ion interactions become noticeable. At the density for which electron interactions cease ($\geq 7 \times 10^{18} \text{ m}^{-3}$) an ion tail forms and parametric decay instabilities are found. The ion tail extends to 20 keV, and if its creation is due to perpendicular ion Landau damping then, from Eqs. (18) and (19) we would infer the presence of waves with $n_{\parallel} = 153$. The dispersion relation shows that only slow waves have such large $n_{\parallel}$ values at this density. Our calculations of fast wave attenuation by drift wave scattering [Cf. Eq. (33)] show this to be a plausible mechanism for such mode mixing.

The current drive efficiency, $\gamma = 0.017\text{--}0.019$ lies close to the value usually obtained with lower hybrid waves at $T_e = 0.1$ keV; very roughly $\tilde{j}/\tilde{p} = 100$. The lack of directivity in current drive dependence on antenna phasing mars the results to some extent. It is apparent, though, that maximum values of γ with zero phasing is not due to heating, as the bulk temperature drops during the rf pulse. The symmetric spectrum selectively supports the one-sided slideaway tail of the preexisting ohmic discharge.

3.4.7 JFT-2M (200 MHz)

By operating at high field (1.07 T) and relatively low frequency (200 MHz), this experiment has $\Omega^2 = 0.082$ and $n_e^{\text{LHR}} = 1 \times 10^{18} \text{ m}^{-3}$. Thus, mode mixing and parasitic slow wave damping are expected to be detrimental for operation at densities a few times 10^{18} m^{-3} . If operation can be pushed to several times 10^{19} m^{-3} the lower hybrid resonance may be of less consequence, and this would verge on becoming an attractive test of the LFFW technique. An additional advantage of using this relatively low frequency is that a large window of n_i values are accessible and not cutoff; from Fig. A7 we find $n_i = 1.1\text{-}5.0$ should propagate at densities $\sim 3 \times 10^{18} \text{ m}^{-3}$. This corresponds closely with the broad power spectrum calculated for the antenna [31] with $\pi/2$ phasing. Such a broad spectrum results since only two elements of a three-loop array are activated.

Coupling tests verify that the fast wave is launched: at $\bar{n}_e$ well below $1 \times 10^{18} \text{ m}^{-3}$ antenna resistance is zero, while radiated power increases with $\bar{n}_e$ at higher densities. Likewise, resistance increases as the antenna/plasma distance is reduced.

Good confinement and initial ohmic currents $\geq 100 \text{ kA}$ provide a fairly hot target plasma with estimated electron temperatures of several hundred electron volts. It is likely that much higher tail temperatures are supported during current drive. Under these circumstances it appears that the broad radiated spectrum will couple readily to electrons via Landau damping with $u \approx 1.3\text{-}4.5$. Nonresonant damping and other power sinks are small, so most of the rf power is delivered directly to the resonant current carriers.

Wave power loss to ions might be expected when $\bar{n}_e \approx n_e^{\text{LHR}}$. Our calculations indicate wave scattering by density fluctuations should be a significant factor, and, indeed, parasitic decay to slow waves was observed near the current drive density limit [32]. The loss of power to slow waves near the lower hybrid resonance may not completely explain the loss of current drive, however. For example, the parametric decay waves vanish at $\bar{n}_e \geq 1 \times 10^{19} \text{ m}^{-3}$. At $\bar{n}_e = 1.5 \times 10^{19} \text{ m}^{-3}$ the resonance occurs at $r/a = 0.9$ (in the low density edge), and, although current drive is not evident, there is still a strong wave interaction with electrons in the range 40-100 keV [33]. One conclusion is certain; the observed density limit for current drive is several times the value expected from lower hybrid current drive experiments. Possi-

bly fast wave current drive occurs at $n_e > 10^{19} \text{ m}^{-3}$ but is being masked by the increase of metal impurities at high rf power. With the limited rf power available ($\sim 40 \text{ kW}$) the driven current would be much smaller than the pre-existing ohmic current when $n_e \geq 10^{19} \text{ m}^{-3}$. Any small drop ΔV_e would be overcome by an increase in voltage required to hold the ($\geq 100 \text{ kA}$) total current constant in the presence of the higher Z_{eff} .

Experiments were done in both proton and deuteron plasmas, and generally deuterium provided the best results. In deuterium the density limit was higher, about $3 \times 10^{18} \text{ m}^{-3}$, and γ was somewhat better than for protons. If we take a typical value $\gamma = 0.031$ and set $T_e = 1 \text{ keV}$ in Eq. (26) we find $\tilde{j}/\tilde{p} = 19$. Hence, the efficiency is comparable with lower hybrid current drive experience.

3.4.8 JFT-2M (750 MHz)

By increasing the wave frequency to $f = 750 \text{ MHz}$ the JFT-2M investigators were able to compare fast and slow wave current drive under identical conditions in the same tokamak [32]. The slow wave was produced from a waveguide grill at the same frequency that the fast wave loop antenna was operated. The comparison found nearly identical results, including the same density limit ($\sim 9 \times 10^{18} \text{ m}^{-3}$).

The similar performance for both wave couplers is not surprising. Both couplers radiate power concentrated at $n_{\parallel} < 2$. Examination of the dispersion relation (see Fig. A8) shows $n_{\parallel}^a = 2$ for $n_e = 1 \times 10^{19} \text{ m}^{-3}$, so either coupler will launch power which is reflected as the opposite polarization near the current drive limit. There are subtle differences between the two polarizations, however. The fast wave shows less evidence of parametric decay waves, which might be attributed to the lower $n_{\parallel}$ values of the launched fast waves. Also, hot electron tails are produced at higher densities for the fast wave ($8 \times 10^{18} \text{ m}^{-3}$ vs. $6 \times 10^{18} \text{ m}^{-3}$ for the slow wave), which also suggests less parasitic power loss when the fast wave is launched. Nevertheless, it is likely that some fast wave power is converted by mode mixing into the slow wave branch. This would provide the upshifted $n_{\parallel}$ wave components to fill in the spectral gap when operating at $n_e \leq 2 \times 10^{18} \text{ m}^{-3}$. We note that the fast wave attenuation length predicted by Eq. (33) is on the order of the tokamak dimensions.

The final observation in this experiment is the identical current drive efficiency with both wave polarizations, as the theory predicts. For the best case, $\gamma = 0.06$, we find $\tilde{j}/\tilde{p} = 38$ if we use $T_e = 1$ keV in Eq. (26).

3.4.9 PLT

PLT provided another opportunity to compare HFFW and lower hybrid current drive under the same conditions. At the frequency (800 MHz) and field chosen (3.1 T) the lower hybrid resonance occurred at $n_e^{LHR} = 4.2 \times 10^{19} \text{ m}^{-3}$, so both fast and slow waves could propagate in the plasma for typical current drive conditions ($n_e < 9 \times 10^{18} \text{ m}^{-3}$).

Both a six-element loop coupler and a 3×4 element dielectric waveguide array were tested and provided HFFW current drive, although the latter provided the best performance [34,35]. Coupling improved with density and displayed the phase dependence expected for the fast wave. The waves were launched into an initial high current ohmic discharge, and the change of $\dot{I}$ was monitored after the transformer was shut off. The current drive effect was only mildly sensitive to waveguide phasing, even when phasing was reversed. Evidently the array provided power in the range $n_{\parallel} \approx 1.4$ with travelling waves propagating in both directions, and current directionality was determined solely by the preexisting asymmetry in the electron distribution function.

The density limit was identical for both wave polarizations. We note from Fig. A9 that at this high frequency only a narrow $n_{\parallel}$ window of fast waves can propagate at $n_e \approx 4 \times 10^{18} : 1.2 \leq n_{\parallel} \leq 2.5$. Hence it is possible that some mechanism is providing high $n_{\parallel}$ (slow) waves to fill in the spectral gap. Scattering from drift waves is a plausible explanation as the attenuation length given by Eq. (33) is very short. Parametric decay and ion tails are also associated with the density limit, further suggesting that high $n_{\parallel}$ slow waves are involved. We note, however, that the ion effects are localized near the edge and not in the center where the ion temperature is presumably highest. Further discussion of the density limit is provided in Ref. [35].

The PLT data confirmed that the efficiency γ was identical for fast and slow waves.

3.5 Conclusions from Fast Wave Experiments

Although fast wave experiments are at an early stage, several important physics issues have been clarified. Based on the analysis above we can summarize our conclusions.

- a. The fast wave has been positively identified as the launched wave in these experiments, as inferred from antenna loading characteristics and probe measurements.
- b. The HFFW, for which the lower hybrid resonance density is near or above the experimental density, has not demonstrated current drive at densities above the limit for lower hybrid current drive.
- c. Diagnostics reveal fast wave attenuation in distances too short to be explained by nonresonant or electron Landau damping. Such behavior might be accounted for by scattering from turbulent density fluctuations, and the resulting changes in $n_{\parallel}$ and $n_{\perp}$ values could couple the launched high frequency fast wave energy into slow waves which experience the usual density limit for current drive.
- d. For the LFFW (in which the slow wave resonance is pushed to very low density, into the limiter shadow) current drive is attainable at densities seemingly higher than would be expected from lower hybrid wave scaling. This is shown in Figs. 1 and 2 where the experimental fast wave limit is plotted vs. two different slow wave scalings. Note in particular that LFFW current drive has been achieved at higher densities than was possible with low frequency slow waves (in the frequency range ~ 200-400 MHz) [36,37,38].
- e. Fast wave current drive exhibits directionality in start up experiments. A dependence on phase speed has been found in some cases, indicative of the Landau damping mechanism. The efficiency $\gamma = \bar{n}_e I R / P_{rf}$, appears constant at densities below the limit, and the ratio of γ / T_e is comparable with values found in lower hybrid current drive experiments. This all suggests that the Fisch-Karney theory is applicable to the fast wave.

f. The analysis shows that TTMP plays no role in these low temperature experiments; nevertheless the relatively weak Landau damping was adequate to achieve efficient current drive.

3.6 Other Fast Wave Experiments

A few other fast wave tests have been attempted but were not analyzed in detail. These include: Macrotron [39]; Versator-II with a slotted waveguide at 2.45 GHz [40]; PLT minority heating at 30 MHz (density control problems [35]); and minority heating on Pretext [17]. Several new experiments have been proposed or could be considered.

a. JIPP T-IIU

The success of the LFFW experiment at 40 MHz needs to be repeated in a higher magnetic field with better confinement. For this purpose a 130 MHz source (with 1 MW of power) has been obtained [23], and experiments may be initiated in 1988.

b. JFT-2M

The LFFW at 200 MHz shows electron interactions at densities $\geq 10^{19} \text{ m}^{-3}$, but the increase of Z_{eff} during rf masks any current drive effects. The plan is to increase rf power by a factor of twenty, providing 800 kW of total power [41]. Hot electrons will be provided by ECRH in order to selectively couple to electrons and avoid ion harmonic damping.

c. Versator II

Plans call for testing 800 MHz fast wave current drive. Our analysis suggests this frequency will not result in a significant increase in the density limit relative to the slow wave; a lower frequency might prove advantageous.

d. DIII

This tokamak may host the first definitive LFFW demonstration. In 1989 a 30-60 MHz ICRF system at 2.25 MW will be installed [42]. Several

years later this will increase to 9 MW. In addition, 10 MW of ECRH will be available to provide a hot electron target. With adequate central electron temperatures (> 10 keV) it is expected that TTMP will be effective.

e. Tore Supra

This long pulse tokamak, with $B = 4$ T, will have 12 MW of ICRF (35-120 MHz) available for LFFW current drive. It has been proposed also to provide hot electrons via ECRH.

f. JET

Studies of LFFW current profile control via TTMP have been made for JET [19,43]; although ~ 30 MW of ICRF power is available at the generators, the present antenna system has poor directionality [44] and little current drive would be expected. Other fast wave current drive possibilities -- minority heating and mode conversion -- are under consideration [3].

3.7 Benchmark Code Comparison and Scaling to a Reactor

Fast wave current drive was considered during the INTOR [45] process as a prime candidate for reactor-scale tokamaks. In order to compare numerical codes from different countries the participants calculated the efficiency γ for a standard case: $R = 4.9$ m, $A = 4.2$, $\kappa = 1.6$, $B = 5.5$ T, $q_{\text{axis}} = 1.0$, $I = 8.0$ MA, $\bar{n}_e = 7.0 \times 10^{19} \text{ m}^{-3}$, $\bar{T}_e = 20$ keV, and $Z_{\text{eff}} = 1.5$. Densities, temperatures, and current density profiles were required to be centrally peaked.

The HFFW was studied by three groups. Japan reported two independent calculations of γ at frequencies $f \approx 0.3$ GHz. Firstly, using a ray tracing/1D quasilinear Fokker Planck code, it was shown that low frequencies (~ 0.2 GHz) result in strong ion losses. Also, $f \lesssim 0.4$ GHz results in centrally peaked current density but requires multiple passes through the plasma to achieve wave absorption. For the benchmark case $\gamma = 0.18$ at $f = 0.4$ GHz if we assume that the 40% of the power not absorbed on the first pass is lost. In Table I (reprinted from Ref. 45), however, we assume the remaining power is reflected and drives current at the same efficiency, so we have $\gamma = 0.18/(0.6)$. The effects of spectral width and central n_i were also presented. Of particular

interest is the conclusion that γ maximizes when the parallel wave phase velocity is ~ 2 -3 times the electron thermal speed at the plasma center, i.e., $u = (\omega/k_{\parallel} v_{e0}) \approx 2$. This result of quasilinear damping/current drive calculations agrees with the linear damping model results reported by the USA. The alternative calculation by Japan utilized a full-wave antenna calculation which implicitly accounts for multipass linear absorption. This model predicts that current generation is dominated by waves with $u \approx 3$ -4 and found, for $f = 0.3$ GHz, $\gamma = 0.26$. Japan estimates 2D velocity space effects would raise this by a large amount, to $\gamma \approx 0.6$, as recorded in Table I. The calculations of the USSR also demonstrate that current can be centrally peaked for $f \lesssim 0.3$ GHz. Using a full wave antenna calculation and a 1-D Fokker-Planck code the USSR finds $\gamma \approx 0.31$ for the benchmark, although ion damping is not included in their calculation (circular flux surfaces in a torus of infinite aspect ratio). (This value of γ is a power law temperature interpolation based on results presented at $\bar{T}_e = 15$ keV and 30 keV for $f = 0.21$ GHz.) The value of γ for the USSR includes a factor of two enhancement to account for higher current drive efficiency expected from more realistic 2-D Fokker-Planck studies. The USA also shows that current may be centrally peaked. By selecting a variety of frequencies, $0.3 \text{ GHz} \leq f \leq 1.0 \text{ GHz}$ and a tailored power spectrum with $1.4 \leq n_{\parallel} \leq 2.8$ it is possible in principle to generate a current density in two dimensional MHD equilibrium with $\beta = 0.036$ and $I_0 = 8$ MA. This benchmark calculation results in $\gamma = 0.41$. The larger γ obtained by the US may be related to the relatively wide equilibrium current profile obtained, compared to the highly peaked, more Gaussian profile found by the USSR for a particular antenna geometry. The encouraging conclusions of these studies are that accessibility does not impose a fatal constraint on $n_{\parallel}$ at the benchmark density and that the large radial group velocity of waves with $0.3 \text{ GHz} \leq f \leq 1.0 \text{ GHz}$ and $n_{\parallel} \leq 1.7$ leads to centrally peaked current profiles.

These same groups also studied γ dependence on $\bar{T}_e$; see Fig. 3. The increase of γ with $\bar{T}_e$ is quite strong. The drastic reduction of γ found by the Japanese ray tracing at low $\bar{T}_e$ ($\lesssim 10$ keV) is due to poor wave damping on electrons, resulting from the high phase speed ($n_{\parallel} \approx 1.5$) retained in their calculation. The linear theory of Landau damping would require larger $n_{\parallel}$ to achieve strong damping at ~ 5 keV. The USA [20] provides the following fit for the HFFW, $\gamma = \bar{T}_e^{0.77} [0.034 + 0.196 \beta]$ where β is the equilibrium beta and

assuming $Z_{\text{eff}} = 1.5$. Figure 4 shows the γ (Z_{eff}) dependence. The numerical results are rather well approximated by the analytic expression for the Z_{eff} dependence, given in Ref [20].

The LFFW refers to fast waves below about the fifth ion cyclotron harmonic; since these waves can readily damp on ions, care must be taken to avoid parasitic ion damping. The principal current drive method is direct transit time electron magnetic pumping (TTMP) by the fast wave. Japan used a full antenna calculation with a 1-D Fokker-Planck code. Their $\gamma \approx 0.08$ is rather low but is of questionable relevance as the calculation was done for JET at $\bar{T}_e = 5$ keV, far below the benchmark temperature. The USA ray tracing code gave $\gamma = 0.33$ with a highly peaked current profile. The safety factor drops well below unity at the axis, but it appears that refinements of the calculation should yield reasonable $q(\psi)$ profiles. The USSR performed full-wave antenna calculations in a cylindrical plasma. Without a field gradient there are no ion resonances and all damping is due to TTMP. For the benchmark INTOR they found $\gamma = 0.21$ at 40 MHz and $\gamma = 0.27$ at 106 MHz. The latter value is entered in Table I, although the frequency would be adjusted and γ might be reduced in a toroidal plasma, due to the ion resonances. A new suggestion was made that fast wave frequencies slightly below the tritium fundamental could be useful. Computation yielded $\gamma \approx 0.26$ at $f = 22$ MHz, with $\bar{T}_e = 20$, $\bar{n}_e = 1.5 \times 10^{20} \text{ m}^{-3}$, and $Z_{\text{eff}} = 1$; this low frequency avoids all ion and alpha damping and seems very promising for INTOR. Even lower frequencies (≤ 5 MHz) would encounter Alfvén wave resonances and neoclassical trapping if $u \leq 1$. The USSR also showed that the LFFW at frequencies up to $f \approx 200$ MHz is unlikely to lose significant power to alphas. In these calculations it was possible to get centrally peaked current density with a desirably broad width in minor radius.

Additional calculations by the USSR indicated that for the LFFW γ increases with $\bar{T}_e$ and decreases with Z_{eff} , however comprehensive surveys of variations have not yet been done.

Besides TTMP a number of other LFFW current drive methods are possible. Minority (He_3 or proton) heating by the fast wave and by ion Bernstein waves (IBW) was studied, but in the best case only $\gamma \approx 0.02$ (at $\bar{T}_e = 20$ keV) was found. Also IBW heating of alphas was considered but found to be inefficient for current drive. The Japanese considered fast wave mode conversion to an

ion Bernstein wave but did not actually compute γ . They concluded that outboard launch may result in almost total damping on ions and negligible current drive. Alternatively they propose an inboard antenna location (admittedly difficult in INTOR) or top or bottom launch, to avoid ion damping.

4. CONCLUSIONS AND RECOMMENDATIONS

The preliminary experimental results are encouraging so far in that the fast wave has been successfully excited and has driven current in small scale tokamaks. In particular, the LFFW shows the most promise of exceeding the density limit found with lower hybrid current drive. Many experimental observations coincide with the theoretical models developed, which gives us confidence that the theory can be extrapolated to reactors. It is important along these lines to note that simulations done for INTOR indicate that good results are possible in a reactor: good central current drive is predicted with an efficiency that increases with T_e and reaches $\gamma = 0.4$.

Equally important is the point that much of the rf technology required for fast wave current drive is already available. In fact, the ICRF power (~50-100 MHz) needed to test LFFW current drive is already being installed in large tokamaks for other purposes. Moreover, the electric/rf efficiency for current drive systems at $f \sim 100$ MHz is expected to be much higher than very high frequency (100 GHz) systems, such as are needed for electron cyclotron current drive. This suggests that fast wave current drive will have an advantage for reactor applications.

We recommend that fast wave current drive be tested on large, hot tokamaks. The highest priority should be given to the LFFW, where $f \sim 100$ MHz. In order to avoid harmonic ion damping it will be necessary to locate the ion resonances away from the central plasma region; additional central ECRH will be helpful to increase wave damping on the electrons. In the USA it appears that DIII is well suited to carry out such a program.

Finally, a secondary recommendation would be to study alternative damping/current drive techniques at low frequencies (ICRF). These include minority heating, mode conversion to an ion Bernstein wave, and possibly sub-fundamental (~10 MHz) fast Alfvén wave drive. These alternatives require hardware which is compatible with the LFFW method using direct electron damping.

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Table I - INTOR [45]
 Benchmark Steady State γ [10^{20} A $\cdot$ W $^{-1}$ $\cdot$ m $^{-2}$]
 Values for $\bar{T}_e = 20$ keV, $\bar{n}_e = 0.7 \times 10^{20}$ m $^{-3}$, $E = 0$

Driver	EC	JAPAN	USA	USSR
LH $f = 2 - 10$ GHz $1.7 \leq n_{ } \leq 4.0$ $Z = 1.5$	(0.5) ^a	(0.3) ^a	(0.3) ^a	(0.5-0.8) ^a
NBCD 0.4 MeV $\leq E_D \leq 0.7$ MeV	0.39	0.37	0.37	0.5
HFFW $f = 0.3 - 1.0$ GHz $1.4 \leq n_{ } \leq 2.8$ $Z = 1.5$	--	0.3, ^b ray tracing 0.6, ^c full wave	0.41	0.31 ^{d,e}
LFFW $f = 22 - 70$ MHz $3.0 \leq n_{ } \leq 4.5$ $Z = 1.5$, TTMP	--	(0.08) ^{e,f}	0.33	0.27 ^e

a - Centrally peaked current density not found at $\bar{T}_e = 20$ keV if accessibility or frequency constraint is imposed.

b - Single pass result multiplied by $p^{in}/p^e = (0.6)^{-1}$, assuming multipass absorption.

c - Includes factor of 2.5 to account for 2-D velocity space.

d - Scaled by value at 15 keV by $(20/15)^{0.34}$.

e - Includes factor of 2.0 to account for 2-D velocity space.

f - Calculated at $\bar{T}_e = 5$ keV; uses $n_{||} = 12$.

Figure 1
Fast wave current drive density limit.

Figure 2
Fast wave current drive density limit.

Figure 3

Current drive efficiency with HFFW vs. electron temperature ($Z_{eff} = 1.5$): JPN-W is full wave calculation, not including benefits of 2D velocity space, plotted against bottom abscissa; other values plotted against top abscissa. JPN-R is ray tracing assuming power not absorbed on first pass to be lost.[45]

Figure 4
Current drive efficiency with HFFW vs. Z_{eff} : USA -- $\bar{T}_e = 18$ keV; USSR -- $\bar{T}_e = 20$ keV; JPN-W -- $T_{e0} = 30$ keV, not including benefits of 2D velocity space.[45]

APPENDIX A
EXPERIMENTAL DATA

EXPERIMENT: Synchrotron

LABORATORY: Nagoya

1. REFERENCES: M. Fukuda et al., J. Phys. Soc. Jpn. 41 (1976) 1376; M. Fukuda & K. Matsuura, J. Phys. Soc. Jpn. 44 (1978) 1344.

2. STANDARD CONDITIONS

major radius	R (m) =	0.25
minor radius	a (m) =	0.04
toroidal field	B (T) =	0.0128
fill pressure	p_0 (Torr) =	1×10^{-3}
atomic mass	A_i (amu) =	40 (argon)
ion charge	Z_i =	1
typical density	$\bar{n}_e$ (10^{18} m^{-3}) =	7
preexisting ohmic current	I_{OH} (kA) =	0
rf current alone, typ.	I_{rf} (kA) =	0.150
drop of loop voltage, typ.	$\Delta V_L/V_L$ =	---
wave frequency	f (MHz) =	3.0
typical parallel index	$n_{ }$ =	300

3. CALCULATED DISPERSION PROPERTIES (Cold Plasma)

gyrofrequency harmonic	ω/Ω_i =	614
frequency range	Ω^2 =	5.14
lower hybrid resonant density	n_e^{LHR} (10^{18} m^{-3}) =	---
approximate Murakami limit	$\bar{n}_e^m$ (10^{18} m^{-3}) =	1.9
typical perpendicular index	$n_{\perp}$ =	465

4. CALCULATED WAVE DAMPING (Warm Plasma)

background plasma	T_i (keV) =	0.001 (est.)
	T_e (keV) =	0.004
tail electrons	source:	---
effective tail temperature	T_h (keV) =	---
nonresonant damping	P_{nr}/P_{eLd} =	15.5
ion Landau damping	P_{iLd}/P_{eLd} =	0
TTMP	P_{TTMP}/P_{eLd} =	0
wall damping	Q_{wall}^{-1} =	6.5×10^{-3}
electron Landau damping	Q_{eLd}^{-1} =	2000

5. CURRENT DRIVE

SURVEY OF RESULTS

A_i amu	$\bar{n}_e$ 10^{18} m^{-3}	P_{rf} kW	I_{OH} kA	$\dot{I}$ kA/s	$\Delta V_L/V_L$	I_{rf} kA	γ $10^{20} \text{ AW}^{-1} \text{ m}^{-2}$	Remarks
40	5.6	62	0	0	0	0.250	5.6×10^{-5}	
	5.6	72				0.220	4.3×10^{-5}	
	6.0	62				0.185	4.5×10^{-5}	
	7.8	52				0.140	5.3×10^{-5}	
	9.2	54				0.130	5.5×10^{-5}	
	10.6	53				0.103	5.2×10^{-5}	
	13.0	54				0.070	4.2×10^{-5}	

experimental cutoff	$\bar{n}_{exp} (10^{18} \text{ m}^{-3}) =$	> 13
theoretical cutoff (Sverdrup & Bellan)	$\bar{n}_B (10^{18} \text{ m}^{-3}) =$	1.6×10^{-3}
frequency scaling cutoff	$\bar{n}_f (10^{18} \text{ m}^{-3}) =$	6.6×10^{-4}
density fluctuations	$\langle (\delta n_e/n_e)^2 \rangle^{1/2} =$	---
correlation length	$L_T (m) =$	---
scattering length calculated	$L_S (m) =$	---
scattering length observed	$L_S (m) =$	---
CD vs. phase speed	$u =$	~ 1.2
typical γ vs. temperature	$\gamma/T_e (keV) =$	$5 \times 10^{-5}/(.004) =$ 1.3×10^{-2}
	$\gamma/T_h (keV) =$	---
rf pulse length	$\tau_{rf} (s) =$	0.005
startup, attainable current	$I_{su} (kA) =$	0.250
startup, achieved safety factor	$q_{edge} =$	~ 2
startup, ramp rate	$\dot{I} (kA/s) =$	---

Figure A1

EXPERIMENT: ACT-I

LABORATORY: Princeton

1. REFERENCES: J. Goree et al., Phys. Rev. Lett 55 (1985) 1669.

2. STANDARD CONDITIONS

major radius	R (m) =	0.59
minor radius	a (m) =	0.081
toroidal field	B (T) =	0.447
fill pressure	p_0 (Torr) =	1×10^{-4}
atomic mass	A_1 (amu) =	4 (He)
ion charge	Z_1 =	1
typical density	$\bar{n}_e$ (10^{18} m^{-3}) =	2
preexisting ohmic current	I_{OH} (kA) =	0
rf current alone, typ.	I_{rf} (kA) =	0.030
drop of loop voltage, typ.	$\Delta V_L/V_L$ =	---
wave frequency	f (MHz) =	18
typical parallel index	$n_{ }$ =	9

3. CALCULATED DISPERSION PROPERTIES (Cold Plasma)

gyrofrequency harmonic	ω/Ω_1 =	10.6
frequency range	Ω^2 =	0.0152
lower hybrid resonant density	n_e^{LHR} (10^{18} m^{-3}) =	0.03
approximate Murakami limit	$\bar{n}_e^m$ (10^{18} m^{-3}) =	---
typical perpendicular index	$n_{\perp}$ =	80

4. CALCULATED WAVE DAMPING (Warm Plasma)

background plasma	T_i (keV) =	0.005 (est.)
	T_e (keV) =	0.015
tail electrons	source:	400 V cathode
effective tail temperature	T_h (keV) =	~ 0.4
nonresonant damping	p_{nr}/p_{eLd} =	~ 1
ion Landau damping	p_{iLd}/p_{eLd} =	0
TTMP	p_{TTMP}/p_{eLd} =	0
wall damping	Q_{wall}^{-1} =	1.3×10^{-3}
electron Landau damping	Q_{eLd}^{-1} =	1.4×10^{-3}

5. CURRENT DRIVE

SURVEY OF RESULTS

A_i amu	$\bar{n}_e$ 10^{18} m^{-3}	P_{rf} kW	I_{OH} kA	$\dot{i}$ kA/s	$\Delta V_e/V_e$	I_{rf} kA	γ $10^{20} \text{ AW}^{-1} \text{ m}^{-2}$	Remarks
4	3.0	1.0	0	~0	0	0.0110	1.9×10^{-4}	
	4.5					0.0085	2.3×10^{-4}	
	5.6					0.0067	2.2×10^{-4}	
	6.7					0.0020	0.8×10^{-4}	
	1.5					0.0400	3.5×10^{-4}	

experimental cutoff	$\bar{n}_{exp} (10^{18} \text{ m}^{-3}) =$	≥ 6.7
theoretical cutoff (Sverdrup & Bellan)	$\bar{n}_B (10^{18} \text{ m}^{-3}) =$	0.010
frequency scaling cutoff	$\bar{n}_f (10^{18} \text{ m}^{-3}) =$	0.013
density fluctuations	$\langle (\delta n_e/n_e)^2 \rangle^{1/2} =$	---
correlation length	$L_T (m) =$	---
scattering length calculated	$L_S (m) =$	---
scattering length observed	$L_S (m) =$	---
CD vs. phase speed	$u =$	~ 3
typical γ vs. temperature	$\gamma/T_e (keV) =$	$3.5 \times 10^{-4} / (0.015) =$ 2.3×10^{-2}
	$\gamma/T_h (keV) =$	$3.5 \times 10^{-4} / (0.4)$ 8.8×10^{-4}
rf pulse length	$\tau_{rf} (s) =$	0.005
startup, attainable current	$I_{su} (kA) =$	---
startup, achieved safety factor	$q_{edge} =$	---
startup, ramp rate	$\dot{i} (kA/s) =$	---

Figure A2

EXPERIMENT: Irvine Torus

LABORATORY: U. C. Irvine

1. REFERENCES: R. C. Platt & R. McWilliams, in Applications of Radio-Frequency Power to Plasmas, S. Bernabei & R. W. Motley, eds., AIP (New York) 1987, p. 171; R. McWilliams & R. C. Platt, sub. to Phys. Rev. Lett.

2. STANDARD CONDITIONS

major radius	R (m) =	0.56
minor radius	a (m) =	0.035
toroidal field	B (T) =	0.1
fill pressure	p_0 (Torr) =	8.8×10^{-5}
atomic mass	A_i (amu) =	40 (argon)
ion charge	Z_i =	1
typical density	$\bar{n}_e$ (10^{18} m^{-3}) =	4.0
preexisting ohmic current	I_{OH} (kA) =	0
rf current alone, typ.	I_{rf} (kA) =	0.001
drop of loop voltage, typ.	$\Delta V_L/V_L$ =	---
wave frequency	f (MHz) =	94
typical parallel index	$n_{ }$ =	10.6

3. CALCULATED DISPERSION PROPERTIES (Cold Plasma)

gyrofrequency harmonic	ω/Ω_i =	2463
frequency range	Ω^2 =	82.65
lower hybrid resonant density	n_e^{LHR} (10^{18} m^{-3}) =	---
approximate Murakami limit	$\bar{n}_e^m$ (10^{18} m^{-3}) =	---
typical perpendicular index	$n_{\perp}$ =	90

4. CALCULATED WAVE DAMPING (Warm Plasma)

background plasma	T_i (keV) =	0.003 (est.)
	T_e (keV) =	0.010
tail electrons	source:	350 V
		thermionic emission
effective tail temperature	T_h (keV) =	0.350
nonresonant damping	p_{nr}/p_{eLd} =	~ 1
ion Landau damping	p_{iLd}/p_{eLd} =	0
TTMP	p_{TTMP}/p_{eLd} =	0
wall damping	Q_{wall}^{-1} =	1.3×10^{-3}
electron Landau damping	Q_{eLd}^{-1} =	1120

5. CURRENT DRIVE

SURVEY OF RESULTS

A_i amu	$\bar{n}_e$ 10^{18} m^{-3}	P_{rf} kW	I_{OH} kA	$\dot{I}$ kA/s	$\Delta V_e/V_e$	I_{rf} kA	γ $10^{20} \text{ AW}^{-1} \text{ m}^{-2}$	Remarks
--------------	---	----------------	----------------	-------------------	------------------	----------------	--	---------

40	4.0	0.0205	0	~ 0	0	0.00134	0.0015	
		0.0103				0.00108	0.0023	
		0.00515				0.00087	0.0038	
		0.00258				0.00060	0.0052	
		0.00129				0.00030	0.0052	

experimental cutoff	$\bar{n}_{exp} (10^{18} \text{ m}^{-3}) =$	≥ 4.0
theoretical cutoff (Sverdrup & Bellan)	$\bar{n}_B (10^{18} \text{ m}^{-3}) =$	0.13
frequency scaling cutoff	$\bar{n}_f (10^{18} \text{ m}^{-3}) =$	0.19
density fluctuations	$\langle (\delta n_e/n_e)^2 \rangle^{1/2} =$	0.06 (measured)
correlation length	$L_T (m) =$	2.0×10^{-2} (est.)
scattering length calculated	$L_S (m) =$	0.036
scattering length observed	$L_S (m) =$	~ 0.10
CD vs. phase speed	$u =$	~ 3.6
typical γ vs. temperature	$\gamma/T_e (keV) =$	0.0052/0.01=0.52
	$\gamma/T_h (keV) =$	0.0052/0.35 =
		0.015
rf pulse length	$\tau_{rf} (s) =$	---
startup, attainable current	$I_{su} (kA) =$	---
startup, achieved safety factor	$q_{edge} =$	---
startup, ramp rate	$\dot{I} (kA/s) =$	---

Figure A3

EXPERIMENT: CCT

LABORATORY: UCLA

1. REFERENCES: K. F. Lai et al., in Applications of Radio-Frequency Power to Plasmas, S. Bernaber & R. W. Motley, eds., AIP (New York) 1987, p. 111; R. J. Taylor, private communication.

2. STANDARD CONDITIONS

major radius	R (m) =	1.50
minor radius	a (m) =	0.40
toroidal field	B (T) =	0.05
fill pressure	p_0 (Torr) =	5.0×10^{-5}
atomic mass	A_i (amu) =	1
ion charge	Z_i =	1
typical density	$\bar{n}_e$ (10^{18} m^{-3}) =	0.3
preexisting ohmic current	I_{OH} (kA) =	---
rf current alone, typ.	I_{rf} (kA) =	2.0
drop of loop voltage, typ.	$\Delta V_L/V_L$ =	---
wave frequency	f (MHz) =	22
typical parallel index	$n_{ }$ =	25

3. CALCULATED DISPERSION PROPERTIES (Cold Plasma)

gyrofrequency harmonic	ω/Ω_i =	28.8
frequency range	Ω^2 =	0.453
lower hybrid resonant density	n_e^{LHR} (10^{18} m^{-3}) =	0.0294
approximate Murakami limit	$\bar{n}_e^m$ (10^{18} m^{-3}) =	~ 0.5
typical perpendicular index	$n_{\perp}$ =	50

4. CALCULATED WAVE DAMPING (Warm Plasma)

background plasma	T_i (keV) =	0.01 (est.)
	T_e (keV) =	0.02
tail electrons	source:	---
effective tail temperature	T_h (keV) =	0.15
nonresonant damping	P_{nr}/P_{eLd} =	$6 \times 10^{-2} - 36.0$
ion Landau damping	P_{iLd}/P_{eLd} =	0
TTMP	P_{TTMP}/P_{eLd} =	0
wall damping	Q_{wall}^{-1} =	2.4×10^{-4}
electron Landau damping	Q_{eLd}^{-1} =	$2.8 - 0.0044$

5. CURRENT DRIVE

SURVEY OF RESULTS								
A_i amu	$\bar{n}_e$ 10^{18} m^{-3}	P_{rf} kW	I_{OH} kA	$\dot{I}$ kA/s	$\Delta V_e/V_e$	I_{rf} kA	γ $10^{20} \text{ AW}^{-1} \text{ m}^{-2}$	Remarks
1	0.3	10	---	---	---	0.6	2.7×10^{-4}	22 MHz, 0.05 T
	1.0	10	---	---	---	0.5	7.5×10^{-4}	22 MHz, 0.05 T
	0.3	4.5	---	---	---	0.3	3.0×10^{-4}	80 MHz, 1.0 T
	0.3	10	---	---	---	1.0	4.5×10^{-4}	80 MHz, 1.0 T
	0.3	12	---	---	---	1.2	4.5×10^{-4}	80 MHz, 1.0 T
	0.3	19	---	---	---	1.9	4.5×10^{-4}	80 MHz, 1.0 T
experimental cutoff				$\bar{n}_{exp} (10^{18} \text{ m}^{-3}) = \geq 1.0$				
theoretical cutoff (Sverdrup & Bellan)				$\bar{n}_B (10^{18} \text{ m}^{-3}) = 0.053$				
frequency scaling cutoff				$\bar{n}_f (10^{18} \text{ m}^{-3}) = 0.15$				
density fluctuations				$\langle (\delta n_e/n_e)^2 \rangle^{1/2} = \text{---}$				
correlation length				$L_T (\text{m}) = \text{---}$				
scattering length calculated				$L_S (\text{m}) = \text{---}$				
scattering length observed				$L_S (\text{m}) = \sim 4.0$				
CD vs. phase speed				$u = 2-5$				
typical γ vs. temperature				$\gamma/T_e (\text{keV}) = 7.5 \times 10^{-4}/0.02 = 0.0375$				
				$\gamma/T_h (\text{keV}) = 7.5 \times 10^{-4}/0.15 = 5.0 \times 10^{-3}$				
rf pulse length				$\tau_{rf} (\text{s}) = 0.04$				
startup, attainable current				$I_{su} (\text{kA}) = \text{---}$				
startup, achieved safety factor				$q_{edge} = \text{---}$				
startup, ramp rate				$\dot{I} (\text{kA/s}) = \text{---}$

Figure A4

EXPERIMENT: JIPP T-IIU (40)

LABORATORY: Nagoya

1. REFERENCES: R. Ando et al., Nucl. Fusion 26 (1986) 1619

2. STANDARD CONDITIONS

major radius	$R \text{ (m)} =$	0.91
minor radius	$a \text{ (m)} =$	0.23
toroidal field	$B \text{ (T)} =$	0.2
fill pressure	$p_0 \text{ (Torr)} =$	3×10^{-4}
atomic mass	$A_i \text{ (amu)} =$	1
ion charge	$Z_i =$	1
typical density	$\bar{n}_e \text{ (} 10^{18} \text{ m}^{-3} \text{)} =$	2.0
preexisting ohmic current	$I_{OH} \text{ (kA)} =$	0
rf current alone, typ.	$I_{rf} \text{ (kA)} =$	2
drop of loop voltage, typ.	$\Delta V_L / V_L =$	---
wave frequency	$f \text{ (MHz)} =$	40
typical parallel index	$n_{ } =$	6

3. CALCULATED DISPERSION PROPERTIES (Cold Plasma)

gyrofrequency harmonic	$\omega/\Omega_i =$	13.1
frequency range	$\Omega^2 =$	0.094
lower hybrid resonant density	$n_e^{LHR} \text{ (} 10^{18} \text{ m}^{-3} \text{)} =$	0.040
approximate Murakami limit	$\bar{n}_e^m \text{ (} 10^{18} \text{ m}^{-3} \text{)} =$	1.1
typical perpendicular index	$n_{\perp} =$	120

4. CALCULATED WAVE DAMPING (Warm Plasma)

background plasma	$T_i \text{ (keV)} =$	0.003 (est.)
	$T_e \text{ (keV)} =$	0.01 (est.)
tail electrons	source:	---
effective tail temperature	$T_h \text{ (keV)} =$	---
nonresonant damping	$p_{nr}/p_{eLd} =$	---
ion Landau damping	$p_{iLd}/p_{eLd} =$	---
TTMP	$p_{TTMP}/p_{eLd} =$	---
wall damping	$Q_{wall}^{-1} =$	---
electron Landau damping	$Q_{eLd}^{-1} =$	---

Figure A5

EXPERIMENT: JIPP T-IIU (800)

LABORATORY: Nagoya

1. REFERENCES: K. Ohkubo et al., Inst. of Plasma Physics (Nagoya Univ.) rep. IPPJ-746 (1985); K. Toi et al., in Controlled Fusion & Plasma Heating (Proc. 13th Europ. Conf. Schliersee (1986), Vol. 10c, Part II, EPS (1986) 457; T. Watari et al., in Plasma Physics & Contr. Nucl. Fus. Res. 1986 (11th Conf. Proc. Kyoto 1986) Vol. 1, IAEA (1987) 495.

2. STANDARD CONDITIONS

major radius	R (m) =	0.93
minor radius	a (m) =	0.25
toroidal field	B (T) =	2.64
fill pressure	p_0 (Torr) =	---
atomic mass	A_i (amu) =	1
ion charge	Z_i =	1
typical density	$\bar{n}_e$ (10^{18} m^{-3}) =	3.0
preexisting ohmic current	I_{OH} (kA) =	40
rf current alone, typ.	I_{rf} (kA) =	40
drop of loop voltage, typ.	$\Delta V_L/V_L$ =	1
wave frequency	f (MHz) =	800
typical parallel index	$n_{ }$ =	2

3. CALCULATED DISPERSION PROPERTIES (Cold Plasma)

gyrofrequency harmonic	ω/Ω_i =	19.8
frequency range	Ω^2 =	0.214
lower hybrid resonant density	n_e^{LHR} (10^{18} m^{-3}) =	18.5
approximate Murakami limit	$\bar{n}_e^m$ (10^{18} m^{-3}) =	13.0
typical perpendicular index	$n_{\perp}$ =	1

4. CALCULATED WAVE DAMPING (Warm Plasma)

background plasma	T_i (keV) =	0.030 (est.)
	T_e (keV) =	0.100 (typ.)
tail electrons	source:	slide away; filling spectral gap
effective tail temperature	T_h (keV) =	50
nonresonant damping	p_{nr}/p_{eLd} =	2×10^{-4}
ion Landau damping	p_{iLd}/p_{eLd} =	---
TTMP	p_{TTMP}/p_{eLd} =	0
all damping	Q_{wall}^{-1} =	6.7×10^{-5}
electron Landau damping	Q_{eLd}^{-1} =	2.96

5. CURRENT DRIVE

SURVEY OF RESULTS								Remarks
A_i amu	$\bar{n}_e$ 10^{18} m^{-3}	P_{rf} kW	I_{OH} kA	$\dot{I}$ kA/s	$\Delta V_L/V_L$	I_{rf} kA	γ $10^{20} \text{ AW}^{-1} \text{ m}^{-2}$	
1	3.0	80.0	-1.5	-29	-1.25	51.5	0.017	
	15.0						~ 0	{ hard X-rays remain 5% ion tail
	2.0	43.0	0.1	-67	-1.20	29.9	0.019	onset ion tail
	3.0							{ onset of decrease in hard X-rays
	7.0				0		~ 0	{ minimal ECE ion tail saturates

experimental cutoff	$\bar{n}_{exp} (10^{18} \text{ m}^{-3}) =$	7
theoretical cutoff (Sverdrup & Bellan)	$\bar{n}_B (10^{18} \text{ m}^{-3}) =$	5.3
frequency scaling cutoff	$\bar{n}_f (10^{18} \text{ m}^{-3}) =$	6.6
density fluctuations	$\langle (\delta n_e/n_e)^2 \rangle^{1/2} =$	1.6×10^{-3}
correlation length	$L_T (\text{m}) =$	3.9×10^{-4}
scattering length calculated	$L_S (\text{m}) =$	54
scattering length observed	$L_S (\text{m}) =$	---
CD vs. phase speed	$u =$	1.6
typical γ vs. temperature	$\gamma/T_e (\text{keV}) =$	$0.017/0.100 =$ 0.17
	$\gamma/T_h (\text{keV}) =$	---
rf pulse length	$\tau_{rf} (\text{s}) =$	0.080
startup, attainable current	$I_{su} (\text{kA}) =$	---
startup, achieved safety factor	$q_{edge} =$	---
startup, ramp rate	$\dot{I} (\text{kA/s}) =$	---

Figure A6

EXPERIMENT: JFT-2M (200)

LABORATORY: JAERI

1. REFERENCES: Y. Uesugi et al., in Applications of Radio-Frequency Power to Plasmas (7th Top. Conf., Kissimmee 1987) S. Bernabei and R. W. Motley, eds., AIP (New York) 1987, p. 179; T. Yamamoto et al., in Plas. Phys. and Contr. Nucl. Fusion Res. 1986 (Proc. 11th Conf., Kyoto 1986) IAEA (Vienna) 1987, Vol. 1, p. 545; T. Yamamoto, IAEA Specialists' Mtg. on Noninductive Current Drive, 1986 Garching, report NET-PM-86-003, p. 405.

2. STANDARD CONDITIONS

major radius	R (m) =	1.30
minor radius	a (m) =	0.35 ($b/\kappa a = 0.53$)
toroidal field	B (T) =	1.07
fill pressure	p_0 (Torr) =	---
atomic mass	A_i (amu) =	1
ion charge	Z_i =	1
typical density	$\bar{n}_e$ (10^{18} m^{-3}) =	1.0
preexisting ohmic current	I_{OH} (kA) =	100
rf current alone, typ.	I_{rf} (kA) =	80
drop of loop voltage, typ.	$\Delta V_L/V_L$ =	0.8
wave frequency	f (MHz) =	200
typical parallel index	$n_{ }$ =	2.5

3. CALCULATED DISPERSION PROPERTIES (Cold Plasma)

gyrofrequency harmonic	ω/Ω_i =	12.24
frequency range	Ω^2 =	0.0817
lower hybrid resonant density	n_e^{LHR} (10^{18} m^{-3}) =	1.0
approximate Murakami limit	$\bar{n}_e^m$ (10^{18} m^{-3}) =	16.3
typical perpendicular index	$n_{\perp}$ =	10

4. CALCULATED WAVE DAMPING (Warm Plasma)

background plasma	T_i (keV) =	0.5 (est.)
	T_e (keV) =	1.0 (est.)
tail electrons	source:	---
effective tail temperature	T_h (keV) =	~ 50
nonresonant damping	p_{nr}/p_{eLd} =	4×10^{-5}
ion Landau damping	p_{iLd}/p_{eLd} =	---
TTMP	p_{TTMP}/p_{eLd} =	0
wall damping	Q_{wall}^{-1} =	9×10^{-5}
electron Landau damping	Q_{eLd}^{-1} =	9×10^{-2}

5. CURRENT DRIVE

SURVEY OF RESULTS

A_i amu	$\bar{n}_e$ 10^{18} m^{-3}	P_{rf} kW	I_{OH} kA	$\dot{I}$ kA/s	$\Delta V_k / V_k$	I_{rf} kA	γ $10^{20} \text{ AW}^{-1} \text{ m}^{-2}$	Remarks
1	1.1	---	150	---	---	---	0.031	
1	1.3	---	150	---	---	---	0.022	
1	1.8	---	100	---	---	---	0.011	
1	2.0	---	100	---	---	---	0.006	
1	2.2	---	---	---	---	---	0	onset para-
1	10.0	---	---	---	---	---	0	metric decay
								cessation
								decay waves
2	0.9	24	100	---	0.8	---	0.039	
2	1.0	---	100	---	---	---	0.029	
2	1.7	---	100	---	---	---	0.023	
2	2.1	---	100	---	---	---	0.012	
2	2.4	---	100	---	---	---	0.007	
2	3.0	---	100	---	---	---	0	
2	15.0	40	200	--	---	---	0	hot tail
								electrons

experimental cutoff	$\bar{n}_{exp} (10^{18} \text{ m}^{-3}) =$	2.2 (H^+)
theoretical cutoff (Sverdrup & Bellan)	$\bar{n}_B (10^{18} \text{ m}^{-3}) =$	0.27
frequency scaling cutoff	$\bar{n}_f (10^{18} \text{ m}^{-3}) =$	0.67
density fluctuations	$\langle (\delta n_e / n_e)^2 \rangle^{1/2} =$	1.6×10^{-2}
correlation length	$L_T (m) =$	1.4×10^{-3}
scattering length calculated	$L_S (m) =$	3.0
scattering length observed	$L_S (m) =$	---
CD vs. phase speed	$u =$	1.3-4.5
typical γ vs. temperature	$\gamma / T_e (keV) =$	$0.031 / 1.0 = 0.031$
	$\gamma / T_h (keV) =$	---
rf pulse length	$\tau_{rf} (s) =$	0.080
startup, attainable current	$I_{su} (kA) =$	---
startup, achieved safety factor	$q_{edge} =$	---
startup, ramp rate	$\dot{I} (kA/s) =$	---

Figure A7

EXPERIMENT: JFT-2M (750)

LABORATORY: JAERI

1. REFERENCES: Y. Uesugi et al., in Applications of Radio-Frequency Power to Plasmas (7th Top. Conf., Kissimmee 1987) S. Bernabei & R. W. Motley, eds., (New York) 1987, p. 179.

2. STANDARD CONDITIONS

major radius	R (m) =	1.30
minor radius	a (m) =	0.35 ($b=ka=0.53$)
toroidal field	B (T) =	1.07 (est.)
fill pressure	p_0 (Torr) =	---
atomic mass	A_i (amu) =	1
ion charge	Z_i =	1
typical density	$\bar{n}_e$ (10^{18} m^{-3}) =	6.0
preexisting ohmic current	I_{OH} (kA) =	150
rf current alone, typ.	I_{rf} (kA) =	130
drop of loop voltage, typ.	$\Delta V_L/V_L$ =	0.9
wave frequency	f (MHz) =	750
typical parallel index	$n_{ }$ =	2.0

3. CALCULATED DISPERSION PROPERTIES (Cold Plasma)

gyrofrequency harmonic	ω/Ω_i =	45.9
frequency range	Ω^2 =	1.148
lower hybrid resonant density	n_e^{LHR} (10^{18} m^{-3}) =	---
approximate Murakami limit	$\bar{n}_e^m$ (10^{18} m^{-3}) =	24.5
typical perpendicular index	$n_{\perp}$ =	15

4. CALCULATED WAVE DAMPING (Warm Plasma)

background plasma	T_i (keV) =	0.5 (est.)
	T_e (keV) =	1.0 (est.)
tail electrons	source:	---
effective tail temperature	T_h (keV) =	70
nonresonant damping	p_{nr}/p_{eLd} =	1.1×10^{-5}
ion Landau damping	p_{iLd}/p_{eLd} =	---
TTMP	p_{TTMP}/p_{eLd} =	0
wall damping	Q_{wall}^{-1} =	4.7×10^{-5}
electron Landau damping	Q_{eLd}^{-1} =	1.72

5. CURRENT DRIVE

A_i amu	$\bar{n}_e$ 10^{18} m^{-3}	P_{rf} kW	I_{OH} kA	SURVEY OF RESULTS				γ $10^{20} \text{ AW}^{-1} \text{ m}^{-2}$	Remarks
				$\dot{i}$ kA/s	$\Delta V_L / V_L$	I_{rf} kA			
1	1.2	100	150	~ 0	0.97	---		0.023	
	3.5	---	---	---	0.84	---		0.057	
	4.7	---	---	---	0.65	---		0.060	
	6.0	---	---	---	0.36	---		0.042	
	6.6	---	---	---	0.11	---		0.014	
	8.0	---	---	---	0.06	---		0.0094	
	9.3	---	---	---	0.02	---		0.0036	loss of elec- tron tail
experimental cutoff					$\bar{n}_{\text{exp}} (10^{18} \text{ m}^{-3}) =$	9.3			
theoretical cutoff (Sverdrup & Bellan)					$\bar{n}_B (10^{18} \text{ m}^{-3}) =$	4.2			
frequency scaling cutoff					$\bar{n}_f (10^{18} \text{ m}^{-3}) =$	5.9			
density fluctuations					$\langle (\delta n_e / n_e)^2 \rangle^{1/2} =$	1.6×10^{-2}			
correlation length					$L_T (\text{m}) =$	1.4×10^{-3}			
scattering length calculated					$L_S (\text{m}) =$	3.0			
scattering length observed					$L_S (\text{m}) =$	---			
CD vs. phase speed					$u =$	---			
typical γ vs. temperature					$\gamma / T_e (\text{keV}) =$	$0.06 / 1.0 = 0.06$			
					$\gamma / T_h (\text{keV}) =$	---			
rf pulse length					$\tau_{\text{rf}} (\text{s}) =$	---			
startup, attainable current					$I_{\text{su}} (\text{kA}) =$	---			
startup, achieved safety factor					$q_{\text{edge}} =$	---			
startup, ramp rate					$\dot{i} (\text{kA/s}) =$	---

Figure A8

EXPERIMENT: PLT

LABORATORY: Princeton

1. REFERENCES: R. I. Pinsky et al., in Applications of Radio-Frequency Power to Plasmas (7th Top. Conf., Kissimmee, 1987) S. Bernabei & R. W. Motley, eds., AIP (New York) 1987, p. 175; R. I. Pinsky, Ph.D. thesis, Princeton Univ., 1988.

2. STANDARD CONDITIONS

major radius	R (m) =	1.32
minor radius	a (m) =	0.39
toroidal field	B (T) =	3.1
fill pressure	p_0 (Torr) =	---
atomic mass	A_i (amu) =	2
ion charge	Z_i =	1
typical density	$\bar{n}_e$ (10^{18} m^{-3}) =	8.0
preexisting ohmic current	I_{OH} (kA) =	200
rf current alone, typ.	I_{rf} (kA) =	150
drop of loop voltage, typ.	$\Delta V_L/V_L$ =	---
wave frequency	f (MHz) =	800
typical parallel index	$n_{ }$ =	2

3. CALCULATED DISPERSION PROPERTIES (Cold Plasma)

gyrofrequency harmonic	ω/Ω_i =	33.8
frequency range	Ω^2 =	.311
lower hybrid resonant density	n_e^{LHR} (10^{18} m^{-3}) =	42.3
approximate Murakami limit	$\bar{n}_e^m$ (10^{18} m^{-3}) =	~ 30
typical perpendicular index	$n_{\perp}$ =	5

4. CALCULATED WAVE DAMPING (Warm Plasma)

background plasma	T_i (keV) =	0.3 (est.)
	T_e (keV) =	1.0 (est.)
tail electrons	source:	---
effective tail temperature	T_h (keV) =	---
nonresonant damping	p_{nr}/p_{eLd} =	7×10^{-5}
ion Landau damping	p_{iLd}/p_{eLd} =	---
TTMP	p_{TTMP}/p_{eLd} =	0
wall damping	Q_{wall}^{-1} =	4×10^{-5}
electron Landau damping	Q_{eLd}^{-1} =	~ 1

5. CURRENT DRIVE

SURVEY OF RESULTS

A_i amu	$\bar{n}_e$ 10^{18} m^{-3}	P_{rf} kW	I_{OH} kA	$\dot{i}$ kA/s	$\Delta V_L / V_L$	I_{rf} kA	γ $10^{20} \text{ AW}^{-1} \text{ m}^{-2}$	Remarks
2	7.0	---	---	---	---	---	---	ECE tail onset
	9.0	---	---	---	---	---	---	Loss of current drive onset neutron emission
	9.4	---	---	---	---	---	---	param. decay spectrum fast ion tail
	16.0	---	---	---	---	---	---	Loss of ECE tail

experimental cutoff	$\bar{n}_{exp} (10^{18} \text{ m}^{-3}) =$	9.0
theoretical cutoff (Sverdrup & Bellan)	$\bar{n}_B (10^{18} \text{ m}^{-3}) =$	11.0
frequency scaling cutoff	$\bar{n}_f (10^{18} \text{ m}^{-3}) =$	6.6
density fluctuations	$\langle (\delta n_e / n_e)^2 \rangle^{1/2} =$	0.01 (est.)
correlation length	$L_T (\text{m}) =$	0.01
scattering length calculated	$L_S (\text{m}) =$	0.25
scattering length observed	$L_S (\text{m}) =$	---
CD vs. phase speed	$u =$	---
typical γ vs. temperature	$\gamma / T_e (\text{keV}) =$	---
	$\gamma / T_h (\text{keV}) =$	---
rf pulse length	$\tau_{rf} (\text{s}) =$	---
startup, attainable current	$I_{su} (\text{kA}) =$	---
startup, achieved safety factor	$q_{edge} =$	---
startup, ramp rate	$\dot{i} (\text{kA/s}) =$	---

Figure A9

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