Experimental Evidence of Low Frequency Current Drive in the Phaedrus-T Tokamak

S. Wukitch, M. Vukovic, R. Breun, D. Brouchous, D. A. Diebold, M. Doczy, A. Elfimov,* D. Edgell, N. Hershkowitz, T. Intrator, M. Kishinevsky, C. Litwin, P. Moroz, and P. Probert

Department of Nuclear Engineering and Engineering Physics, University of Wisconsin, Madison, Wisconsin 53706

(Received 26 September 1994)

The first experimental evidence of low frequency current drive in a tokamak has been observed on the Phaedrus-T tokamak. The principal evidence is a fractional loop voltage drop of 0.35 that cannot be accounted for by an increase in plasma temperature, decrease in effective plasma charge, or decrease in stored magnetic energy. The estimated driven current is 20–35 kA out of a total of 64 kA.

PACS numbers: 52.55.Fa, 52.50.Gj

In tokamak magnetic confinement devices, the toroidal plasma current generates the poloidal field necessary for good confinement [1]. In most tokamaks, the toroidal current is created through magnetic induction of a pulsed transformer. To achieve continuous tokamak operation, numerous noninductive current drive schemes have been proposed [2,3]. Experimentally, only lower hybrid current drive (LHCD) has successfully demonstrated sustained tokamak operation without Ohmic induction [4]. Unfortunately, lower hybrid waves are expected to be unable to penetrate into the cores of reactor grade tokamak plasmas [2]. Currents driven by other methods such as neutral beam injection [5], fast waves [6], and electron-cyclotron waves [7] have been observed in tokamak devices, but their application to reactor grade plasmas is still uncertain.

Another proposed noninductive method is low frequency current drive (LFCD), often referred to as Alfvén wave current drive. This method uses waves below the ion cyclotron frequency, ω_{ci}, to drive an electron current. For this frequency regime, power sources are readily available, and the excited waves have been observed to penetrate deep into plasmas [8,9]. Furthermore, waves in this frequency regime have a phase velocity, v_ϕ, near or below the electron thermal speed, v_{Te}; therefore, these waves are resonant with the bulk electron population. LFCD, thus, avoids detrimental relativistic effects that limit the effectiveness of high frequency waves in high temperature plasmas [2]. This method has been previously disregarded because it lacks experimental verification in a tokamak and because of possible detrimental effects of trapped particles.

LFCD experiments were previously performed on nontokamak toroidal devices that had small toroidal currents and successfully measured small RF driven currents [10,11]. These early successes, however, failed to produce significant interest in LFCD, in part, because of early theoretical predictions that low frequency wave interaction with noncurrent carrying, trapped electrons in reactor grade tokamak plasmas could significantly reduce LFCD or suppress it entirely [12]. Furthermore, experiments on the TCA tokamak using low frequency waves experienced uncontrolled density increases that prevented a clear demonstration of low frequency heating [13]. Renewed interest in LFCD has been spurred by theoretical models that suggest the trapped electron effect may not be as serious as previously thought [2,14,15].

In this Letter, we present the first experimental evidence of LFCD in a tokamak. The principal evidence is a 35% decrease in the plasma loop voltage, V_L, with applied RF power. We will argue that the decrease in V_L cannot be accounted for by an increase in conductivity or a decrease in stored magnetic energy and is best explained by the presence of a noninductive current source. Issues regarding the trapped electron effect on LFCD are left for future investigation.

The LFCD experiments described in this Letter were performed on the Phaedrus-T tokamak, a detailed description of which can be found elsewhere [16]. The tokamak has a major radius $R = 0.93$ m and a minor radius of $a = 0.26$ m. The plasma and RF parameters were chosen to maximize the coupled RF power to electrons and to maximize the current drive effect. The plasma current, average density, and peak electron temperature were $I_p \lesssim 65$ kA, $\langle n_e \rangle \approx 2 \times 10^{18}$ m^{-3}, and $T_{e0} = 400$–600 eV, respectively, for these experiments. The low density was selected because for current drive antenna phase, $+\pi/2$, the change in V_L was largest without a significant increase in electron temperature, T_e. Furthermore, the current drive efficiency, ratio of excited current density to absorbed energy density, is proportional to $T_e^{3/2}/n_e$, where n_e is the electron density. In addition to the inverse dependence of efficiency on n_e, experimental data indicated that T_e is weakly dependent on n_e in Phaedrus-T. A factor of 4 decrease in n_e resulted in a 25% increase in the Ohmic T_e.

The density regime for these experiments is atypical for the Phaedrus-T tokamak. However, the discharges were reproducible, and the fast electron current had a negligible contribution to the total current. Although direct measure of the fast electron current is unavailable in Phaedrus-T, the current carried by the fast electrons was inferred to be negligible because discharges where there was significant loss of fast electron flux did not have a correspondingly

 0031-9007/95/74(12)/2240(4)$06.00

higher V_L. The ratio of electron drift velocity, v_d, to electron thermal speed, v_{Te}, is $\lesssim 0.2$ which is less than the criteria for a slide-away discharge [17]. In addition, the derated plasma parameters were expected to show different profiles from typical discharges.

The RF antenna used was a two-strap fast wave antenna with boron nitride limiters and no Faraday shield [18]. The antenna (60° poloidal extent, 0.14 m toroidal separation) was operated with $+\pi/2$ phasing to present the plasma with a k_z spectrum asymmetric about $k_z = 0$. The RF frequency, $f_{\rm RF}$, was 7 MHz, the on-axis toroidal magnetic field was 0.68 T, and the working gas was hydrogen. The deuterium and hydrogen cyclotron resonances were outside the plasma; therefore, ion heating was expected to be negligible. Calculations indicate that v_ϕ/v_{Te} is of order unity over the plasma radius, and this places the experiment near the minimum of the Fisch-Karney efficiency curve [19]. To reduce impurities, an aggressive conditioning campaign of weekly trimethylboron (TMB) boronizations and helium glow discharge cleaning between plasma discharges were performed. With these preparations, the experiments presented here were optimized to maximize the current drive effect in much the same spirit that the first LHCD experiments were performed [20,21].

The data shown in Fig. 1 are a representative example of the plasma response to coupled RF power. The RF was coupled into the plasma at 110 msec and lasted 50 msec with a peak coupled RF power, $P_{\rm RF}$, of 210 kW; see Fig. 1(b). Upon application of the RF, the V_L abruptly decreased to its minimum value in about 2 msec. Averaging over 18 discharges, the maximum fractional V_L drop, $\Delta V_M = (V_0 - V_{\rm RF})/V_0$, was 0.37, where V_0 is the average loop voltage between 105 and 110 msec and $V_{\rm RF}$ is the average between 112 and 117 msec. Individual ΔV_M ranged from 0.35 to 0.40. The V_L remained at this minimum level for $\lesssim 10$ msec, then slowly rose from this minimum. When the RF was terminated, the V_L abruptly increased to a value that exceeded the original Ohmic V_L. This temporal behavior of V_L was dependent upon the RF power coupled into the plasma. The RF power ramps up in approximately 1 msec to reach 75% of full power, then ramps more slowly to reach its peak power in about 10 msec and decays over the next 40 msec to $\lesssim 60\%$ of its peak power. The V_L normalized to RF power, $V_N = V_0 + (V_0 - V_L)P_{\rm RF}/P_{\rm RFmax}$ where V_L is evaluated at $P_{\rm RFmax}$, is approximately constant after the first 10 msec of coupled RF power, suggesting that to first order the temporal behavior of V_L after the first 10 msec is due primarily to the decreasing RF power; see the dotted line V_N in Fig. 1(a). The normalization procedure is supported by the approximately linear dependence that the ΔV_M has on applied RF power, shown in Fig. 2.

To make ΔV_M proportional to the noninductive current, the plasma current is maintained at a constant value. The measured I_P, shown in Fig. 1(c), was observed to be constant within ±0.25 kA. The observed fluctuations in the measured I_P were found to be uncorrelated with the fluctuations in the measured V_L, suggesting that these small current fluctuations had negligible impact on the measured V_L. Since plasma inductance, L, is a function of plasma position, the position was programmed to remain constant, and it varied by $\lesssim 0.002$ m from the Ohmic position prior to the application of RF to the plasma position during RF. Like the small fluctuations

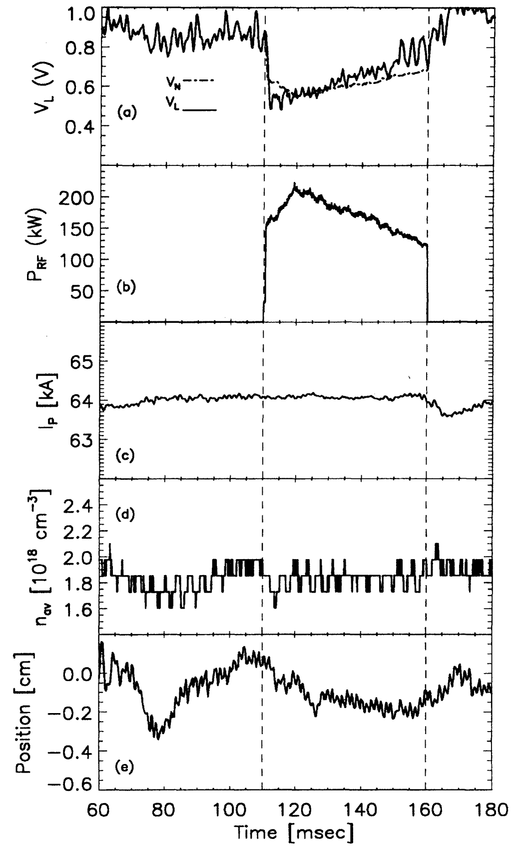

FIG. 1. Representative plasma response to applied RF power: (a) is the loop voltage, V_L, and normalized loop voltage, V_N; (b) applied RF power, $P_{\rm RF}$; (c) total plasma current, I_P; (d) plasma average density, $\langle n_e \rangle$; and (e) radial position.

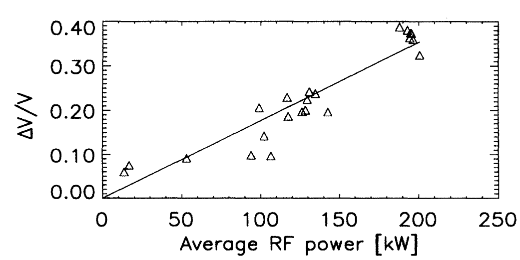

FIG. 2. Fractional loop voltage drop, ΔV, as a function of RF power. The line is the least squares fit ($\Delta V = mP_{\rm RF}$) to the data.

in I_P, the small fluctuations in position were not accompanied by a noticeable change in the V_L. Finally, the $\langle n_e \rangle$ was controlled by decreasing the gas puffing by 15% during the application of RF, and the resulting $\langle n_e \rangle$ was constant within the bit noise of the $\langle n_e \rangle$ measurement.

The Thomson scattering measured T_e profiles and the temporal behavior of the visible bremsstrahlung emission, $j(\lambda)$, measured along a chord through the center of the plasma are shown in Fig. 3. The Thomson scattering measured T_e profiles are calculated by averaging the raw spectral data from 18 discharges during the RF at $t = 115$ msec and 20 discharges prior to the RF at $t = 109$ msec. Except for the point at $r = 3.5$ cm, these T_e profiles show little difference within experimental error, and the calculated change in conductivity is approximately a 2% increase which is within the error of the measurement. For the observed RF generated drop in V_L to be a result of an increase in temperature, a volume averaged temperature, $\langle T_e \rangle$, of 370 eV during the RF would be required, whereas $\langle T_e \rangle$ calculated using Thomson scattering data and assuming a 30 eV temperature near the plasma boundary is 274 ± 32 eV. From these observations, we concluded that the observed drop in V_L during the application of RF was not due to an increase in T_e.

The $j(\lambda)$ is measured with a 1 nm interference filter at the 523.6 nm wavelength and averaged over two discharges. The $j(\lambda)$ increases from a pre-RF value of 2.8 to 4.6 (arb. units), a $\gtrsim 65\%$ increase, in the first

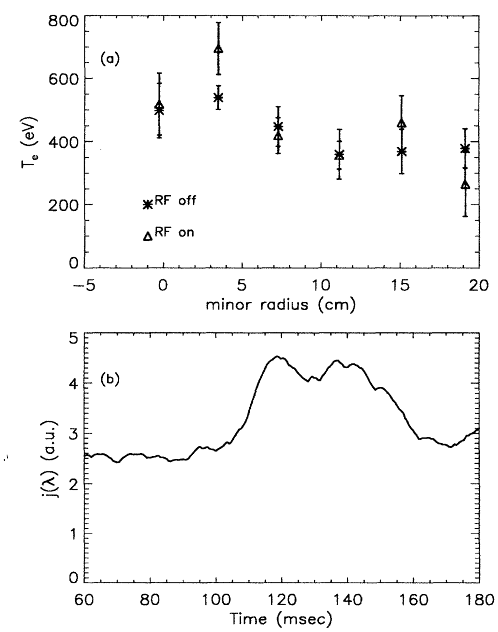

FIG. 3. (a) Thomson scattering measured temperature profiles that were determined from averaging the raw spectral data over 18 discharges for RF and 20 discharges for no RF and (b) visible bremsstrahlung emission, $j(\lambda)$, averaged over two shots and smoothed.

10 msec of the RF before decreasing to an average value of 4.2 (arb. units) over the last 40 msec of the RF, a 60% increase over the $j(\lambda)$ averaged between 100 and 105 msec. Neglecting recombination radiation and assuming the plasma was quasineutral, the $j(\lambda)$ is proportional to $n_e^2 Z_{\rm eff}/T_e^{1/2}$ where $Z_{\rm eff} = \sum Z_i^2 n_i/n_e$ [22]. The observed increase in the $j(\lambda)$ would require a 60% decrease in T_e or a 20% increase in n_e, neither of which was observed. This suggests that the observed $j(\lambda)$ increase resulted from an increase in $Z_{\rm eff}$. Converting the bremsstrahlung signal to $Z_{\rm eff}$, the target plasma had a $Z_{\rm eff} \approx 1.5$ and with the RF the $Z_{\rm eff}$ climbed to approximately 2.3. From these observations, we conclude that the increase $j(\lambda)$ was driven by a 60% increase in the plasma $Z_{\rm eff}$ and that the observed V_L drop during the application of RF was not due to a decrease in $Z_{\rm eff}$.

In these discharges, the input power increased from 60 kW during Ohmic operation to 200 kW during RF. For $\langle T_e \rangle$ to remain constant, the energy confinement time, τ_E, should decrease by approximately a factor of 3.5. Direct measurement of τ_E was unavailable for these discharges; however, the particle confinement, measured by the relative change in H_α at the limiter where an increase in H_α indicates a loss of particle confinement, increased by a factor of 3 with the application of RF. Furthermore, the fast increase in $Z_{\rm eff}$ from a fast influx of impurities suggests that the particle confinement time, τ_p, was degraded with RF. An uncalibrated pyrobolometer signal, which provides a measure of all energy losses, increased by a factor of 4 with the RF over the Ohmic suggesting the power into the system is balanced by the power lost. Therefore, the data suggest that for this experiment the approximate constancy of T_e results from a combination of a reduction in τ_E and the uncertainty of the T_e measurement.

Since V_L is measured at the plasma boundary, one might expect the V_L to change on the plasma L/R time scale, typically measured to be 130 msec at the end of these discharges. This, however, would be the time scale associated with a change in I_P, but here we have kept I_P constant and effectively substituted the driven current, $I_{\rm RF}$, for inductive current. The response of V_L is then dependent upon the time rate of change of the current profile, and this is faster than that indicated by the total L/R time. Using a one-dimensional current diffusion model [23], the redistribution time scale, τ_D, is approximately $\mu_0 \langle \sigma_{\rm Sp} \rangle a^2 / j_{1,1}^2$, where $\langle \sigma_{\rm Sp} \rangle$ is the average Spitzer conductivity, a is the minor radius, and $j_{1,1}$ is the first zero of the J_1 Bessel function. For this experiment, the τ_D is approximately 10 msec and suggests that the V_L should reach an asymptotic value within 20 msec. The model also suggests that for $t > \tau_D$ and assuming that the RF power decreases slowly on the time scale much longer than τ_D, the power normalized V_L, V_N, is approximately constant. This agrees with the V_N trace discussed earlier in Fig. 1(a). The model also suggests that the magnitude of the driven current inferred from V_N is correct to within

20% for these experimental parameters. In addition, the observed faster than L/R time drop in V_L with applied RF has been observed in LHCD. Yamamoto *et al.* had an L/R time of 100 msec for a plasma with similar parameters to Phaedrus-T and observed a decrease in V_L that occurred in $\lesssim$5 msec followed by an approximately constant V_L [20]. Therefore, we conclude that the V_L drop is not a transient effect resulting from a change in inductance.

To estimate the driven current, we begin with

$$\begin{aligned} V_O &= I_O R_{\mathrm{Sp}_O} \\ V_{\mathrm{RF}} &= (I_P - I_{\mathrm{RF}}) R_{\mathrm{Sp}_{\mathrm{RF}}}, \end{aligned} \tag{1}$$

where the subscripts O and RF denote the Ohmic and RF phases of the discharge, R_{Sp} is Spitzer resistivity, and I_{RF} is the driven current. These equations are valid when the stored magnetic contribution to the V_L is negligible, calculated to be 20 msec into the RF phase. With constant I_P, the V_L can be related to the I_{RF} by

$$\frac{I_{\mathrm{RF}}}{I_P} = 1 - \frac{R_{\mathrm{Sp}_O} V_{\mathrm{RF}}}{R_{\mathrm{Sp}_{\mathrm{RF}}} V_O} = 1 - \frac{Z_{\mathrm{eff}_O}}{Z_{\mathrm{eff}_{\mathrm{RF}}}} \frac{T_{e\mathrm{RF}}^{3/2}}{T_{eo}^{3/2}} \frac{V_{\mathrm{RF}}}{V_O}. \tag{2}$$

Neglecting the measured rise in $j(\lambda)$ and assuming constant temperature based on Thomson scattering, the estimated driven current is 20 kA. Including an increase in Z_{eff} comparable to or less than the increase suggested by the increase in $j(\lambda)$, the driven current is $\lesssim$35 kA out of a total I_P of 64 kA.

To summarize, the first experimental evidence of LFCD in a tokamak is an observed fractional loop voltage of 0.35 with applied RF power that cannot be accounted for by an increase in T_e or a decrease in stored magnetic energy. Furthermore, there is evidence that the plasma Z_{eff} increased by 60%. From this experimental evidence, we conclude that LFCD is the dominant mechanism responsible for the observed V_L drop during the applied RF and that the driven current, I_{RF}, is in the range $20 \lesssim I_{\mathrm{RF}} \lesssim 35$ kA out of a total of 64 kA.

This work was supported by the U.S. Department of Energy, Grant No. DE-FG02-88ER53264.

*Present address: Physics Institute UERJ, 20550-013 Rio de Janeiro, Rio de Janeiro, Brazil.

[1] J. Wesson, *Tokamaks* (Clarendon Press, Oxford, 1987).
[2] N. J. Fisch, Rev. Mod. Phys. **59**, 175 (1987).
[3] Ya. I. Kolesnichenko, V. V. Parail, and G. V. Pereverzev, in *Reviews of Plasma Physics,* edited by B. B. Kadomtsev (Consultants Bureau, New York, 1986).
[4] S. Bernabei *et al.,* Phys. Rev. Lett. **49**, 1255 (1982).
[5] W. H. M. Clark *et al.,* Phys. Rev. Lett. **45**, 1101 (1980).
[6] R. I. Pinsker *et al.,* in *Proceedings of the 14th International Atomic Energy Agency Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992* (IAEA, Vienna, 1993), Vol. 1, p. 683.
[7] D. F. H. Start *et al.,* Phys. Rev. Lett. **48**, 624 (1982).
[8] G. A. Collins *et al.,* Phys. Fluids **29**, 2260 (1986).
[9] H. Weisen *et al.,* Phys. Rev. Lett. **63**, 2476 (1989).
[10] S. M. Osovets and I. A. Popov, in *Proceedings of the 5th European Conference on Controlled Fusion Plasma Physics, Grenoble, France, 1972* (European Physical Society, Grenoble, 1972), Vol. 1, p. 8.
[11] S. M. Osovets and I. A. Popov, Sov. Phys. Tech. Phys. **21**, 401 (1976).
[12] R. J. Bickerton, Comments Plasma Phys. Controlled Fusion **1**, 95 (1972).
[13] B. Joyce *et al.,* Plasma Phys. Controlled Fusion **30**, 743 (1987).
[14] A. G. Elfimov and S. Puri, Nucl. Fusion **30**, 1215 (1990).
[15] V. S. Marchencko, Nucl. Fusion **34**, 740 (1994).
[16] R. Breun *et al.,* Fusion Tech. **19**, 1327 (1991).
[17] R. R. Parker *et al.,* Nucl. Fusion **25**, 1127 (1985).
[18] R. Majeski *et al.,* Fusion Eng. Design **24**, 159 (1994).
[19] N. J. Fisch and C. F. F. Karney, Phys. Fluids **24**, 27 (1981).
[20] T. Yamamoto *et al.,* Phys. Rev. Lett. **45**, 716 (1980).
[21] S. C. Luckhardt *et al.,* Phys. Rev. Lett. **48**, 152 (1982).
[22] I. H. Hutchinson, *Principles of Plasma Diagnostics* (Cambridge Univ. Press, Cambridge, 1987).
[23] C Litwin, N. Hershkowitz, T. Intrator, and S. Wukitch, Bull. Am. Phys. Soc. **39**, 1630 (1994).