# Experimental Observation of rf Driven Plasma Flow in the Phaedrus-T Tokamak

S. Wukitch,* C. Litwin, M. Harper, R. Parker, and N. Hershkowitz
*Department of Nuclear Engineering and Engineering Physics, University of Wisconsin, Madison, Wisconsin 53706*
(Received 26 February 1996)

We have observed frequency shifts of the 2/1 tearing mode in a tokamak that are consistent with injecting momentum with low frequency rf waves. The 2/1 frequency increased for current drive antenna phasing, decreased for anticurrent drive phasing, and was linear with rf power and driven current. The change in the toroidal velocities derived from the frequency shifts and the calculated rf momentum is consistent. The frequency change also increased with magnetic field, independent of antenna phasing. This is the first demonstration of modifying the 2/1 frequency through rf momentum input. [S0031-9007(96)00568-6]

PACS numbers: 52.55.Fa, 52.30.–q

Both theory and experiment suggest that plasma rotation can significantly modify the stability and transport characteristics of tokamak plasmas. Simultaneous improvement of the plasma confinement and stability has been identified in reactor studies as the most significant means for improving the economic attractiveness of the tokamak concept [1,2].

Plasma rotation's impact on plasma stability has been examined recently. In tokamak plasmas surrounded by a resistive shell, toroidal plasma rotation has been found to increase tearing mode stability [3]. Theoretical analysis suggests that external kink modes are also stabilized by toroidal rotation [4]. Experimental evidence of this stabilization has been reported by Strait *et al.* where the stabilization was achieved with rotation velocities a fraction of the Alfvén speed [5]. External control of the momentum input can be utilized to prevent locked modes which cause degradation of confinement and often are precursors to plasma disruptions [6,7]. In addition, sheared plasma rotation has been predicted to cause linear coupling of ballooning modes. This increases damping of these modes which may allow tokamak plasmas to reach the second stability regime [8,9].

Models developed to describe the transport in experimentally observed enhanced confinement modes have identified the importance of plasma rotation and sheared rotation in the formation of transport barriers [10]. These models are consistent with the observation of shear flows in *H*-mode plasmas [11] and negative central shear mode plasmas in the DIII-D tokamak [12]. Experiments also have shown degradation of *VH* mode with decreasing local toroidal plasma flow [13]. In addition, the power threshold for transport barrier formation is predicted to decrease with increased shear [14].

External control of the momentum input has been demonstrated with neutral beam injection. While the net momentum transfer is efficient, the deposition profile is broad. In addition, calculations suggest that plasma rotation driven by radio-frequency (rf) waves can be more efficient than neutral beams if the parallel index of refraction $N_{\parallel} \geq 30$ [15]. Several experiments have reported changes in the plasma toroidal rotation velocity with the application of ion cyclotron heating [16–18]. The rotation is generated by the spatial diffusion or loss of fast, resonant ions which leads to a modification of the radial electric field ($E_r$) [19]. This mechanism requires no toroidal momentum injection and relies on rf induced diffusion or loss of fast ions.

In this Letter we present the first observation of plasma rotation as measured by the 2/1 frequency modification due to rf wave momentum. The data indicate that the 2/1 frequency can be increased or decreased by varying the directionality of the rf wave. The upshift in frequency for current drive antenna phasing was linear with rf power and driven current. The change in toroidal plasma velocity calculated from the observed frequency shifts and the calculated rf momentum are comparable. In addition the shift in the 2/1 frequency increased with increasing magnetic field $B_T$, independent of the rf wave directionality.

The experiments were done on the Phaedrus-T tokamak, an ISX-B class tokamak (major radius $R = 0.93$ m, minor radius $a = 0.255$ m, $B_T = 0.6-0.9$ T). In these experiments, no neutral beam injection was present and the rf is characterized by a vacuum $N_{\parallel} = 80$. Waves are excited by a two-strap, fast-wave antenna (toroidal separation = 0.155 m, strap width = 0.05 m, poloidal extent = 60°) located on the low field side of the tokamak. The antenna excites a mode which mode converts at the Alfven resonance to an electrostatic kinetic Alfvén wave (KAW) that is absorbed approximately at the Alfvén resonance [20]. Previous experiments have shown that the rf power deposition position can be controlled by varying the $B_T$ field for a given antenna phase and plasma density [20]. For current drive phasing and plasma density of $7 \times 10^{18}$ m$^{-3}$, analysis of the loop voltage indicates that the Alfvén resonance moves from $r \approx 0.10$ m at $B_T \approx 0.75$ T to $r \approx 0.18$ m at $B_T \approx 0.65$ T. We have previously reported the first demonstration of heating [21] with symmetric phasing and driven current using this technique [22]. We have, also, argued that the loop voltage temporal behavior requires the rf current source to be localized [23]. This implies that momentum can

 0031-9007/96/77(2)/294(4)$10.00 

be injected local to the Alfvén resonance allowing for tailoring of the plasma flow profile. In addition, the KAW has been predicted to drive poloidal flow by a mechanism analogous to helicity current drive [24].

The working gas is hydrogen and plasma parameters are $n_{e0} = 7.0 \times 10^{18}$ m$^{-3}$, central electron temperature $T_{e0} = 500$ eV, and effective plasma charge $Z_{\rm eff} = 1.7-2.0$ with carbon as the dominant impurity. The ratio of the electron-ion collision frequency to the trapped electron bounce frequency $\leq 0.1$ for $r = 0.05-0.2$ m, where the electron-ion collision frequency $v_{ei}$ is approximately $6 \times 10^4$ s$^{-1}$. The rf power coupled to the plasma is approximately 300 kW for $\phi_{\rm ant} = \pi/2, -\pi/2$, and $\pi$, where $\phi_{\rm ant}$ is the phase between the currents in the two antenna straps. Of these phases, $\pi/2$ phase yields current drive [22], $\pi$ phase heats the plasma [21], and $-\pi/2$ should drive current opposite to the Ohmic current. The hydrogen cyclotron resonance is outside the plasma and the carbon cyclotron resonance (and species with similar charge to mass ratios) is on the high field side plasma edge.

The plasma rotation frequency is determined from the frequency of the 2/1 tearing mode which is located at $r \approx 0.18$ m (estimated by assuming all the toroidal current flows inside the $q = 2$ surface). This assumes that the tearing mode field perturbation is frozen within the plasma; hence, the frequency is related to the plasma flow velocity. This interpretation has been experimentally confirmed elsewhere with a comparison of flow velocities determined from Doppler spectroscopy and tearing modes [5,25]. However, Doppler spectroscopy measurements are unavailable on Phaedrus-T. Thus we must be aware that changes in the pressure profile could result in a change in the tearing mode frequency.

In a right hand $(r, \theta, \zeta)$ coordinate system, the sign convention is as follows: the toroidal magnetic field $B_T$ is in the positive toroidal direction (counterclockwise viewed from above), the poloidal field $B_\theta$ is negative (downward at the inboard median), plasma current is in the negative toroidal direction, ion diamagnetic drift is negative, and electron diamagnetic drift is positive. The 2/1 mode was observed to be rotating in the electron drift direction. For $\phi_{\rm ant} = \pi/2$ the wave momentum is coinjected with electron drift direction, whereas for $\phi_{\rm ant} = -\pi/2$ the momentum is antiparallel. For $\phi_{\rm ant} = \pi$, the net momentum injected should be zero and due to the poloidal symmetry of the antenna no poloidal momentum should be injected.

The shift in the 2/1 frequency ($\Delta f_{2/1}$) with the application of rf for $\phi_{\rm ant} = \pm\pi/2$, $\pi$ and $B_T = 0.6-0.8$ T is shown in Fig. 1. From the data, several features are apparent: $\Delta f_{2/1}$ is dependent on $\phi_{\rm ant}, \pm\pi/2$ are approximately symmetric about $\pi$, and $\Delta f_{2/1}$ scales with $B_T$ independent of $\phi_{\rm ant}$. This agrees with the expectation that the frequency of the 2/1 mode would upshift with the application of $\phi_{\rm ant} = \pi/2$ and downshift fo r$\phi_{\rm ant} = -\pi/2$. However, the $\Delta f_{2/1}$ for $\phi_{\rm ant} = \pi$ was unexpected based on the momentum injection argument. Examining the frequency evolution in more detail, an asymptotic frequency was reached in <5 ms and an averaged frequency evolution is shown in Fig. 2. The data shown in Fig. 2 are an average of 12 similar discharges, where the time history was divided into 1 ms intervals and the power spectra were found using a maximum entropy method. The error bars represent one standard deviation and the data were fit with $f(t) = f_{\rm OH} + \Delta f_{2/1}(1 - e^{-t/\tau_m})$, where $f_{\rm OH}$ is the 2/1 frequency prior to the rf and $\tau_m$ represents the characteristic momentum diffusion time. The $\tau_m$ was found to be $0.6 \pm 0.6$ ms. The $\Delta f_{2/1}$ associated with $\pi/2$ was found to scale linearly with applied rf power and fractional change in loop voltage (which is proportional to the driven current). This is shown in Fig. 3(a).

Since the scaling on $B_T$ is independent of $\phi_{\rm ant}$, this component is removed by fitting a line to the $\pi$ data and subtracting the contribution for the $\pm\pi/2$ $\Delta f_{2/1}$ data. Thus the $\Delta f_{2/1}$ is flat for $0.65 \leq B_T \leq 0.8$ T, and the average $\Delta f_{2/1} = 0.92 \pm 0.19$ kHz and $= -0.79 \pm 0.16$ kHz for $\pm\pi/2$, respectively. The mechanism responsible for this $B_T$ scaling will be discussed later.

The observed dependence on $\phi_{\rm ant}$ indicates that the shift in the frequency is not due to modifications in the diamagnetic frequency, the plasma transport properties, or the current profile. The diamagnetic contribution to mode frequency is dependent upon the pressure gradient. If $\Delta f_{2/1}$ was a result of diamagnetic changes, $\phi_{\rm ant} = \pi$ should have the largest $\Delta f_{2/1}$ and $\pm\pi/2$ phasing would have the same $\Delta f_{2/1}$. Transport driven mechanisms like fast ion diffusion or loss [19] are also independent of $\phi_{\rm ant}$. However, the rf is not resonant with the ions, and the edge transport properties and energy and particle confinement

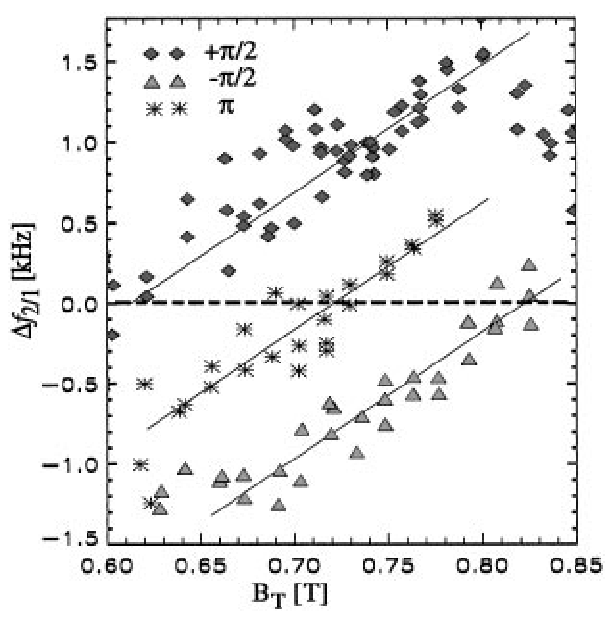


FIG. 1. The $\Delta f_{2/1}$ scales linearly with magnetic field for all of the antenna phases examined. The lines drawn have the same slope between 0.65 and 0.8 T. Upon subtraction of the $\pi$ data, the $\Delta f_{2/1}$ is $0.92 \pm 0.19$ and $-0.79 \pm 0.16$ kHz for $\pm\pi/2$, respectively.

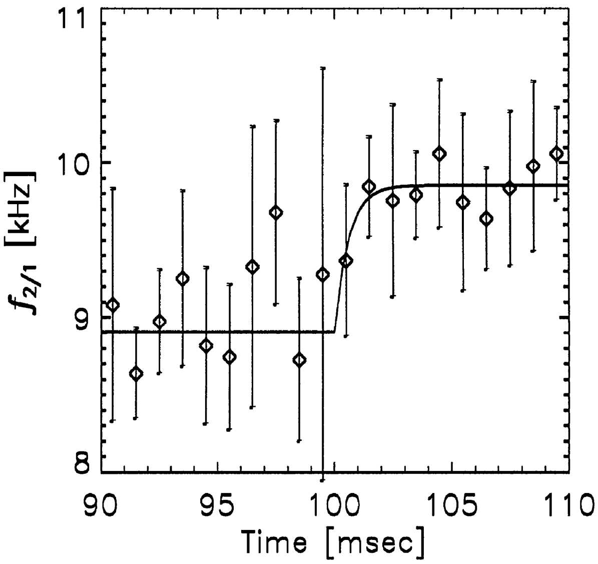


FIG. 2. The average temporal behavior of the 2/1 frequency with the application of rf, where the errors bars represent one standard deviation. The 2/1 frequency was found by maximum entropy analysis of the Mirnov signal for 1 ms time intervals.

times with rf are independent of $\phi_{\mathrm{ant}}$. Another potential mechanism is changes in the $q = 2$ location. However, for a given $B_T$ field, the $\phi_{\mathrm{ant}} = \pm\pi/2$ will drive current in opposite directions at the same location in the plasma. Thus one will cause the current profile to steepen while the other will cause it to broaden. Consequently, the $\Delta f_{2/1}$ scaling with $B_T$ for $\pm\pi/2$ should have the opposite sign. In addition, the time scale associated with the frequency change is $\leq 5$ ms but the current diffusion time is 20–25 ms for these discharges.

The $\phi_{\mathrm{ant}}$ dependent $\Delta f_{2/1}$'s are interpreted as changes in the toroidal plasma flow velocity. The frequency shift is related to the change in plasma flow velocity, $\Delta\mathbf{v}$, by

$$\Delta f_{2/1} = \frac{1}{2\pi}[\mathbf{k} \cdot \Delta\mathbf{v}] = \frac{1}{2\pi}[\mathbf{k}_\theta \cdot \Delta\mathbf{v}_\theta + \mathbf{k}_\zeta \cdot \Delta\mathbf{v}_\zeta], \tag{1}$$

where $\mathbf{k} = \mathbf{k}_\theta + \mathbf{k}_\zeta = m\hat{\theta}/r + n\hat{\zeta}/R$ is the wave number of the 2/1 tearing mode, $r$ is the minor radius, and $R$ is the major radius. Although KAW's have been predicted to drive poloidal flow [24], the proposed mechanism requires an asymmetric poloidal launch of the KAW. In Phaedrus-T, the vacuum poloidal antenna spectrum is symmetric. In addition, rf driven parallel current would not result in a $\Delta f_{2/1}$. For parallel driven current, the poloidal flow is $v_\theta = -v_{rf}B_\theta/B\hat{\theta}$ and $v_\theta = v_{rf}B_\zeta/B\hat{\zeta}$, where $v_{rf}$ is plasma flow velocity resulting from the rf momentum input, and one finds that $\mathbf{k} \cdot \Delta\mathbf{v} \to 0$ at rational surfaces. Thus $\Delta f_{2/1}$ would be zero. The estimated change in velocity, $\Delta v$, from $\Delta f_{2/1}$ is approximately $(6 \pm 1.2) \times 10^3$ m/s for $+\pi/2$ where the error is dominated by the uncertainty in the measured frequency shift.

The $\Delta v$ due to the addition of rf momentum is estimated by considering the ion toroidal momentum balance. The ion momentum balance can be written as

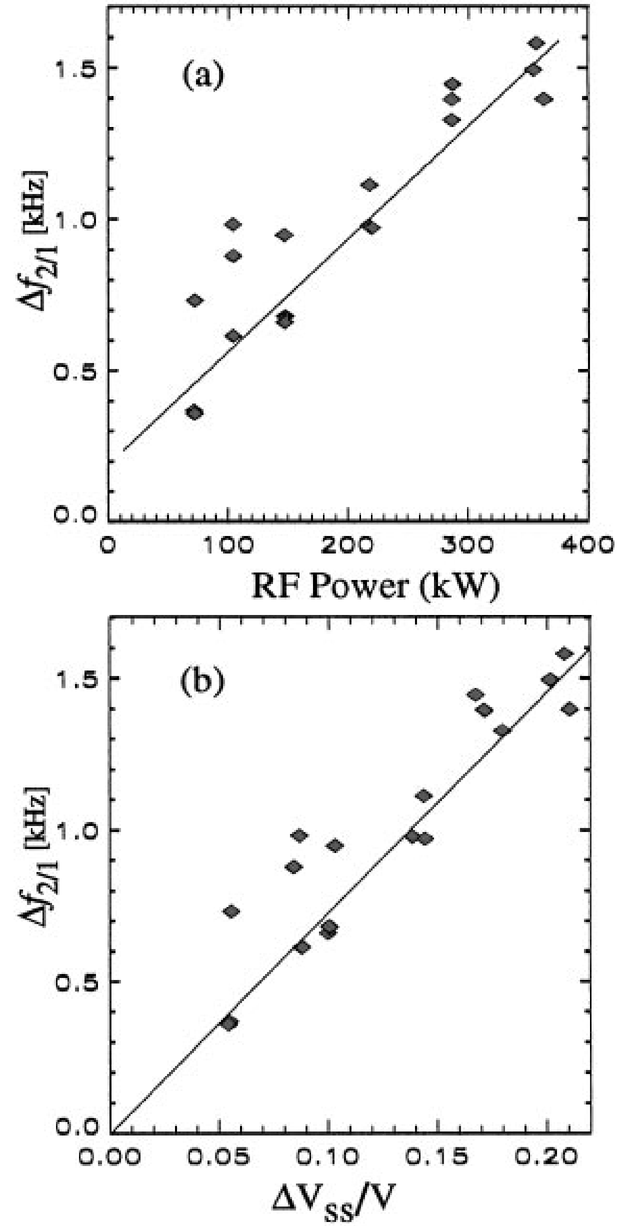


FIG. 3. The $\Delta f_{2/1}$ is (a) proportional to the rf power and (b) the steady-state fractional loop voltage change which is proportional to the driven current.

$$m_i \frac{dv_i}{dt} = m_e v_e v_{ei} + m_i \frac{E_r}{B_\theta}\frac{1}{\tau_m} - \frac{m_i v_i}{\tau_m}, \tag{2}$$

where $v_e$ is the electron velocity driven by the rf, $v_i$ is the ion flow velocity, $m_e$ and $m_i$ are the electron and ion masses, and $\tau_m$ is the ion momentum diffusion time. The right hand side of Eq. (2) represents the rf momentum input, the toroidal flow driven by viscous damping of the parallel plasma flow neglecting pressure gradient contributions, and viscous diffusion. To estimate the $\Delta v$, we assume that the plasma flow velocity is equal to the ion flow velocity and the change in $E_r/B_\theta$ is negligible compared with the rf term. In steady state, $\Delta v$

is given by

$$\Delta v \cong \pm \frac{m_e}{m_i} \frac{I_\zeta}{e n_e} \frac{\tau_m}{\tau_e} \hat{\zeta} \quad \phi = \pm \pi/2, \tag{3}$$

where $I_\zeta$ is the rf driven current, $n_e$ is the local plasma density, $e$ is electron charge, $\tau_e = 1/v_{ei}$, and $\tau_m$ is the momentum diffusion time (estimated from Fig. 2). Thus the $\Delta v$ is approximately the momentum input from the rf times the ratio of ion momentum confinement time to the parallel electron momentum confinement time. For $\phi_{\rm ant} = \pi$, the $\Delta f_{2/1} = 0$ because the net rf momentum input is zero. For $\phi = +\pi/2$, the driven current is 10–15 kA [current channel cross sectional area is (0.1–0.2)$\pi a^2$] which is estimated from the observed change in loop voltage. The corresponding $\Delta v$ is $(3.5 - 7) \times 10^3$ m/s, which is consistent with $\Delta v$ derived from $\Delta f_{2/1}$.

As for the $\Delta f_{2/1}$ scaling with $B_T$, this scaling is equivalent to stating that $\Delta f_{2/1}$ increases as the Alfvén resonance moves closer to the $B_T$ axis. Since the $B_T$ scaling is independent of $\phi_{\rm ant}$, this implies that the scaling could be a result of a modification to $E_r$ or the diamagnetic contribution. However, the $\phi_{\rm ant} = \pi \Delta f_{2/1}$ data indicate that mechanism changes sign as a function of power deposition location.

From elementary magnetohydrodynamic theory, one can show that the 2/1 flow velocity is the sum of the bulk plasma flow, electron drift velocity, and the electron diamagnetic flow [25]. For Phaedrus-T (in the absence of rf), this can be expressed as

$$v_{2/1} = \left| \frac{E_r}{B_\theta} \right| + v_d + \frac{|\nabla p_e \times \mathbf{B}|}{n_e e B^2}, \tag{4}$$

where $p_e$ is the electron presssure, $v_d$ is the electron drift velocity, and $v_{2/1}$ is in the positive toroidal direction. The first term of Eq. (4) is from the bulk plasma flow and is determined from the ion momentum balance. The other terms are due to electron dynamics: electron drift velocity and diamagnetic drift. As mentioned above, the plasma is rotating in the electron drift direction. Thus the $E_r$ is deduced to be inward which is typical of Ohmic discharges [26]. Concentrating $\phi_{\rm ant} = \pi$ data (rf momentum is zero and $v_d$ is constant), the $\Delta f_{2/1}$ $B_T$ scaling can be a result of modifying $E_r$ or the electron diamagnetic drift. The modification of the electron diamagnetic contribution, however, provides a simpler mechanism: pressure profile broadening and peaking due to rf heating. For rf deposition near the plasma center (high $B_T$), the diamagnetic contribution would increase because of the increase in $T_{e0}$. For off axis, the pressure profile would broaden and result in a decrease in the diamagnetic contribution. However, direct measurements of the $E_r$ and $T_e$ required to verify this are unavailable.

In conclusion, we have observed frequency shifts of the 2/1 resistive tearing mode that are consistent with injecting toroidal momentum with low frequency rf waves. The frequency up shifts with $\pi/2$ and down shifts with $-\pi/2$. The $\Delta f_{2/1}$ associated with $\pi/2$ was observed to be approximately linear with rf power and rf driven current. The observed phase dependence of $\Delta f_{2/1}$ also indicates that the observed $\Delta f_{2/1}$ is not a result of changes to diamagnetic contributions or modifications to the $q = 2$ location. The calculated $\Delta v$ from the observed $\Delta f_{2/1}$ were found to be in approximate agreement with that expected from the ion drag on the rf driven toroidal current. The observed scaling of $\Delta f_{2/1}$ with magnetic field may be a result of modification to the diamagnetic term through plasma heating. This is the first demonstration of rf modification of plasma flow velocity through momentum input.

The authors would like to acknowledge P. Probert, C. Hegna, M. Vukovic, and the Phaedrus-T staff for their assistance. This work was supported by the office of Fusion Energy of the United States Department of Energy, Grant No. DE-FG02-88ER53264.

*Current address: Max-Planck-Institute for Plasma Physics, D-85748 Garching, Germany.

[1] J.D. Galambos, L.J. Perkins, S.W. Haney, and J. Mandrekas, Nucl. Fusion **35**, 551 (1995).
[2] P.A. Politzer, Trans. Fusion Technol. **27**, 150 (1995).
[3] T.H. Jensen and M.S. Chu, J. Plasma Phys. **30**, 57 (1983).
[4] A. Bondeson and D.J. Ward, Phys. Rev. Lett. **72**, 2709 (1994).
[5] E.J. Strait *et al.*, Phys. Rev. Lett. **72**, 2709 (1994).
[6] J.A. Snipes *et al.*, Nucl. Fusion **28**, 1085 (1988).
[7] R.J. LaHaye, A.W. Hyatt, and J.T. Scoville, Nucl. Fusion **32**, 2119 (1992).
[8] R.L. Miller and R.E. Waltz, Phys. Plasmas **1**, 2835 (1994).
[9] R.L. Miller, F.L. Waelbroeck, A.B. Hassam, and R.E. Waltz, Phys. Plasmas **2**, 3676 (1995).
[10] P.H. Diamond, Y-M. Laing, B.A. Carreras, and F.W. Terry, Phys. Rev. Lett. **72**, 2565 (1994).
[11] J. Kim *et al.*, Phys. Rev. Lett. **72**, 2199 (1994).
[12] E.J. Strait *et al.*, Phys. Rev. Lett. **75**, 4421 (1995).
[13] R.J. LaHaye *et al.*, Nucl. Fusion **35**, 988 (1995).
[14] P.H. Diamond, V.B. Lebedev, D.E. Newman, and B.A. Carreras, Phys. Plasmas **2**, 3685 (1995).
[15] W. Nevins, in Proceedings of the 11th International Conference on the Applications of RF Power to Plasmas, Palm Springs, CA, 1995 (to be published).
[16] L.-G. Eriksson *et al.*, Plasma Phys. Controlled Fusion **34**, 863 (1992).
[17] K. Ida *et al.*, Nucl. Fusion **31**, 943 (1991).
[18] H. Hsuan *et al.* (Ref. [15]).
[19] T. Hellsten, Plasma Phys. Controlled Fusion **31**, 1391 (1989).
[20] M. Vukovic, Ph.D. thesis, University of Wisconsin, 1995.
[21] R. Majeski *et al.*, Phys. Fluids B **5**, 2506 (1993).
[22] S. Wukitch *et al.*, Phys. Rev. Lett. **74**, 2260 (1995).
[23] C. Litwin, Phys. Plasmas **2**, 4542 (1995).
[24] G.G. Craddock and P.H. Diamond, Phys. Rev. Lett. **67**, 1537 (1991).
[25] O. Klueber *et al.*, Nucl. Fusion **31**, 907 (1991).
[26] G.A. Hallock *et al.*, Phys. Rev. Lett. **56**, 1248 (1986).