Poloidal rotation velocities in the outer half of Alcator-*C* plasmas

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Poloidal rotation velocities in the outer half of ohmically heated Alcator-*C* plasmas have been determined from the Doppler shift of impurity emission lines. The measurements were made using a high-resolution photon-counting detector, sensitive to wavelengths from ~1200 to ~2000 Å, mounted in the exit plane of a 1-m Ebert-Fastie spectrometer. The following transitions were used: $2s2p\ ^1P_1^\circ - 2p^2\ ^1D_2$ at 1371.292 Å in O V, $2s\ ^2S_{1/2} - 2p\ ^2P_{1/2}^\circ$ at 1242.804 Å in N V (both of which exist near the limiter radius in Alcator-*C*), and $1s2s\ ^3S_1 - 1s2p\ ^3P_2^\circ$ at 1623.63 Å in O VII (which exists at $r/a \sim 0.8$). The measured rotation velocities are $4-5\times10^5$ cm/s in the direction of the electron diamagnetic drift at the radius of the O V emission shell and $\sim 6\times10^5$ cm/s at the radius of the O VII emission shell, again in the electron diamagnetic drift direction. Therefore poloidal rotation of the outer half of the Alcator-*C* plasma with a velocity of several times 10^5 cm/s in the direction of the electron diamagnetic drift is firmly established by these measurements.

I. INTRODUCTION

The theoretical study of plasma confinement in a magnetic field requires the determination of the stability limits of the equilibrium states which exist in a particular magnetic field geometry. Early theoretical studies considered only stationary (nonrotating) equilibria. In 1969, Stringer[1] showed that poloidal rotation ($v_\theta \neq 0$) in a toroidal plasma resulted in a significant enhancement of radial diffusion, although the poloidal velocity was introduced into the equilibrium as an external parameter. Later that same year, however, Rosenbluth and Taylor[2] considered this problem in more detail and demonstrated that the poloidal rotation velocity was determined by a set of hydrodynamic equations. Furthermore, they demonstrated that the stationary equilibrium state ($v_\theta = 0$) was unstable.

Interest in plasma rotation has increased in the past decade, largely as a result of the increased use of neutral beam injection as an auxiliary heating source. This heating mechanism brings with it the possibility of large unbalanced forces which may be used to impart significant momentum to the plasma, inducing flows which can be comparable to the ion thermal velocity. Measurement of the decay rate of the induced rotation (following cessation of the momentum source, e.g., the neutral beams) provides information on momentum relaxation processes[3] and may provide insight into the role magnetic and/or electrostatic fluctuations play in the radial transport of plasma constituents.[4]

This paper discusses measurements of the poloidal rotation velocity in the outer half of ohmically heated Alcator-*C* plasmas.[5] It is important to note that these measurements were made during the quasi-steady-state portion of ohmically heated discharges. Alcator *C* has no neutral beam injection system, an auxiliary heating scheme which has been shown to drive large bulk plasma motion in other tokamaks.[4,6] However, poloidal rotation velocities on the order of 10^5 cm/s in ohmic discharges, determined using the Doppler shift of impurity emission lines, have been reported in the LT-3 tokamak[3] and more recently in the TM-4 (Ref. 7) and DIII-D (Ref. 8) tokamaks.

The measurements reported here were made using a high-resolution, photon-counting detector[9] mounted at the exit plane of a 1m Ebert-Fastie spectrometer. The detector consists of a microchannel plate based image intensifier, sensitive from ~1200 to ~2000 Å, fiber optically coupled to a linear self-scanning photodiode array. The resolving power of the spectrometer-detector system $\lambda/\Delta\lambda_I$ [$\Delta\lambda_I$ is the full width at half maximum (FWHM) of the spectrometer-detector system] is ~5300 at 1200 Å and ~12,900 at 1800 Å. The high resolution and geometric stability of the photon-counting detector[9] made possible the measurement of small wavelength shifts ($\Delta\lambda \sim 0.01$ Å) and, therefore, the determination of small rotation velocities. This detector is described in more detail in Sec. II.

Section III discusses the method used to determine the poloidal rotation velocity in the outer half of Alcator-*C* plasmas from the Doppler shift of the O V, N V, and O VII emission lines. Section IV compares the results of these measurements to theoretical predictions as well as measurements of the poloidal rotation velocity in other tokamaks.

II. INSTRUMENTATION

The photon-counting detector[9] consists of a high-gain image intensifier fiber optically coupled to a linear self-scanning photodiode array. The image intensifier contains three high-strip-current (~300 μA at 1000 V) microchannel plates butt mounted in a "Z" configuration. It is a sealed unit with a MgF_2 input window and a fiber-optic output. The quantum efficiency of the detector has been enhanced by coating the surface of the first plate with a film of CsI ~3000 Å thick. The output of the microchannel plate stack is proximity focussed onto a P-46 phosphor screen, chosen as the output phosphor because it exhibits a decay time of ≤ 150 nsec to 10% of peak brightness. This phosphor was deposited on the input face of the fiber-optic bundle which serves as the output for the intensifier. This bundle is brought out of the vacuum chamber and a linear self-scanning photodiode array is optically coupled to the external face. The geometric stability of this system (i.e., no moving parts), coupled with the high resolution ($<50\mu$M) achievable with the photodiode array,[9] made possible the measurement of small wavelength shifts ($\Delta\lambda \sim 0.01$ Å) and, therefore, the determination of small rotation velocities. The modal gain of the intensifier is in excess of 3×10^7 and the spot size on the phosphor screen is $\sim 350\mu M$ (FWHM).

The photodiode array is a Reticon RL128SF,[10] containing 128 photodiodes with a slitlike geometry. Using a scanning circuit designed for the authors,[11] the maximum pixel scanning frequency was determined to be ~ 4 MHz. Through the use of pixel selection. i.e., reading out less than the entire array, and the simultaneous clocking of both video lines, scan times for the array of as little as 8 μsec are possible, allowing frame rates in excess of 100 kHz. The separation of the video lines necessitates reconstruction of the photoevents in software.

The high spatial resolution of the detector is achieved by viewing the amplified output from each photoevent. The "center of gravity" of this output is calculated and is assumed to represent the location of the detected photon. (With the detector mounted in the spectrometer's focal plane, this location corresponds to a known wavelength.) This centroid is stored along with the frame number (i.e., the time of arrival of the photoevent) and is used to create a histogram which represents the measured line shape (intensity versus wavelength during a chosen time interval). Operation of the detector in a photon-counting mode eliminates problems often associated with microchannel plate based image intensifier photodiode detector systems, such as fixed pattern noise[12,13] and intensity-dependent profiles.[12,13]

Examples of line-shape histograms are shown in Fig. 1 for the emission lines used for the poloidal rotation measurements described here. The crosses are the measured data and the solid line is at least-squares fit to the data assuming a sum of (unresolved) Zeeman components[14] for the line profile. Changes in the location of the line center as the spectrometer line of sight is scanned across the plasma cross section (see Fig. 2 and Sec. III) are attributed to Doppler shifts, making possible measurements of bulk plasma motion.

III. MEASUREMENT OF THE POLOIDAL ROTATION VELOCITY

This section discusses the geometry of the experimental apparatus used on Alcator C to measure Doppler shifts of impurity emission lines. These shifts are shown to depend linearly on both the rotation velocity and the impact radius of the spectrometer line of sight in the plasma. Measured wavelength shifts of O V and O VII emission lines firmly establish poloidal rotation of the outer half of ohmically heated Alcator-C plasmas in the direction of the electron diamagnetic drift.

Figure 2 shows the viewing geometry used to make the poloidal rotation measurements in Alcator C. The rotation velocity is determined by scanning the line of sight of the spectrometer (using the plasma scanning mirror) across the plasma cross section on a shot-to-shot basis during a series of "identical" discharges. To eliminate systematic drifts in the position of the line center, the spectrometer line of sight started at the plasma center and was scanned out in major radius. The line of sight was then returned to the center of the plasma and scanned inward in major radius. The restricted access to the plasma (a consequence of the Bitter magnet structure used on Alcator C) made possible the measurement of the poloidal rotation velocity only.

The wavelength shift ($\Delta\lambda_s = \lambda_0 - \lambda$) of an emission line due to directed motion of the emitting species is given by (see Fig. 2)

$$\frac{\Delta\lambda_s}{\lambda_0} = \frac{v}{c}\cos\gamma \ , \tag{1}$$

where λ_0 is the rest wavelength of the line, v is the magnitude of the velocity, c is the speed of light, and γ is the angle between the velocity and the spectrometer line of sight. For the geometry shown in Fig. 2, the angle γ is a function of r, the impact (minor) radius of the spectrometer line of sight, only and $\Delta\lambda_s$ is therefore also a function of r. Furthermore, it is easy to show that

$$\cos\gamma(r) = \sin\left[\sin^{-1}\left[\frac{r}{a}\right]\right] = \frac{r}{a} \ . \tag{2}$$

Therefore,

$$\Delta\lambda_s = \lambda_0 \frac{v}{c}\frac{r}{a} \ , \tag{3}$$

and the measured wavelength shifts are expected to fall on a straight line when plotted against r. The slope of the best straight-line fit to the measured shifts is therefore proportional to the poloidal rotation velocity.

The emission lines used to determine the poloidal rotation velocity in the outer half of the Alcator-C plasma were due to the $2s2p\ {}^1P_1^\circ - 2p^2\ {}^1D_2$ transition in O V, with a rest wavelength[15] of 1371.292 Å, the $2s\ {}^2S_{1/2} - 2p\ {}^2P_{1/2}^\circ$ transition in N V, with a rest wavelength[15] of 1242.804 Å, and the $1s2s\ {}^3S_1 - 1s2p\ {}^3P_2^\circ$ transition in O VII, with a rest wavelength[15] of 1623.63 Å. The determination of the position of the line center λ from the fit to the data contains an uncertainty, determined statistically[16] from the fit to the data, which was approximately 0.01 Å ($\sim \frac{1}{30} - \frac{1}{50}$ of the measured linewidth) for these measurements of the line shifts for all three lines. A study of the poloidal rotation of Alcator-C plasmas reported earlier[17] had available only the data shown in Figs. 3(a) and 3(b).

Figure 3(a) shows the measured wavelength shift $[\Delta\lambda = \lambda(r) - \lambda(r=0)]$ versus the impact radius r for the O V emission line at a line average density of $\bar{n}_e \simeq 1.7\times10^{14}$ cm^{-3} ($a = 12.5$ cm). Also shown is the best straight-line fit to the data, which exhibits a slope of $-1.51\times10^{-3} \pm 0.27\times10^{3}$ Å/cm with a linear correlation coefficient of -0.76. (This value of the linear correlation coefficient implies that the probability that the data could be drawn from an uncorrelated population is less than 0.001.[18]) This value of the slope corresponds to a poloidal rotation velocity of $v_\theta = 4.1\times10^5 \pm 0.5\times10^5$ cm/s in the direction of the *electron* diamagnetic drift in the toroidal magnetic field.

CO_2 laser scattering experiments designed to study density fluctuations in Alcator-*C* plasmas[19] measured a poloidal group propagation velocity for these density fluctuations of approximately 3×10^5 cm/s in the direction of the electron diamagnetic drift for discharges with a line average density of $\bar{n}_e \sim 1.5\times10^{14}$ cm^3. At this density, the amplitude of the density fluctuations peaks at $r/a \sim 0.7$ ($a = 16.5$ cm). At higher densities ($\bar{n}_e > 2\times10^{14}$ cm^{-3}), the poloidal group propagation velocity was measured to be $\sim 9\times10^4$ cm/s in the *ion* diamagnetic drift direction and the amplitude of the density fluctuations peaks at the limiter radius. Such behavior would not be expected of the bulk plasma rotation based on theoretical studies of the problem[1,3,20] and measure-

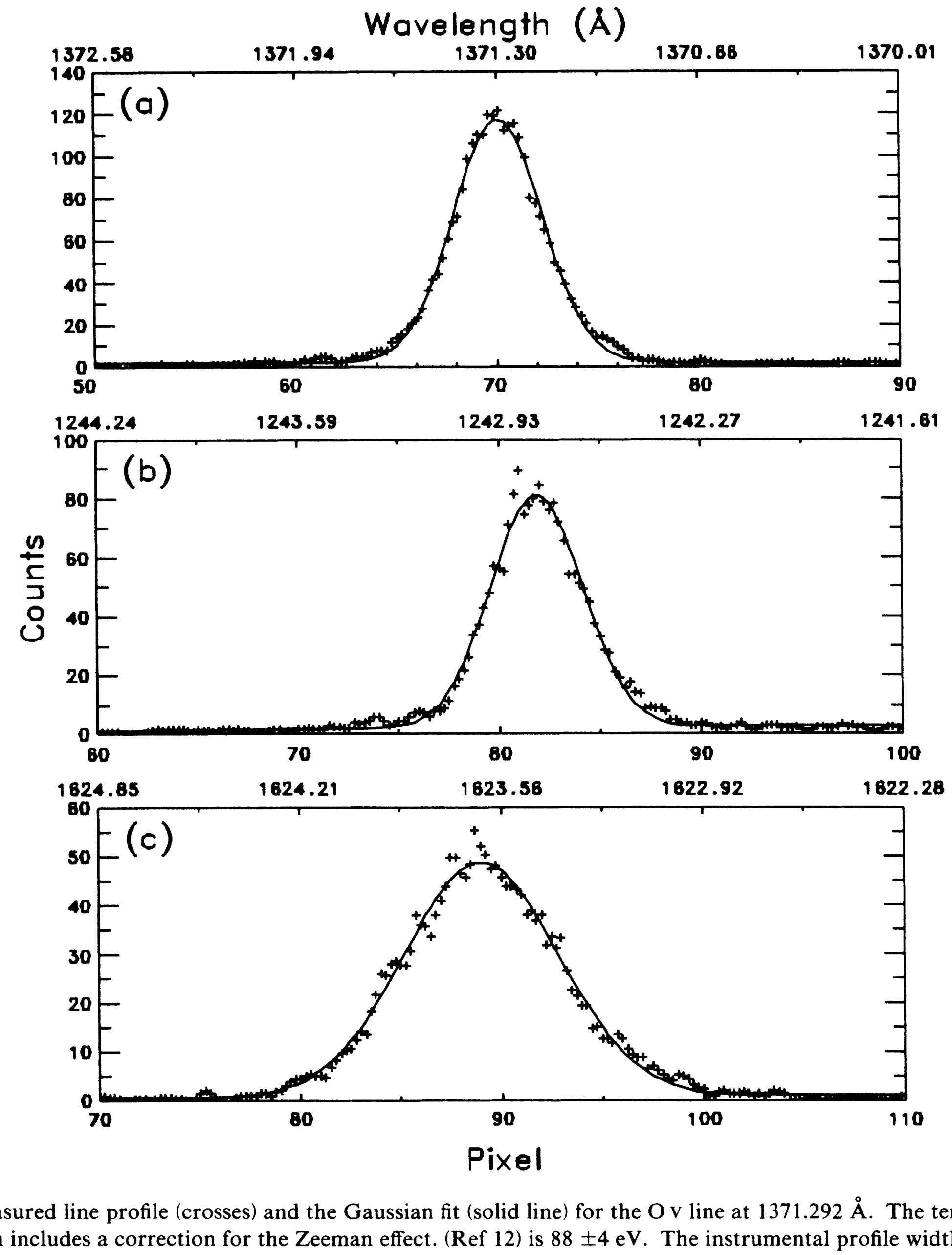

FIG. 1. (a) Measured line profile (crosses) and the Gaussian fit (solid line) for the O v line at 1371.292 Å. The temperature derived from the fit, which includes a correction for the Zeeman effect. (Ref 12) is 88 ±4 eV. The instrumental profile width corresponds to a temperature of 52 eV. (b) Measured line profile (crosses) and the Gaussian fit (solid line) for the N v line at 1242.804 Å. The temperature derived from the fit, which includes a correction for the Zeeman effect (Ref. 12) is 81 ±5 eV. The instrumental profile width corresponds to a temperature of 74 eV. (c) Measured line profile (crosses) and the Gaussian fit (solid line) for the O vii line at 1623.63 Å. the temperature derived from the fit, which includes a correction for the Zeeman effect (Ref. 12) is 275 ±15 eV. The instrumental profile width corresponds to a temperature of 23 eV.

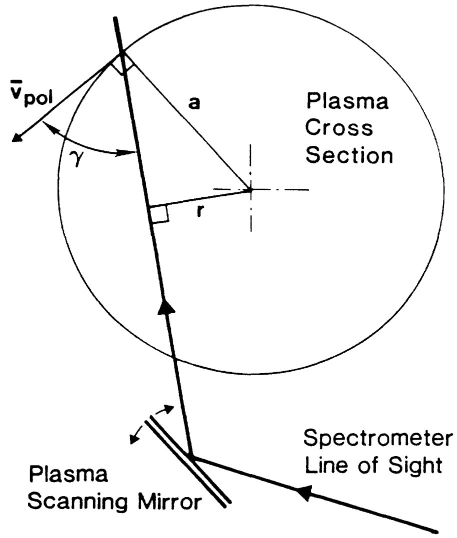

FIG. 2. Geometry of the system used to measure the poloidal rotation velocity of Alcator-*C* plasmas.

ments of the poloidal rotation velocity of the impurities were therefore repeated at line average densities greater than $\bar{n_e} \sim 1.7\times10^{14}$ cm^{-3} to determine if the laser scattering measurements were indicative of bulk plasma motion.

The first experiment at higher densities measured the wavelength shift of the N V emission line at a line average density of $\bar{n_e} \sim 2.3\times10^{14}$ cm^{-3}, shown in Fig. 3(b) ($a = 12.5$ cm). Also shown is the best straight-line fit to the data, which exhibits a slope of $0.5\times10^{-4} \pm 3.9\times10^{-4}$ Å/cm with a linear correlation coefficient of ~ 0.03. (This value of the linear correlation coefficient implies that the probability that the data could be drawn from an uncorrelated population is ~ 0.5,[18] a much larger probability than that displayed by the O V measurement discussed earlier.) This value of the slope corresponds to a poloidal rotation velocity of $v_\theta = 1.7\times10^4 \pm 8.0\times10^4$ cm/s in the direction of the ion diamagnetic drift, although the magnitude of the error bar associated with this measurement certainly allows for zero rotation or even a small rotation velocity in the opposite direction.

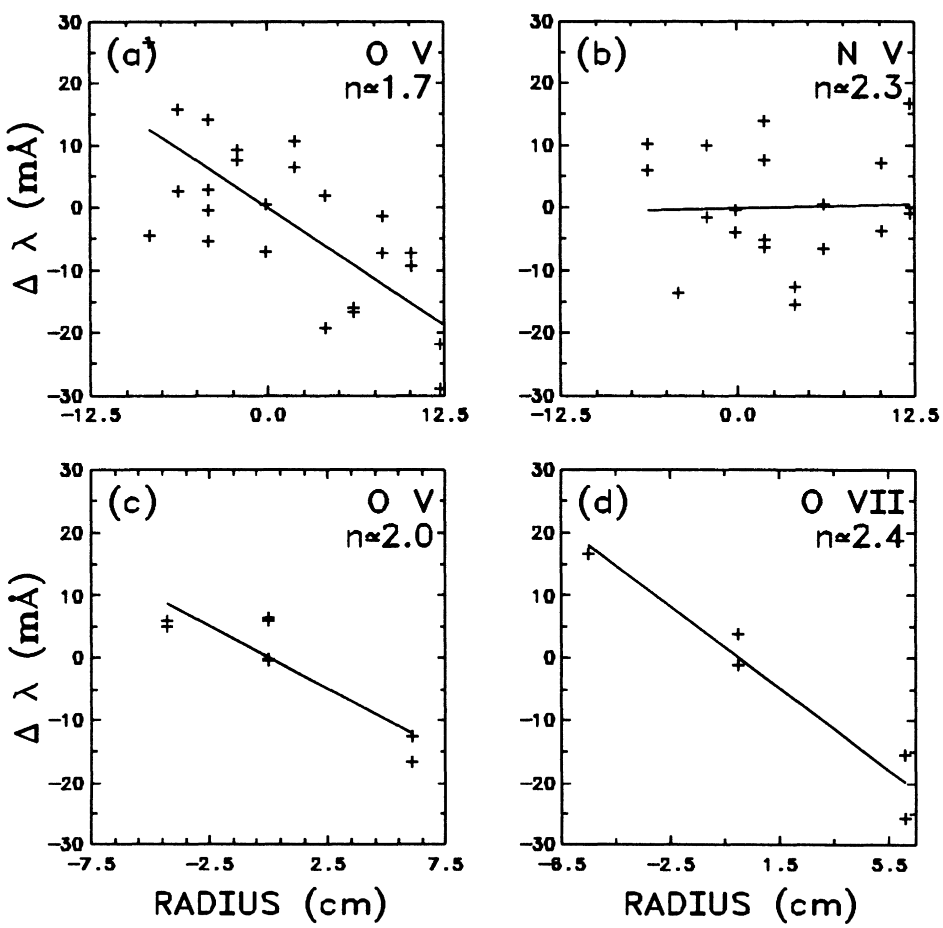

FIG. 3. Measured wavelength shift, and the best straight line fit to the data vs impact radius for (a) the O V emission line at 1371.29 Å; (b) the N V emission line at 1242.80 Å; (c) the O V emission line at 1371.29 Å; (d) the O VII emission line at 1623.63 Å. Densities are in units of 10^{14} cm^{-3}.

(This velocity and the associated uncertainty are significantly smaller than previously reported,[17] due to an improvement in the data handling techniques. This also resulted in a reduced uncertainty in the velocity deduced from the O V measurements discussed above.) Furthermore, it is worth noting that removing two points from the data set yields a slope of $-4.9\times10^{-4}\pm3.8\times10^{-4}$ Å/cm, corresponding to a velocity of $1.5\times10^{5}\pm0.8\times10^{5}$ cm/s in the electron diamagnetic drift direction. Due both to the large uncertainty (relative to the measured velocity) in the first fit to this data set, and the impact deleting only two data points has on the results of fitting the data, this measurement of the direction of v_θ using the wavelength shift of N V is suspect, although the magnitude of the velocity is certainly less than 3×10^{5} cm/s.

The measurement of the O V wavelength shift was therefore repeated at a line average density of $\overline{n_e}\sim2.0\times10^{14}$ cm^{-3} , with the results shown in Fig. 3(c) ($a=11.5$ cm). Each point in this plot is an average wavelength from 15 consecutive discharges. (This was done in an attempt to lower the uncertainty in the result of the measurement.) The best straight-line fit to these points, shown as a straight line in the plot, exhibits a slope of $-2.01\times10^{-3}\pm0.42\times10^{-3}$ Å /cm with a linear correlation coefficient of ~0.89 (This value of the linear correlation coefficient implies that the probability that the data could be drawn from an uncorrelated population is ~0.002.[18]) This value of the slope corresponds to a poloidal rotation velocity of $v_\theta=5.1\times10^{5}\pm0.7\times10^{5}$ cm/s in the direction of the *electron* diamagnetic drift, which is consistent with the earlier O V measurement.

To ensure that the results of the O V measurements of v_θ were not systematic to the O V emission line, a measurement of v_θ in the region of the Alcator-*C* plasma where $r/a\simeq0.8$ was made using the O VII emission line at a line average density of $\overline{n_e}\sim2.4\times10^{14}$ cm^{-3}. The measurement also serves to provide some information on the radial nature of the poloidal rotation. The results of the measured wavelength shift are shown in Fig.3(d) along with the best straight-line fit to the data. (As in the case of the second O V measurement of v_θ, each point in this plot represents an average of the wavelength measured during several consecutive discharges.) The slope of this fit is $-3.04\times10^{-3}\pm0.42\times10^{-3}$ Å/cm with a linear correlation coefficient of -0.97. (This value of the linear correlation coefficient implies that the probability that the data could be drawn from an uncorrelated population is ~0.005.[18]) This value of the slope corresponds to a poloidal rotation velocity of $v_\theta=6.5\times10^{5}\pm0.6\times10^{5}$ cm/s in the direction of the *electron* diamagnetic drift, consistent with the O V measurements. On the basis of the consistency displayed by the measurements using O V and O VII, a poloidal rotation of the Alcator-*C* plasma in the direction of the electron diamagnetic drift at the radius of the O V and O VII emission shells and at electron densities between ~1.5 and 2.4×10^{14} cm^{-3} is firmly established.

IV. COMPARISON TO THEORETICAL PREDICTIONS AND MEASUREMENTS IN OTHER TOKAMAKS

The results of fluid theory[2] and neoclassical transport theory[3,20] were used to predict expected values of the poloidal rotation velocity in these plasmas, with the results shown in Table I. The expressions derived from neoclassical transport theory depend on the local value of the gradient in the ion temperature profile, which was not measured during these experiments. (Only the central ion temperature was measured.) These expressions were therefore evaluated using both a Gaussian and a parabolic temperature profile. (For the expression derived by Bell, only the contribution due to the third term, involving the temperature gradient, was evaluated.) Note that the ion temperatures derived from the measurements of the line shapes of O V, N V, and O VII cannot be used to construct an ion temperature profile in the outer half of the plasma, since the measurements of these different ionization stages occurred under widely varying plasma conditions.

Comparing the theoretical predictions with the results of the experimental determinations of v_θ, the predicted velocities are all in the direction of the electron diamagnetic drift in the toroidal magnetic field and fall in the range of $(0.9-4.2)\times10^{5}$ cm/s. Therefore, with the exception of the N V measurement, all of the predicted veloci-

TABLE I. Measured and predicted poloidal rotation velocities for different plasma conditions in Alcator *C*. Gauss. and Para. refer to the use of Gaussian and parabolic temperature profiles, respectively. Velocities given in units of 10^5 cm/s A positive value is in the direction of the electron diamagnetic drift.

		Predicted v_θ				
			Hazeltine[a]		Bell[b]	
Ion	v_θ	Fluid[c]	Gauss.	Para.	Gauss.	Para.
O V	4.1 ± 0.5	2.0	0.95	1.7	1.3	2.3
N V	-0.17 ± 0.8	2.2	0.99	2.1	1.3	2.8
O V	5.1 ± 0.71	1.9	1.2	2.5	1.6	3.4
O VII	6.5 ± 0.65	2.8	2.2	3.0	3.1	4.2

[a] Reference 20.
[b] Reference 3.
[c] Reference 2.

ties are in the same direction as the measured velocities. Also, the predicted poloidal rotation velocity for O VII is larger than the predicted O V rotation velocities, in agreement with the measured velocities. However, all of the predicted velocities are smaller than the measured velocities, generally by a factor of 2–4. Finally, the measured rotation velocity for O V is larger in the $a = 11.5$-cm case [Fig. 3(c)] than in the $a = 12.5$-cm case [Fig. 3(a)], in agreement with the predictions of neoclassical transport theory and in disagreement with the fluid theory prediction.

The use of a parabolic ion temperature profile yields better agreement between the measured velocities and the transport theory predictions than the use of a Gaussian profile. Also, the predictions based on Bell's[3] expression (evaluating only the T_i' term) yield better agreement with the measured velocities than Hazeltine's[20] expression. However, this may be misleading, since terms involving $\partial n/\partial r$ were not evaluated in Bell's expression and the effects of these terms are not known since the density profiles in the outer region of the Alcator-*C* plasma are not well known. Finally, the expressions of Bell and Hazeltine were derived using standard neoclassical transport theory, which is not an adequate description of transport in Alcator *C* under normal operating conditions.[21]

Measurements of the poloidal rotation velocity in ohmically heated discharges in the LT-3 tokamak[3] yielded a maximum value of $v_\theta = 1.6\times 10^5 \pm 0.4\times 10^5$ cm/s in the direction of the electron diamagnetic drift approximately 2 ms after the peak in the plasma current. (The LT-3 discharges discussed in this reference exhibited no flat top in the time history of the plasma current and, hence, no quasi-steady-state existed during these discharges.) Approximately 1 ms prior to this maximum, the poloidal velocity was $\sim 1.4\times 10^5$ cm/s and the predicted velocity[3] at this time, using only the temperature gradient term derived by Bell, is $\sim 1.6\times 10^5$ cm/s, which is consistent with this measurement of v_θ in LT-3.

Attempts to measure the poloidal rotation velocity in the poloidal divertor experiment (PDX) tokamak[4] during ohmically heated discharges yielded $v_\theta = 0 \pm 3\times 10^5$ cm/s, i.e., the poloidal rotation velocity was less than the uncertainty of the measurement.

Measurements of the poloidal rotation in the TM-4 tokamak[7] during ohmically heated discharges, using emission lines of C III, O V, and C V to measure the radial profile of the poloidal rotation, yielded a peak velocity (from the shift of the O V emission line) of $v_\theta \simeq 2\times 10^5 \pm 0.3-0.5\times 10^5$ cm/s in the direction of the electron diamagnetic drift, which is consistent with the measurements in LT-3 and the measurements reported here.

Three of the four measurements (LT-3, TM-4 and Alcator *C*) yield poloidal rotation velocities in the outer half of the tokamak plasma which are several times 10^5 cm/s, and the PDX measurements are consistent with this result, since the error bars associated with the PDX measurements are too large to allow a meaningful determination of a velocity of this magnitude. This is particularly interesting considering the wide range of plasma parameters represented by the three nonzero measurements of v_θ: LT-3,

$$\bar{n}_e \sim 3\times 10^{13}\ \text{cm}^{-3},\quad T_i(0) \sim 30\ eV\ ,$$

Tm-4;

$$\bar{n}_e \sim 4\times 10^{13}\ \text{cm}^{-3},\quad T_i(0) \sim 120\ eV,$$

Alcator;

$$\bar{n}_e \sim 1.7-2.4\times 10^{14}\ \text{cm}^{-3},\quad T_i(0) \sim 1000\ \text{eV}\ ,$$

i.e., the Alcator densities are a factor of 5–8 higher than the densities of the other machines and the Alcator central ion temperature is a factor of 8–30 times higher, yet the measured poloidal rotation velocities in the outer half of the Alcator-*C* plasma are comparable to those measured in the other machines.

V. SUMMARY

The two measurements of v_θ using the measured wavelength shift of the O V emission line firmly establish the poloidal rotation, at the radius of the O V emission shell, of ohmically heated Alcator *C* discharges with a velocity in the direction of the electron diamagnetic drift of

$$v_\theta \sim (4-5)\times 10^5\ \text{cm/s}\ ,$$

a result which is 2–3 times higher than the poloidal rotation velocities measured in a similar manner in the LT-3[3] and TM-4[7] tokamaks. Furthermore, rotation at the radius of the O VII emission shell with a velocity of

$$v_\theta \sim 6\times 10^5\ \text{cm/s}\ ,$$

in the direction of the electron diamagnetic drift has been demonstrated by the measured wavelength shift of the O VII emission line. These results are for discharges with line average electron densities in the range from 1.5 to 2.4×10^{14} cm^{-3}. In addition,if it is assumed that a plasma potential is created as a result of neoclassical transport, and if the ion temperature gradient is estimated, then the poloidal rotation velocity predicted by neoclassical theory can be evaluated. The measurements of v_θ in the outer half of the Alcator-*C* plasma are 2–4 times higher than these predictions. However,this comparison should not be taken too seriously, since (i) the transport in Alcator *C* is known to behave nonneoclassically[21] and (ii) the actual shape of the ion temperature profile in the outer region of the Alcator-*C* plasma has not been measured.

The result of the N V measurements remains an open question. A condition which must be satisfied for an emission line of an impurity to be useful as a velocity diagnostic is

$$\xi = \tau_Z^I / \tau_Z^v \gg 1\ , \tag{4}$$

where τ_z^I is the ionization time for the ion and τ_Z^v is the time required for the ion to acquire a velocity v. This condition requires the lifetime of the ion in the plasma to be much longer than the time required to gain momentum. Based on the material in Bugarya *et al.*,[7] Summers,[22] and Trubnikov,[23] ξ was evaluated for both N V and O V, with the result that

$$\xi_{\mathrm{N}\,V} \simeq 10.6 ,$$

$$\xi_{\mathrm{O}\,V} \simeq 8.6 .$$

Therefore, on the basis of this condition, the emission lines of both N V and O V are equally valid as velocity diagnostics and the failure of the N V measurement is not understood at this time.

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