Self-Acceleration of a Tokamak Plasma during Ohmic H Mode

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(Received 28 May 1999)

Core plasma rotation is observed to change from counter direction to co-current direction during the transition from low (L) to high (H) confinement mode, in Alcator C-Mod plasmas that are heated *purely Ohmically* and, hence, have no momentum input. The changes of the toroidal velocities, deduced independently from impurity Doppler measurements and from magnetic perturbations associated with sawteeth, agree. The magnitude of the change is consistent with the previously documented scaling for rotation in ion cyclotron rf–heated H modes. The rotation in this Ohmic experiment is obviously not an rf effect but demonstrates unequivocally a transport effect accelerating the plasma.

PACS numbers: 52.55.Fa, 52.25.Fi, 52.30.–q

Flow velocity in magnetically confined plasmas is important because the shear in this flow can act to stabilize the turbulence responsible for enhanced transport [1] and because it reflects on the underlying cross-field transport mechanisms. In the core of a tokamak plasma, the flow is predominantly in the toroidal direction of symmetry. In the past, with few exceptions, high confinement (H-mode) tokamak plasmas, in which toroidal rotation measurements have been made, have been heated and diagnosed using neutral beams. These beams provide momentum directly to the core plasma, and are observed to affect the rotation. As a result, the opinion has developed that tokamak core rotation is merely a balance between momentum sources and momentum diffusion, the latter being turbulent but of the same order of magnitude as the energy diffusion. Recent measurements on Alcator C-Mod and JET using ion cyclotron rf (ICRF) heating have shown strong core rotation in H-mode plasmas without neutral beams [2,3]. Interpretations of those observations have focused on possible rf mechanisms of flow generation [4]. In attempting to clarify this situation, the experiments reported here were undertaken, where no auxiliary power at all is applied to the plasma, thus removing all possibility of neutral beam or ICRF momentum transfer. Nevertheless, we find that the core plasma rotates rapidly, at speeds consistent with the scalings found for ICRF H-mode rotations. These observations are thus inconsistent with the prevailing outlook in which momentum transport is considered to be purely diffusive. They prove that there must be a mechanism of momentum transport *up the velocity gradient*.

The Alcator C-Mod plasmas studied are illustrated by Fig. 1. H-mode operation without auxiliary heating is obtained using low values of the edge safety factor, $q_{95} = 2.5$, which maximizes the ratio of Ohmic heating (approximately proportional to plasma current) to toroidal field (to which the H-mode power threshold is approximately proportional). Plasma currents ranged from 0.8 to 1.45 MA, and toroidal fields from 3 to 5.8 T. The field direction is that favorable for attaining H mode. The plasma geometry is major radius $R = 0.67$ m, minor radius $a = 0.22$ m, with elongation of 1.6 and triangularity of 0.5 at the x point. The density at the H-mode transition, marked by a dramatic drop in the deuterium Balmer α radiation, is typically 1.5×10^{20} m^{-3} and rises throughout the (edge-localized-mode–free) H-mode phase until the Ohmic power becomes inadequate to sustain the H mode and a reversion to L mode occurs. Temperatures are typically 1 to 1.5 keV for both electrons and ions at the plasma center, with broad profiles that are rather flat within the half radius $r/a < 0.5$ and approximately linear outside.

The present measurements of toroidal rotation are made by two independent diagnostics. The velocity is measured spectroscopically at the plasma axis by observing the Doppler shift of x-ray lines from highly charged argon impurities (Ar^{17+}). It is also measured by observing the rate of rotation of helical ($n = 1$) magnetic perturbations associated with the sawtooth instability.

The x-ray spectra were recorded with a spatially fixed von-Hamos–type crystal x-ray spectrometer [5], whose line of sight is tangent to the plasma axis in the positive

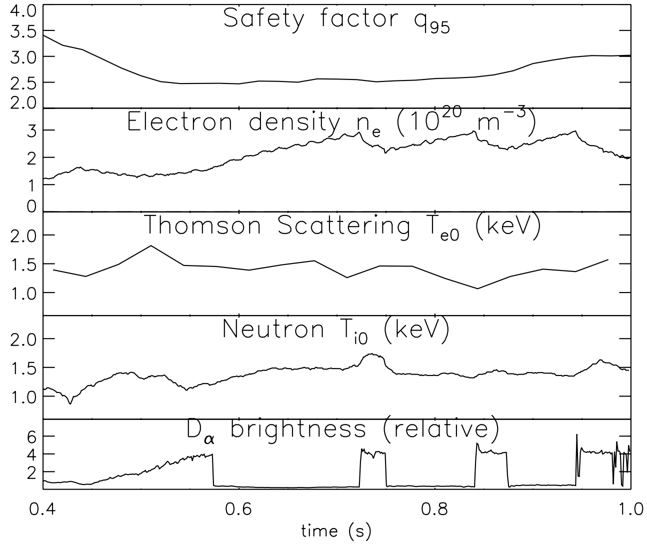

FIG. 1. Parameters of an Ohmic H mode. The safety factor, line-average density, central electron and ion temperatures, and the Balmer α intensity (indicating H and L phases) are shown.

0031-9007/00/84(15)/3330(4)$15.00

toroidal direction, counter to the current. The spectrometer has a resolving power ($\lambda/\Delta\lambda$) of $\sim$4000 and spectra are collected every 20 ms. Rotation velocities have been determined from the Doppler shifts of the Ar^{17+} Lyman α doublet [6] ($1s\,{}^1S_{1/2}$-$2p\,{}^2P_{3/2}$ at 3.7311 Å, and $1s\,{}^1S_{1/2}$-$2p\,{}^2P_{1/2}$ at 3.7365 Å). This line is emitted over a centrally peaked profile that is roughly triangular with half-width at $r = 0.07$ m. The tangential view and the approximately 2 cm viewing resolution lead to a sensitivity profile of half-width approximately 6 cm. The determination of the spectral line center is subject to estimated systematic uncertainties of ± 5 km/s and statistical uncertainties from spectrum to spectrum of up to the same value, depending on emission intensity. Observations of plasmas with magnetic fields in the opposite direction confirm the reversal of the rotation direction with field and the absolute wavelength calibration.

The magnetic perturbations are measured by up to 30 fast magnetic pickup coils located in the limiters on the outboard side of the plasma a distance of approximately 3.5 cm beyond the last closed flux surface. They are at four unequally spaced toroidal angles, which allows unequivocal mode-number resolution of low n, and at vertical positions spaced by about 3 cm thus providing both poloidal and toroidal mode information. The coils are sensitive to the time derivative of poloidal magnetic field. Not all plasmas have sufficient magnetic perturbation amplitude to make the precursors or postcursors to sawteeth visible. Fortunately, the low-q plasmas needed for Ohmic H modes have large and usually visible sawtooth magnetic signals, at least when the rotation frequency is significantly greater than zero. The perturbations are approximately field aligned, and their direction of rotation is determined by the phase difference between nearby coils. Corotating frequency components, equivalent to ion-diamagnetic direction rotation, are plotted as positive frequencies, and counter (electron-diamagnetic) rotation as negative frequencies. It is impossible with single helicity perturbations to distinguish between poloidal and toroidal rotation on the basis of the magnetic measurements alone. The sawtooth perturbations are characteristic of the radius at which the safety factor is equal to 1. For the low-q Ohmic H-mode plasmas, this resonant radius is typically half the minor radius: $r \approx 0.12\ \mathrm{m} \approx 0.5a$.

If the MHD perturbation rotates relative to the plasma ions, this would systematically shift the magnetics velocity relative to the plasma velocity. Linear theory predicts rotation relative to the frame of reference in which the radial electric field is zero either at the electron diamagnetic velocity, if the mode is of tearing character, or at half the ion diamagnetic velocity if the mode is "ideal" [7]. But we are far beyond the linear phase when detectable signals are obtained. Moreover, in some (corotating) cases where there are both precursors and postcursors, we observe only small ($\sim$20%) reductions in mode velocity across the sawtooth crash, which suggests that the diamagnetic contributions to the mode rotation are small. The magnitude of the electron diamagnetic velocity, from measured pressure gradients prior to the sawtooth crash, is anyway less than about 40% of the observed rotation speed. After the crash, it is almost zero because the crash flattens the pressure profile. Comparisons on JET of the C^{6+} velocity with sawtooth-related magnetic perturbation velocity showed good agreement [8]. There is substantial evidence, therefore, to suppose that the mode velocity is the plasma ion velocity. In any case, however, it is the perturbation propagation velocity (although not especially of sawteeth perturbations) that is important in the mechanism of shear suppression that motivates much of our interest.

An example of the velocity measurements is shown in Fig. 2. This plasma has three H-mode periods indicated by low values of the D_α trace. The magnetic perturbation spectrum, in which intensity indicates spectral power, shows sawteeth crashes as broad-frequency vertical bands. Postcursor $n = 1$ oscillations are visible with narrow frequency bands, particularly during the H-mode phase. Their frequency (up to about $\nu = +8$ kHz in this case) gives the rotation velocity of the plasma (since $n = 1$); up to $2\pi R \times \nu = 34$ km/s. During the first L-mode phase, prior to 0.57 s, the frequency is close to zero, or slightly negative (counterrotating) as indicated by the negative frequency sawtooth crashes. But the $n = 1$ frequency cannot be reliably determined. The argon ion velocity is also shown. Its time dependence agrees quite well with the magnetics measurements. Both show a velocity drop following the first return to L mode (0.725 to 0.75 s), and reestablishment of the rotation during the second H phase. Following the second return to L mode, the rotation does not return to the higher level of the prior two H phases, for reasons that are unknown. It has been observed in

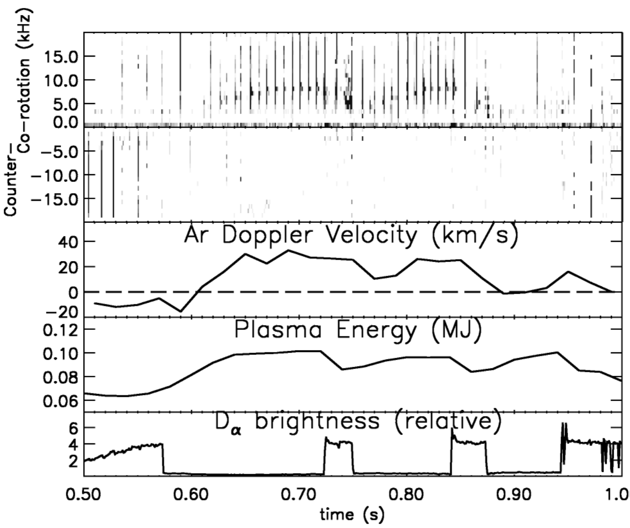

FIG. 2. Velocity measurements. The top two panels are spectral plots versus time of the corotating (positive frequency) and counterrotation (negative) magnetic fluctuations with spectral power density corresponding to intensity.

ICRF-heated H modes that the rotation increases approximately proportional to the stored energy. This feature is present also in the current experiments, but, as with the ICRF observations, the rotation velocity lags the stored energy rise and fall, in its response to transients, by a delay comparable to the energy confinement time, ~40 ms here.

To compare the rotation observed in these Ohmic H modes with prior observations during ICRF heating, we plot the velocity obtained by the two diagnostic techniques versus the approximate scaling parameter found for the ICRF H modes, equal to the plasma stored energy, W, divided by the plasma current, I_p. Figure 3 shows the results for a range of shots obtained in the 1999 operational campaign in which both diagnostic techniques were simultaneously available. The magnetics measurements show essentially linear dependence. Plasmas with ICRF heating have typically higher velocities, but the Ohmic H modes lie on the same scaling line. Their lower velocities are consistent with the lower stored energy that is obtained with lower overall heating power. The highest Ohmic toroidal velocities are approximately 0.1 times the sound speed, whereas up to 0.3 times the sound speed is obtained in ICRF-heated plasmas.

The Doppler velocity measurements seem to lie above the magnetics measurements on average in ICRF-heated cases. The cause of this systematic difference appears to be that the ICRF-heated velocity profiles are peaked in the center (where the Doppler measurements are made) relative to the sawtooth radius characterized by the magnetics. Nevertheless, there appears to be quantitative consistency between previous (ICRF) rotation scalings and the present Ohmic results. Observations using other spectrometers sensitive to poloidal ion rotation indicate zero poloidal rotation (change) during Ohmic H modes within the uncertainties (±3 km/s) consistent with theory and previous measurements.

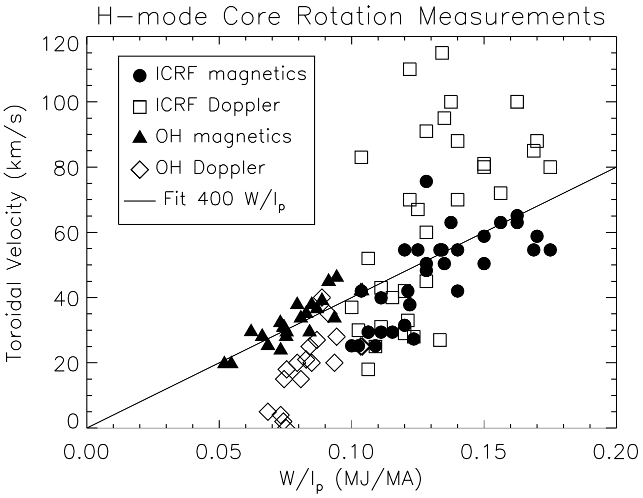

FIG. 3. Comparison of H-mode rotation velocities with and without ICRF heating, as measured by the two diagnostics.

The most significant result here is that very substantial toroidal rotation velocity develops during H modes that have *no* momentum sources in the core. The result requires the mechanism generating the rotation to be a transport process, and thus provides unequivocal evidence that this transport process exists.

A result consistent with the present observations has been observed on the COMPASS tokamak [9] where plasma toroidal rotation in the core changes from counter-rotating at about −10 km/s in the L-mode phase to corotating in the H mode at up to 18 km/s, but the published results show velocities that do not reach a steady state because the H phase is so short. In their case, Doppler measurements of chlorine central impurities and boron impurities near the edge were used.

In view of the present lack of detailed profile information, we cannot be certain whether the corotation-generating process is present in the center of the plasma or is localized to the edge and inner part of the H-mode pedestal region. If the plasma toroidal velocity is uniform in the core, then no process other than momentum diffusion is needed to explain the core profile. That this momentum diffusion is present is known from many previous studies although results are ambiguous as to whether a "momentum pinch" (inward momentum transport in the absence of a velocity gradient) is [10] or is not [11] needed to explain those observations. The time response of the present Ohmic rotation to the transients is consistent with momentum diffusivity of the order of the thermal diffusivity, as in previous experiments, or perhaps slightly lower.

Our previous ICRF-heated results showed substantial peaking of the toroidal velocity within the inner half of the profile [2], requiring a central momentum source or a mechanism for momentum transport up the velocity gradient there. The Ohmic cases have insufficient resolution on the Doppler measurements to obtain a profile. So we have only a central measurement from the Doppler spectrometer and the magnetics measurement, characteristic of a minor radius of about 0.12 m ($r/a \approx 0.5$). Within measurement uncertainties, the velocities are the same, indicating a flat profile.

There are, however, at least two mechanisms by which the argon velocity might be systematically lower than the bulk ion velocity in the core. One is the effect of the parallel electric field and the resulting electron friction. This effect is predicted [12] to give a velocity on the axis of the impurities, relative to the hydrogenic species in the counter direction (negative), of [13]

$$v_{\parallel I} - v_{\parallel i} = -4.19 \times 10^3 f \frac{Z_i}{\sqrt{\mu}} \frac{V_\ell}{R} \frac{T_i^{3/2}}{n_{20}} \ \mathrm{m/s}, \qquad (1)$$

where I refers to impurities and i to bulk hydrogenic ions, Z_i is the charge number, μ is the mass in proton masses, T_i is the temperature in keV, and n_{20} is the density in units of 10^{20} m^{-3} all of the background ions; V_ℓ is the loop voltage, and R is the major radius in meters. The factor f is essentially unity for this trace-impurity case. This expression evaluates to about 5 km/s for the fastest-rotating Ohmic H-mode cases here. The other effect is the combination of parallel frictions arising from velocity and heat flux [14]. This again would cause the argon ions to acquire a counterrotation velocity with respect to the bulk ions. The theoretical expression

$$v_{\|I} - v_{\|i} \approx \frac{3}{2}\left(\frac{3}{2}\sqrt{\frac{r}{R}}\right)\frac{1}{eB_\theta}\frac{dT_i}{dr}\,, \qquad (2)$$

where B_θ is the poloidal field, would give a velocity of about 6 km/s when evaluated at the sawtooth radius, $r/a \approx 0.5$, using the measured ion temperature with a scale length corresponding to the average over a sawtooth cycle, and the poloidal magnetic field $B_\theta = 0.5$ T at the midplane from equilibrium reconstructions. The combined effect of these two theoretical contributions to the velocity difference is significant at the precision needed to establish whether or not there is a substantial gradient in the core of toroidal velocity of the bulk ions. We therefore consider the presence or absence of a core ($r/a < 0.5$) gradient to be unresolved on the basis of the present measurements. There definitely is a very strong gradient in the edge region of the H-mode barrier.

The theoretical possibility of a neoclassical momentum pinch has recently been raised both within the context of standard theory [15] and as a result of finite Larmor radius corrections [16]. The former gives an inward velocity at which momentum is convected, approximately the Ware pinch velocity, $E_\phi/B_\theta \approx 0.5$ m/s (at $r/a = 0.5$). This value is not obviously negligible, since when combined with a diffusivity estimate based on the energy confinement time, $\chi \approx a^2/8\tau_E \approx 0.1$ m^2/s, it gives a scale length about equal to the minor radius (0.21 m). However, this momentum flux, being purely convective, does not appear to be capable of sustaining a *velocity* gradient, because the increase of momentum density arising from its divergence is directly attributable to the increase in particle density, not velocity. The finite Larmor radius correction effects are quantitatively significant only within the steep H-mode barrier.

Mechanisms outside the collisional neoclassical theory should also be considered. Energetic ion loss may be important within the edge barrier but is normally invoked to explain counterrotation (negative radial electric field, which is present in the edge, as evidenced in C-Mod by the edge magnetics rotation [17]) but not the positive radial electric field implied by the core corotation we see here. "Reynolds stress" from turbulence may also be a possibility.

Further detailed experiments and theory are needed to explain this intriguing plasma "self-acceleration."

We are grateful for valuable input from C. Fiore, J. Irby, M. Greenwald, A. Hubbard, D. Mossessian, J. Terry, and S. Wolfe, and for the support of the whole Alcator group. This work was supported by DOE Grant No. DE-FC02-99ER54512.

[1] K. H. Burrell, Science **281**, 1816 (1998).
[2] J. E. Rice *et al.*, Nucl. Fusion **38**, 75 (1998).
[3] L.-G. Eriksson *et al.*, Plasma Phys. Controlled Fusion **39**, 27 (1997).
[4] C. S. Chang *et al.*, in Proceedings of the 17th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Yokohama, 1998 [IAEA-F1-CN-69/THP2/34].
[5] E. Källne, J. Källne, E. S. Marmar, and J. E. Rice, Phys. Scr. **31**, 551 (1985).
[6] E. S. Marmar *et al.*, Phys. Rev. A **33**, 774 (1986).
[7] S. Migliuolo, Nucl. Fusion **33**, 1721 (1993).
[8] J. A. Snipes, D. J. Campbell, T. C. Hender, M. von Hellermann, and H. Weisen, Nucl. Fusion **30**, 205 (1990).
[9] I. H. Coffey *et al.*, in *Proceedings of the 11th Colloquium on UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas, Nagoya, Japan, 1995,* Frontiers Science Series No. 15, edited by K. Yamashita and T. Watanabe (Universal Academy Press, Tokyo, Japan, 1996), p. 431.
[10] K. Nagashima, Y. Koida, and H. Shirai, Nucl. Fusion **34**, 449 (1994).
[11] S. Scott *et al.*, Phys. Fluids B **2**, 1300 (1990).
[12] Y. B. Kim, P. H. Diamond, and R. J. Groebner, Phys. Fluids B **3**, 2050 (1991).
[13] J. E. Rice *et al.*, Nucl. Fusion **37**, 421 (1997).
[14] D. R. Ernst *et al.*, Phys. Plasmas **5**, 665 (1998).
[15] H. Sugama and W. Horton, Phys. Plasmas **6**, 2215 (1997).
[16] A. L. Rogister, Phys. Plasmas **6**, 200 (1999).
[17] I. H. Hutchinson, R. S. Granetz, A. Hubbard, J. A. Snipes, T. Sunn Pedersen, M. Greenwald, B. LaBombard, and the Alcator Group, Plasma Phys. Controlled Fusion **41**, A609 (1999).