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Tokamak Plasma Rotation without Momentum Input

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Abstract

Toroidal rotation in the core of Alcator C-Mod changes from counter- to co-current direction when the plasma enters the H-mode phase, even when there is no direct external momentum source. There is therefore some kind of self-acceleration mechanism, presumably arising from transport, that opposes the diffusive momentum loss. Simultaneously, the magnetic fluctuations at the edge rotate in the opposite direction, at speeds that imply a large (100 to 200 kV/m) equivalent radial electric field. Latest measurements indicate that the edge pressure gradients may be sufficient to balance this field; thus the ion diamagnetic and electric field drifts probably substantially cancel. Core rotation in ohmically heated plasmas scales the same as ICRF-heated, and the ICRF-heated speed does not vary significantly with wave resonance position.

1 Introduction

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. Measurements on Alcator C-Mod and JET using ion cyclotron (ICRF) heating have shown strong core rotation in H-mode plasmas without neutral beams[1, 2, 3, 4]. More recently measurements have been obtained on C-Mod 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*. This paper summarizes some of these ohmic measurements [3] and related observations of edge rotation, which is also observed to undergo major transitions with the confinement mode.

2 Core Rotation

The core rotation is measured on Alcator C-Mod by two independent techniques, high-resolution Doppler spectroscopy of argon seeded impurities, and the rotation of n=1 magnetic perturbations associated with sawteeth. The spectroscopic signal is dominated by the axial region within $r/a < 0.3$, while the sawtooth pre- and post-cursors are near the $q = 1$ surface, whose position depends on edge safety factor, but for the low-q plasmas typical of ohmic H-mode is as far out as $r/a \approx 0.5$.

The limitations of the two measurements are that the Doppler spectroscopy requires additional impurities and requires careful baseline calibration to determine absolute velocity, while the sawtooth measurement requires sufficiently large sawtooth precursors and also sufficiently rapid rotation (since its signal is proportional to the derivative of the field).

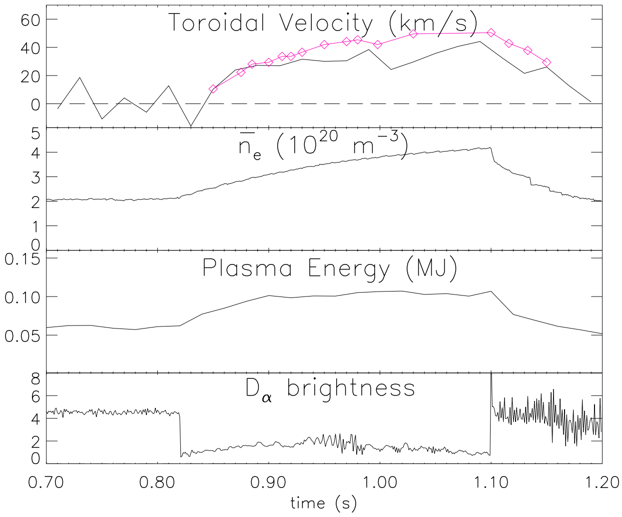

Figure 1: Time evolution of parameters during an ohmic H-mode. The Doppler velocity is the unmarked line and the magnetics velocity is marked with diamonds.

In figure 1 we illustrate an example of ohmic H-mode in which both measurements were available. Their time dependence is in quite good agreement, within the uncertainties ($\sim \pm 10$ km/s) of each.

Figure 2 shows a compilation of rotation measurements plotted as a function of the scaling that has been found to fit the observations, namely, $v_\phi \sim 400W/I_p$ where W is the stored kinetic plasma energy, and I_p is the plasma current[5]. There is some tendency in this data for the central argon velocity to exceed the magnetics measurement at high ICRF heating power (and hence W/I_p) and to drop below it during ohmic operation. This might be a sign that the profile is becoming more centrally peaked in the high-power cases, perhaps due to an ICRF flow drive mechanism, absent in the ohmic cases. But this trend does not appear to be universal, so its significance is as yet uncertain.

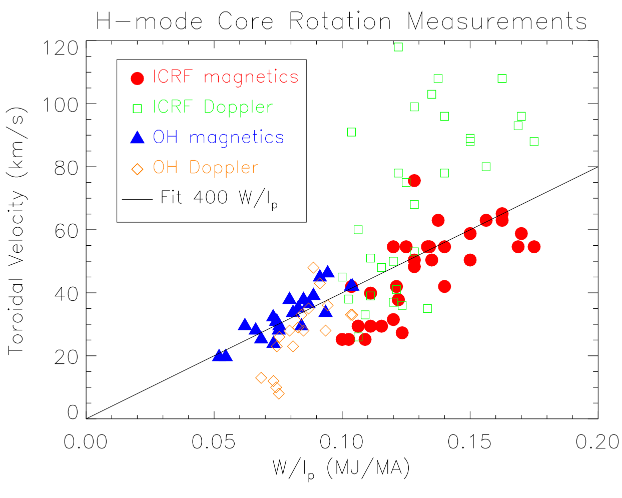

Figure 2: Comparison of H-mode rotation velocities with and without ICRF heating, as measured by the two diagnostics.

A recent experiment explored the specific predictions of some ICRF flow-drive theories [6] that the rotation they induce should reverse sign when the position of the resonance is scanned from inboard to outboard of the magnetic axis. In all cases the rotation in first 200 ms of the H-mode was in the co-current direction, at essentially a constant magnitude, showing none of the predicted effect. However, in some cases with the resonance approximately 0.1 m inboard of the axis, substantial density and temperature profile evolution during the H-mode was accompanied by a slowing and slight reversal of the core velocity after 500 ms. These phenomena are still under investigation.

3 Edge Rotation

The edge rotation is measured by observation of the propagation of broad-band magnetic fluctuations using magnetic probes mounted in the outboard limiter. These fluctuations[7] have mode numbers typically $1 \leq n \leq 8$. A well defined poloidal velocity is determined (when it exists) from the time-delay cross correlation between nearby probes separated by a few centimeters poloidally. The fluctuations are highly elongated and to within measurement uncertainties field-aligned. Therefore this measurement really measures only the poloidal component of the perpendicular velocity of the fluctuations, not distinguishing toroidal and poloidal velocities per se.

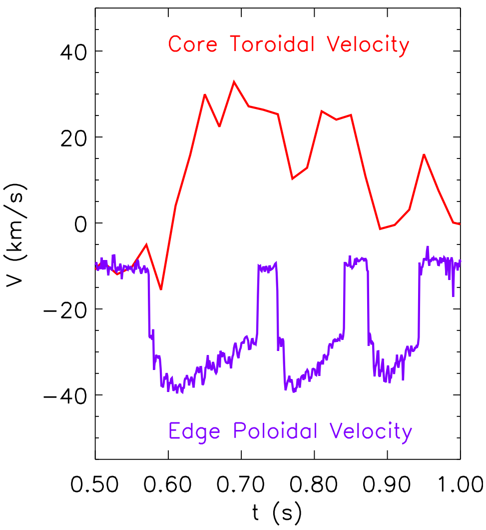

Figure 3: Simultaneous variation of the core and edge velocities as the plasma transitions in and out of H-mode.

Figure 3 shows how the core and edge velocities track as a plasma transitions in and out of H-mode. At the transitions the edge velocity responds within the time-resolution of the measurement, which is about 1 ms. The edge rotates in the electron-diamagnetic direction, or counter-I_p direction, that is, opposite to the plasma core, with a poloidal velocity that is about 4 times faster in H-mode than it is in L-mode. There is also some slower evolution of the velocity during the H-phase. The core rotation, by contrast, responds quite slowly to the transitions. It accelerates or decelerates with a time-constant of approximately 50 ms, comparable to (or perhaps slightly larger than) the energy confinement time.

The edge rotation shows substantial variation with plasma parameters. It has been shown before [7] that the edge velocity decreases as the chamber neutral pressure increases. This suggests that there may be an effect of neutral viscosity. The present measurements show a strong dependence on plasma current. In figure 4 this scaling is shown. Measurements of the height of the H-mode pedestal during these plasmas show that it also has an approximately linear dependence on current, while the pressure-gradient scale-length. λ_p is, if anything, slightly decreasing as current increases.

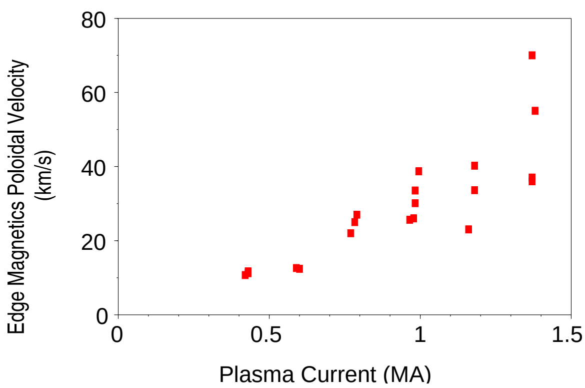

Figure 4: The edge velocity scales with plasma current.

The measured electron pedestal profiles for these plasmas then yield diamagnetic velocity $v_{dia} \sim T/eB\lambda_p \sim 20$ km/s and an equivalent electric field $E_r \sim T/e\lambda_p \sim 80$ kV/m, at 1 MA plasma current. This value is about half of the measured magnetic propagation velocity. However, recent higher-resolution measurements[8] show that the peak pressure gradient may have a scale length shorter than $\lambda_p \sim 5$ mm, used in the above estimate. In that case the diamagnetic velocity would be larger, resolving the discrepancy.

4 Discussion

In the absence of a full profile of rotation, it is not yet possible to demonstrate unequivocally that there exists a strong gradient of velocity in the core of Ohmic H-mode plasmas. The rotation is substantial, up to 10% of the sound speed, but it is conceivable that the velocity is approximately uniform in the core and that all the velocity gradient is in the edge pedestal region where the gradient scale-lengths are very short, and the radial electric field is strong. Doppler measurements [9] of intrinsic boron impurities in the pedestal region and just inside, indicate co-rotation (not counter, like the magnetics fluctuations) but substantially slower than the core, but we have not yet obtained sufficient spatial resolution to establish the ion velocity near the edge, inboard of the pedestal. This question is critical because it determines whether the self-acceleration mechanism needed to explain these results is required to oppose the momentum diffusion throughout the main plasma or only in the very complex pedestal region.

Nevertheless, it is clear that the dominant effect causing the core rotation in Alcator C-Mod is *not* an effect of auxiliary heating or direct momentum input from beams or applied RF, but rather an intrinsic rotation arising from the effects of transport. Our present results have not been able to show any effects on the rotation from the minority ICRF that can be clearly separated from the ohmic rotation mechanism.

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