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Spontaneous core toroidal rotation in Alcator C-Mod L-mode, H-mode and ITB plasmas

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Abstract
Spontaneous toroidal rotation, self-generated in the absence of an external momentum input, exhibits a rich phenomenology. In L-mode plasmas, the rotation varies in a complicated fashion with electron density, magnetic configuration and plasma current and is predominantly in the counter-current direction. The rotation depends sensitively on the balance between the upper and lower null and plays a crucial role in the H-mode power threshold. Rotation inversion between the counter- and co-current directions has been observed following small changes in the electron density and plasma current, with very distinct thresholds. In contrast, the intrinsic rotation in H-mode plasmas has a relatively simple parameter dependence, with the rotation velocity proportional to the plasma stored energy normalized to the plasma current, and is nearly always directed co-current. In plasmas with internal transport barriers, formed either with off-axis ICRF heating or LHCD, the core rotation velocity increments in the counter-current direction as the barrier evolves.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In tokamak discharges, rotation and velocity shear play important roles in the transition to the high confinement mode (H-mode) [1–5], in the formation of internal transport barriers (ITBs) [6, 7] and in suppression of resistive wall modes (RWMs) [8, 9]. On most devices, the toroidal rotation is driven externally by neutral beam injection. In future reactors such as ITER, beam injection may be of limited utility and other approaches for generation and control of rotation need to be investigated. One possible solution is to take advantage of the intrinsic (spontaneous, self-generated in the absence of an external momentum input) rotation widely observed under a variety of operating conditions [10]. A comparison of spontaneous rotation in H-mode plasmas from several devices leads to a relatively simple scaling, with the observed Mach number proportional to the normalized pressure [10].
The paper summarizes observations of toroidal rotation in Ohmic L-mode plasmas and reviews results for H-mode and enhanced L-mode rotation. The rotation in ITB plasmas is also described. The observations include the dependence of rotation on electron density, plasma current, toroidal magnetic field, and magnetic configuration. The central toroidal rotation velocity is shown as a function of average electron density for favorable and unfavorable ion drift directions. The plots indicate differences between LSN and USN configurations, with higher H-mode power thresholds for unfavorable drift at higher densities. The paper also discusses the implications of these observations for understanding spontaneous rotation and the role of impurities in plasma rotation.

2. Observed rotation in Ohmic L-mode plasmas

Toroidal rotation in Ohmic L-mode plasmas exhibits a rich and complex parameter dependence. The rotation velocity is found to be sensitive to the electron density, plasma current, toroidal magnetic field, and magnetic configuration. It is usually directed counter to the plasma current, with the magnitude ranging from $-60 \text{ km s}^{-1}$ (counter-current) to $+20 \text{ km s}^{-1}$ (co-current).

Shown in Figure 1 is the central toroidal rotation velocity as a function of average electron density for favorable and unfavorable ion $B \times \nabla B$ drift directions in L-mode plasmas with both forward and reversed magnetic field. In L-mode plasmas, the rotation is usually in the counter-current direction [23], consistent with neo-classical predictions for on-axis rotation [24]. For the $\nabla B$ drift down ($\sim$ lower portion of the plot), there is considerable difference between LSN (favorable) and USN (unfavorable) at higher densities ($\geq 1 \times 10^{20} \text{ m}^{-3}$) for these 5.4 T, 0.8 MA discharges. This difference manifests itself in the higher H-mode power threshold [11, 12, 16, 18] for the unfavorable drift. For electron densities near $1 \times 10^{20} \text{ m}^{-3}$, the velocities in LSN and USN are nearly the same, and for USN plasmas, as the density falls, the velocity reverses direction to co-current, in disagreement with the predictions of neo-classical theory. Similar and possibly related rotation inversions with density have been seen in TCV plasmas [13–15, 17]. For the $\nabla B$ drift up ($\sim$ upper portion of the plot), there is a suggestion of symmetry for USN (favorable) and LSN (unfavorable) compared with the bottom portion of the figure; for densities between 1 and $1.5 \times 10^{20} \text{ m}^{-3}$, the magnitude of the counter-current rotation is larger for the unfavorable drift. These trends reflect, and are a result of, the differences seen.
in the scrape off layer flows \[12, 16\]. For different magnetic fields and plasma currents, the dependence of rotation on the electron density and the magnetic configuration is somewhat different \[18\].

The rotation in DN plasmas can be anywhere between the LSN and USN values and depends very sensitively on SSEP, the distance between the primary and secondary separatrices \[11, 12, 18\]. The core rotation velocity as a function of SSEP, for different values of the electron density, is shown in figure 2. For negative values of SSEP, which is representative of LSN, there is little variation with the average electron density, which is consistent with the green dots shown in figure 1. For values of SSEP between 0.5 and 1.0 cm, which is trending towards USN, there is a strong dependence on density, similar to the red asterisks in figure 1. For values of SSEP between \(-0.2\) and \(+0.5\), which corresponds to different varieties of DN plasmas, there is an intermediate dependence on the electron density.

The trend of rotation direction reversal for changes in density with unfavorable drift has been observed in a single discharge by density ramping, as has been observed in TCV. Shown in figure 3 are the time histories of the electron density and central rotation velocity for a 1.2 MA, USN discharge with a density ramp beginning at 1.1 s. Similar to the TCV results (although not as abrupt in this case), there is an inversion of the rotation velocity from co- to counter-current as the electron density crosses a critical value (near 1.2 s), which for these conditions is around \(1.6 \times 10^{20} \text{ m}^{-3}\). The density value for the inversion during the density ramp down (at 0.6 s) was around \(1.45 \times 10^{20} \text{ m}^{-3}\), so there is some hysteresis. This may be due to the momentum confinement time longer than the particle confinement time.

Figure 1. The core rotation velocity as a function of the electron density for 5.4 T, 0.8 MA L-mode discharges. Red asterisks are for USN and green dots are for LSN plasmas with the \(\nabla B\) drift downward. Negative values denote counter-current rotation. Tan asterisks are for LSN and purple dots are for USN discharges with the \(\nabla B\) drift upward and with positive values for counter-current rotation. Dots are for the favorable drift direction and asterisks for unfavorable. Black diamonds are for limited plasmas.
Changes in the plasma current or the magnetic field can also lead to rotation reversal. Shown in figure 4 is the central toroidal rotation velocity as a function of the magnetic field at a constant electron density for 0.8 MA LSN (favorable drift) plasmas, during a shot-to-shot scan. As the magnetic field is lowered, the rotation velocity trends from strongly countercurrent toward zero velocity [18]. This effect may also be achieved dynamically during a
3. Observed rotation in H-mode and enhanced L-mode plasmas

Core rotation in the Alcator C-Mod (ICRF and Ohmic) H-mode (and enhanced confinement L-mode plasmas) without an external momentum input has been found to be mostly in the co-current direction [27–34]. Similar observations have been made in COMPASS-D [35] (Ohmic), JET [36] (ICRF) and DIII-D [37] (ECH and Ohmic) plasmas. An example of an ICRF heated C-Mod H-mode is shown in figure 6. There is strong co-current rotation, with a core velocity up to 70 km s\(^{-1}\), following the H-mode transition at 0.77 s. The rotation time history follows the stored energy evolution, with a delay due to the momentum transport from the edge plasma. Co-current central rotation is indicative of a positive core radial electric field.

The complete \(E_r\) profile evolution for this discharge is shown in figure 7, which is inferred from the product of the measured toroidal rotation profile and the calculated poloidal magnetic...
field. For this inner region of the plasma \((r/a \leq 0.8)\), there is no measurable poloidal rotation and the diamagnetic contribution is small because of the large value for \(Z\) for argon [27]. Before the ICRF injection at 0.7 s, the rotation is in the counter-current direction and the radial electric field is negative, with a value of around \(-15 \text{ kV m}^{-1}\) near \(r/a = 0.5\). During the fully developed H-mode phase, \(E_r\) reaches a value of \(+40 \text{ kV m}^{-1}\) near \(r/a = 0.4\).

A database containing nearly 1000 discharges has been populated from plasmas under a wide range of ‘machine’ parameters, electron density \((0.6–6 \times 10^{20} \text{ m}^{-3})\), plasma current \((0.4–1.6 \text{ MA})\), magnetic field \((2.1–7.9 \text{ T})\) and ICRF power \((0–5.5 \text{ MW})\), with forward and reverse current, in an assortment of magnetic configurations: USN, LSN, DN and inner wall limited. The best simple minded scaling with dimensional parameters for H-mode and enhanced L-mode plasmas is shown in figure 8, which depicts the change in the central rotation velocity, between L- and (EDA and ELM-free) H-modes, as a function of the change in the stored energy, normalized to the plasma current. The large points represent a simple binned average of the data points and the thin curve is the best linear fit, which is very close to \(\Delta V_{\text{tor}}(0) = \Delta W_p/I_p\). This is very similar to figure 2 of [31]. The fits as a function of \(\Delta W_p\) or \(\Delta W_p/I_p^2\) are not as good, with lower correlation coefficients. The best simple minded scaling with dimensionless parameters is shown in figure 9, which is a plot of the change in the ion thermal Mach number as a function of the change in the normalized plasma pressure, \(\beta_N\). This scaling has been found to capture the trends on several different devices [10].

4. Rotation in ITB plasmas

Previously, plasmas with ITBs have been produced in Alcator C-Mod with off-axis ICRF heating and have formed naturally in certain Ohmic H-mode discharges [31, 38–42]. These
Figure 6. Time histories (from top to bottom) of the plasma stored energy, electron density, central electron temperature, ICRF power, $D_\alpha$ brightness and central rotation velocity for a 0.8 MA ICRF heated H-mode plasma.

Figure 7. The inferred radial electric field profile evolution for an H-mode discharge.

ITBs are characterized by very peaked density profiles, which develop over a time scale considerably longer than the energy confinement time and evolve from certain H-mode discharges. Concurrent with the density peaking is a reduction and reversal (usually) of the core (inside of the ITB foot) rotation velocity. A typical example of an off-axis ICRF heated ITB discharge is shown in figure 10. In the middle frame is the density peaking factor, the ratio between the central electron density and that at $r/a = 0.7$. The usual sequence of events for ITBs induced with off-axis ICRF heating is first an L- to H-mode transition (in this case at 0.71 s), after which the electron density builds up at the edge and then fills in to a relatively
Figure 8. The change in the central toroidal rotation velocity as a function of the change in the plasma stored energy, normalized to the plasma current. The large points represent the binned average. The thin curve is the best linear fit, while the thick line has a slope of unity.

Figure 9. The change in the ion thermal Mach number as a function of the change in the normalized pressure. The large points are the binned averages, and the line is the best fit.
flat profile on a particle transport time scale. During this same interval, the toroidal rotation jumps to a co-current value at the edge, then propagates in to the center on a similar momentum confinement time scale [32, 33]. The H-mode is fully developed at 0.85 s in this discharge. The next sequence is the relatively slow (100s of milliseconds, much longer than energy, particle and momentum confinement times) peaking of the electron density and a counter-current trend of the rotation velocity, which in this plasma occurs between 0.85 and 1.4 s. Remarkably similar behavior is seen in LHCD L-mode discharges [43], as seen in figure 11. Following application of LHCD power at 0.7 s, there is a similarly slow increase in the density peaking factor and a corresponding counter-current trend in the central toroidal rotation velocity. The time scale for these events is close to the current relaxation time, but long compared with the transport times. Why the time scales for the ITB development in these two very different types of plasmas is not known.

5. Discussion and conclusions

Spontaneous rotation in C-Mod plasmas exhibits a rich phenomenology. In Ohmic L-mode discharges, the rotation is mostly in the counter-current direction, has a complex dependence on electron density, plasma current and magnetic configuration and comprises an important factor in the H-mode power threshold. A complete understanding of the H-mode transition must include the role of rotation. In H-mode and ICRF heated enhanced L-mode plasmas, the core toroidal rotation is predominantly co-current and follows a relatively simple scaling, with the rotation velocity proportional to the stored energy (pressure) normalized to the plasma current. Extrapolation of these results to ITER plasmas, with $\beta_N \geq 2.5$, suggests that the expected spontaneous rotation, with the Alfvén Mach number $M_A \geq 2\%$, may be large enough for RWM suppression without necessitating neutral beam injection. In ITB plasmas, the rotation inside the barrier foot trends in the counter-current direction and illustrates the
interplay between particle, energy and momentum transport. These discharges demonstrate a correlation between an inward particle pinch and an outward momentum pinch.

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