The dependence of core rotation on magnetic configuration and the relation to the H-mode power threshold in Alcator C-Mod plasmas with no momentum input

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Abstract

The observed toroidal rotation in Alcator C-Mod Ohmic L-mode plasmas has been found to depend strongly on the magnetic configuration. For standard discharges with a lower single null and the ion $B \times \nabla B$ drift downward, and with $B_T = 5.4$ T, $I_p = 0.8$ MA and $n_e = 1.4 \times 10^{20}$ m$^{-3}$, the core toroidal rotation is measured to be in the range of 10–20 km s$^{-1}$ (counter-current). Similar plasmas with upper single null (USN) have significantly stronger counter-current rotation, in the range 30–50 km s$^{-1}$. The rotation depends very sensitively on the distance between the primary and secondary separatrices in near double null plasmas, with changes of $\sim 25$ km s$^{-1}$ occurring over a variation of a few millimetres in this distance. Application of ICRF power has been found to increase the rotation in the co-current direction. The transition to H-mode is seen to occur in these standard plasmas when the core rotation reaches a characteristic value, near 0 km s$^{-1}$; hence higher input power is needed to induce the transition in the USN configuration.

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

1. Introduction

A long standing mystery in tokamak research is why there is a substantially higher H-mode power threshold when the X-point is directed away from the ion $B \times \nabla B$ drift direction [1–3]. This has been seen on many devices [2], and is observed in H-modes induced with neutral beam, ICRF and Ohmic heating. Several attempts have been made to explain this based on neo-classical ion cross-field fluxes driven by poloidal temperature gradients on open field lines in the Scrape-Off Layer (SOL) [4–6]. One problem with these models is that the edge ion temperature gradients have been found experimentally to be the same in both upper and lower single null (USN and LSN) configurations. Recent experiments on Alcator C-Mod have shown that the ambient L-mode SOL flows [7], which couple to the core toroidal rotation [8], depend strongly on the magnetic configuration and that this may have an important effect on the H-mode transition. For electron densities higher than $1.0 \times 10^{20}$ m$^{-3}$, 0.8 MA discharges in the USN configuration rotate significantly more counter-current relative to LSN plasmas [8]. This variation is largest in the inner SOL, suggesting that this location is the origin of the difference [7]. Auxiliary heating power in Alcator C-Mod is provided by ICRF. It has been found that the core rotation velocity increments in the co-current direction in proportion to the stored energy increase following application of ICRF heating power [9–11]. At 0.8 MA, the H-mode transition has been observed to occur when the central rotation velocity changes from counter- to co-current [7, 8]. Since these USN L-mode discharges have a larger counter-current rotation, a higher ICRF power is required to induce the H-mode transition relative to plasmas in the LSN configuration. Immediately following the H-mode transition, this co-current velocity is seen to propagate in from the plasma periphery [8, 12] (on a time scale similar to energy confinement) also suggesting that the edge is the location of the origin of the rotation. The true criterion for the H-mode transition is likely to be the velocity or velocity gradient (or $E_r$ gradient) at the plasma edge, but these profiles are not available in Alcator C-Mod for H-mode plasmas. Core observations indicate the important role of...
rotation in the H-mode transition, but in the absence of edge measurements, the exact criterion has yet to be established.

An outline of this paper is as follows: in section 2 a brief description of the experiment is given, followed by a presentation of rotation observations in L-mode plasmas in sections 3 and 5. Rotation in H-mode plasmas and the relation to the H-mode power threshold are demonstrated in section 4.

2. Description of the experiment

The observations presented here were obtained from the Alcator C-Mod tokamak [13], a compact ($R = 0.67$ m, typical minor radius $\sim 0.21$ m), high field ($B_T \leq 8$ T) device with strong shaping capabilities (elongation, $\kappa \leq 1.8$, upper and lower triangularity, $\delta \leq 0.8$) and metal plasma facing components. For the discharges described here, the ion $B \times \nabla B$ drift was downward, and the plasma was operated in four different magnetic configurations: LSN, double null (DN), USN and inner wall limited. Flux surface reconstructions from the EFIT code [14] for a near DN plasma are shown in figure 1. The primary separatrix is shown in red while the secondary separatrix is depicted in dark blue. SSEP, which is defined as the distance between these two separatrices, mapped to the outboard midplane (with negative values for lower null and positive values for upper null), was $-5$ mm for this case.

Auxiliary heating was provided with up to 3 MW of ICRF power at 80 MHz from two 2-strap antennae with $0-\pi$ phasing with an additional 3 MW at 78 MHz from a 4-strap antenna with $0-\pi-0-\pi$ phasing. There is no external momentum input in C-Mod plasmas, either Ohmic or ICRF heated. Core toroidal rotation measurements were determined from the Doppler shifts of argon x-ray lines recorded with an array of tangentially viewing x-ray spectrometers [8]. Profile coverage in the plasma interior was for $r/a = 0.0, 0.3$ and $0.6$, with a 20 ms time resolution. These core measurements were augmented by velocities in the SOL determined from a variety of Langmuir probes [7] located at different poloidal positions. Probe measurements are not usually available for H-mode plasmas because the heat load is too high, and can damage the probe tips. Electron temperature profile evolution was measured by Thomson scattering and electron cyclotron emission, and electron density profiles were provided by Thomson scattering and from visible bremsstrahlung emission [15].

3. Observed rotation in Ohmic L-mode plasmas

The ambient core L-mode toroidal rotation velocity during the steady-state phase of LSN discharges has been found to be in the range between $-5$ and $-25$ km s$^{-1}$ [8–10, 16]. Here, the minus sign indicates counter-current rotation. The core L-mode rotation velocity as a function of electron density for 5.4 T, 0.8 MA discharges is shown in figure 2. LSN plasmas (green dots) exhibit only modest variation with electron density. For USN discharges (red asterisks), the core rotation is considerably more counter-current [7,8] for electron densities above $1 \times 10^{20}$ m$^{-3}$, while the rotation is the same in both configurations below this value. Related differences in rotation velocities have been found in the SOL [7]. The difference between the rotation velocity in LSN and USN discharges is greatest ($\sim 50$ km s$^{-1}$) in the inner SOL and smallest ($\sim 15$ km s$^{-1}$) in the outer SOL [7]. The principal drive mechanism for the flows is a strong ballooning-like transport asymmetry: parallel flows arise so as to re-symmetrize the resulting poloidal pressure variation in the SOL [7]. SOL flows provide the boundary conditions for rotation in the core, which propagates in on the momentum diffusion time scale, which is comparable to the energy confinement time [8]. Interestingly, the density for which the rotation is the same in the two configurations is very close to the H-mode density threshold for 5.4 T and 0.8 MA; plasmas with a target density below $1 \times 10^{20}$ m$^{-3}$ do not enter H-mode, regardless of the ICRF power level. The inner wall gaps, triangularities, pumping and fuelling locations for LSN and USN discharges in figure 2 were all similar. There are also points from inner wall limited discharges (black $\times$s) that exhibit strong counter-current rotation, similar to the USN discharges.
Toroidal rotation in Alcator C-Mod plasmas

grad B Drift Down

Figure 2. The ambient core ($r/a = 0$) toroidal rotation velocity as a function of average electron density for 5.4 T, 0.8 MA plasmas with the ion $B \times V_B$ drift downwards. Green dots are for LSN and red asterisks are for USN. The black $\times$ s are from limited discharges.

This difference in the rotation velocity for LSN and USN can be seen dynamically in a single discharge, as shown in figure 3. For this plasma, the magnetic configuration was switched from LSN to USN between 0.6 and 0.9 s, as seen in the bottom frame plot of SSEP as a function of time. The central rotation velocity correspondingly became more counter-current at this time [8].

The L-mode rotation velocity has been found to be extremely sensitive to SSEP, as suggested by figure 3, and

Figure 4. The central rotation velocity as a function of SSEP for near DN 5.4 T, 0.8 MA discharges with an average electron density of $1.4 \times 10^{20} \text{ m}^{-3}$.

is shown in figure 4 for a series of near DN 5.4 T, 0.8 MA discharges with an electron density of $1.4 \times 10^{20} \text{ m}^{-3}$. The core rotation velocity falls by 25 km s$^{-1}$ with an SSEP variation of a few millimetres. For comparison, the characteristic width of the SOL for these discharges is of the order of 3 mm [7], about the same distance. This variation of the rotation velocity with SSEP persists out to $r/a = 0.6$, as demonstrated in figure 5. These points are for the same discharges as shown in figure 3; there is considerably more scatter, as the signal levels are lower, but the trend and magnitudes of the rotation velocities are the same at the plasma centre. Similar observations have been

Figure 5. The rotation velocity as a function of SSEP at $r/a = 0.3$ and 0.6, for the near DN discharges of figure 4.
made in the SOL [7], with the largest variation seen in the inner SOL. This sensitivity suggests that care must be taken in defining what is considered to be the DN configuration. All points in figure 4 were from nominally DN discharges; these points were not included in figure 2 because of this extreme sensitivity on SSEP, and they would fill the region between LSN and USN depending on the exact value of SSEP.

4. Rotation and the H-mode power threshold

Application of ICRF power allows access to H-mode in C-Mod [17]. It has been found that as the plasma stored energy increases following ICRF heating, the core rotation velocity increases (in the co-current direction) proportionately [9–11]. Time histories for a LSN H-mode discharge are shown in figure 6. The ICRF power was initiated at 0.7 s, but at a level below the H-mode threshold. The power was ramped up at 1.1 s, and the plasma entered H-mode at 1.139 s, with substantial increases in the stored energy, electron density and temperature and the core rotation velocity. The stored energy and rotation velocity waveforms are nearly alike. Similar results have been found in JET [18] and Tore Supra [19] plasmas. The increase in the central toroidal rotation velocity is also found to be inversely proportional to the plasma current [10, 11, 19].

A comparison of H-mode discharges in three different magnetic configurations (LSN, DN and USN) with the minimum ICRF power necessary to induce the transition is shown in figure 7. Target plasma parameters were the same for these discharges, with the exception of the core rotation velocity. After application of the ICRF heating power, there were noticeable increases in the plasma stored energy and rotation velocity, at least for the USN and DN cases, before the H-mode transition (which can be seen by the abrupt increases in the electron density traces). The ICRF power levels necessary to induce the H-mode transition were: 0.9 MW for LSN, 1.6 MW for DN and 2.9 MW for USN. The USN discharge, with a considerably higher ICRF power level required to induce the H-mode transition, eventually had a higher stored energy, H-factor (HITER-89 of 1.8 compared to 1.5 for the LSN and DN discharges) and central rotation velocity. A further comparison of plasma parameters for these three discharges, with an eye towards the edge temperature, is shown in figure 8. The times have been shifted so that the H-mode transition time is at 0 s. Following initiation of the ICRF heating pulse, in the USN case, there is an evolution (increase) of the edge electron temperature and gradient, and core rotation velocity before the H-mode transition, on a time scale (∼150 ms) longer than the energy confinement time. ITBs in C-Mod evolve on a similar time scale [11, 20, 21]; whether these time scales are related is an open question. During this time the electron density and gradient remained constant. In all three cases the H-mode transition occurred approximately when the core rotation velocity crossed through 0 km s$^{-1}$. This does not imply that the core rotation velocity passing through 0 km s$^{-1}$ is a condition for the transition; it is more probable that the edge velocity or gradient (or $E_r$ gradient) must reach a certain value. The edge rotation velocity and gradient are not measured in H-mode on C-Mod, whereas the core rotation is readily available, and with good time resolution. The core rotation has been shown to be strongly coupled to the edge value, with the rotation propagating into the centre following the EDA H-mode transition with a momentum diffusion time scale similar to the energy confinement time [8, 12]. For the particular set of conditions for the target plasmas in figure 7, 0.8 MA, 5.4 T and average electron density of $1.4 \times 10^{20} \text{ m}^{-3}$, the H-mode transition occurs when the core velocity passes through 0 km s$^{-1}$. For other plasma conditions (electron density, plasma current) the value of the core velocity at the
time of the H-mode transition has not yet been explored, and may be different. The edge electron temperature (and gradient) was a factor of two higher at the H-mode transition in the USN case, compared to LSN, as has been previously reported [3]. With a stronger counter-current rotation in USN, more ICRF power was required to raise the stored energy, and hence the rotation velocity from \(-50\) to \(0\) km s\(^{-1}\). We show in figure 9 the time the central rotation velocity passed through \(0\) km s\(^{-1}\) as a function of the H-mode transition time, for several different LSN, DN and USN discharges (with target plasma conditions similar to those for figures 7 and 8). Some of these discharges had ramps in the ICRF heating power of \(10\) MW s\(^{-1}\) and others had constant ICRF power, but at differing levels above the H-mode threshold, which may explain the differences in the absolute time of the H-mode transition. There is a good correlation between these two times, with a delay of about 20 ms, close to the momentum confinement time.

The H-mode power threshold has been carefully determined as a function of SSEP. Shown in figure 10 are the ambient L-mode central rotation velocities as a function of SSEP (similar to figure 4) for the standard discharge conditions, and the minimum additional ICRF power required for these discharges to achieve H-mode. The shapes of the trends are opposite, with the rotation velocity and threshold power being very sensitive to SSEP in near DN plasmas. There are more points in the top panel because not all of these discharges had enough ICRF power to enter H-mode.

This figure emphasises the fact that care must be taken when operating in the ‘double null’ configuration, especially in future reactor scenarios, because the H-mode power threshold changes over a factor of 2 with a variation of a few millimetres in SSEP. This distance scale is comparable to the SOL width. This may also explain the diverse H-mode power thresholds reported for DN plasmas. The parameter SSEP has been
5. Further rotation observations in Ohmic L-mode plasmas

Further evidence that the H-mode power threshold is related to the L-mode rotation velocity is presented in figure 12. The central rotation velocity is shown as a function of toroidal magnetic field for 0.8 MA LSN L-mode discharges. The core L-mode rotation velocity decreases with increasing $B_T$. This is consistent with the H-mode power threshold being proportional to $B_T$ [2, 22]; at higher magnetic field with stronger counter-current rotation, more power is required to increase the rotation velocity to near co-current.

Most of the previous discussion was for 0.8 MA, 5.4 T target discharges with an average electron density of $1.4 \times 10^{20} \text{m}^{-3}$. As was seen in figure 2, the core rotation velocity depends on the electron density, especially for USN plasmas. A similar plot of the central L-mode rotation velocity as a function of electron density for 1.0 MA discharges is shown in figure 13, for LSN, DN and USN magnetic configurations. In contrast to the 0.8 MA plasmas of figure 2, there is a strong density dependence for LSN discharges, and in all configurations, the velocity is nearly the same at an electron density of $1.4 \times 10^{20} \text{m}^{-3}$. For the DN plasmas in this figure, SSEP was close to 0 cm. A detailed study of the H-mode power threshold for 1.0 MA plasmas in the different magnetic configurations, similar to that shown in figures 10 and 11, has not yet been performed. It is evident that there is a very strong plasma current dependence (and a different density dependence) of the L-mode rotation velocity for LSN and USN discharges. This is shown in figure 14 for USN...
6. Discussion and conclusions

The ambient L-mode rotation velocity, both in the plasma centre and the SOL, has been found to depend strongly on the poloidal magnetic topology. With the ion $B \times \nabla B$ drift direction downwards, USN and inner wall limited discharges have significantly stronger counter-current rotation than do discharges with a LSN, for electron densities above $1 \times 10^{20} \text{m}^{-3}$ at 0.8 MA. The H-mode power threshold is also much higher in USN, as has been well documented on many devices. The L-mode rotation velocity depends sensitively on the distance between the primary and secondary separatrices (SSEP) in near DN configurations, with a variation of $\sim 30 \text{km s}^{-1}$ occurring over a change of a few millimetres in this distance. The SOL width is also a few millimetres in size. Application of ICRF power causes an increment in the co-current direction of the toroidal rotation velocity, in proportion to the stored energy increase. The H-mode power threshold has been found to correlate with the ambient rotation velocity of the target L-mode plasma. In 5.4 T, 0.8 MA discharges with $n_e = 1.4 \times 10^{20} \text{m}^{-3}$, the transition to H-mode occurs when the core rotation velocity becomes co-current. Since the target L-mode plasmas have a stronger counter-current rotation in USN compared to LSN, higher power is required for the L–H transition in USN. This does not imply that the core rotation velocity passing through $0 \text{km s}^{-1}$ is a condition for the transition; it is more probable that the edge velocity or gradient (or $E_x$ gradient) must reach a certain value. The edge rotation velocity and gradient are not measured in C-Mod H-mode plasmas, whereas the core rotation is readily available, and with good time resolution. The core rotation has been shown to be strongly coupled to the edge value, with the rotation propagating into the centre following the H-mode transition. In DN plasmas, the H-mode power threshold is extremely sensitive to the upper/lower boundary. The observation that the L-mode rotation velocity becomes more counter-current with increasing $B_T$ is also consistent with the H-mode power threshold proportionality with $B_T$. Any model of the H-mode power threshold should take into account the dependence of the rotation velocity and the rotation shear at the edge on the magnetic topology. The L-mode rotation velocity is found to be very sensitive to the plasma current and further experiments are planned to map out the relationship between the H-mode transition and the rotation velocity under conditions of different plasma current and electron density.

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