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 magnetic configuration. For standard discharges with a lower single null and the ion Bx▽B drift downward, and with B_T = 5.4 T, I_P = 0.8 MA and n_e = 1.4 x $10^{20}/m^3$, the core toroidal rotation is measured to be in the range of 10-20 km/s (counter-current). Similar plasmas with upper single null have significantly stronger counter-current rotation, in the range of 30-50 km/s. The rotation depends very sensitively on the distance between the primary and secondary separatrices in near double null plasmas, with changes of ~25 km/s occurring over a variation of a few millimeters 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, hence higher input power is needed to induce the transition in the upper single null configuration.

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 Bx▽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 [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 configurations. Recent experiments on Alcator C-Mod have shown that the ambient L-mode scrape-off layer flows, which couple to the core toroidal rotation, depend strongly on the magnetic configuration [7-8] and that this may have an important effect on the H-mode transition.

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

2. Experiment Description

The observations presented here were obtained from the Alcator C-Mod tokamak [9], a compact (R = 0.67 m, typical minor radius ~0.21 m), high field (B_T < 8 T) device with strong shaping capabilities (elongation, κ < 1.8, upper and lower triangularity, δ < 0.8) and metal plasma facing components. For the discharges described here, the ion Bx▽B drift was downward, and the plasma was operated in four different magnetic configurations: lower single null (LSN), double null (DN), upper single null (USN) and inner wall limited. Flux surface reconstructions from the EFIT code [10] for a near DN plasma are shown in Fig.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.

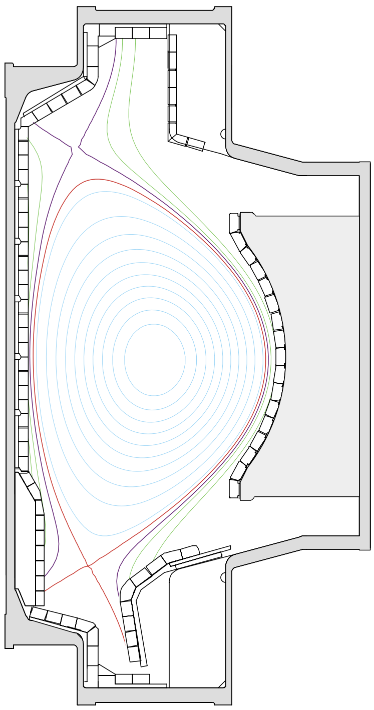

Fig.1 Magnetic flux surfaces for a near double null plasma. The primary separatrix is shown in red while the secondary separatrix is shown in dark blue. SSEP for this case was -5 mm.

Auxiliary heating was provided with up to 3 MW of ICRF power at 80 MHz from two 2-strap antennas with 0-π phasing with an additional 3 MW at 78 MHz from a 4-strap antenna with 0-π-0-π phasing. There is no external momentum input in C-Mod plasmas. Core toroidal rotation velocities were determined from the Doppler shifts of argon x-ray lines recorded with an array of tangentially viewing x-ray spectrometers [7]. Profile coverage in the plasma interior was for r/a = 0.0, 0.3 and 0.6, with 20 ms time resolution. These core measurements were augmented by velocities in the scrape-off layer (SOL) determined from a variety of Langmuir probes [8] located at different poloidal positions. 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 [11].

3. Observed Rotation in 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 [12-14,7]. 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 Fig.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 x $10^{20}/m^3$, while the rotation is the same in both configurations below this value. Related differences in rotation velocities have been found in the SOL [8]. SOL flows provide the boundary conditions for rotation in the core, which propagates in on the momentum diffusion time scale, comparable to the energy confinement time [7]. 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. There are also points from inner wall limited discharges (black Xs) which exhibit strong counter-current rotation, similar to the USN discharges.

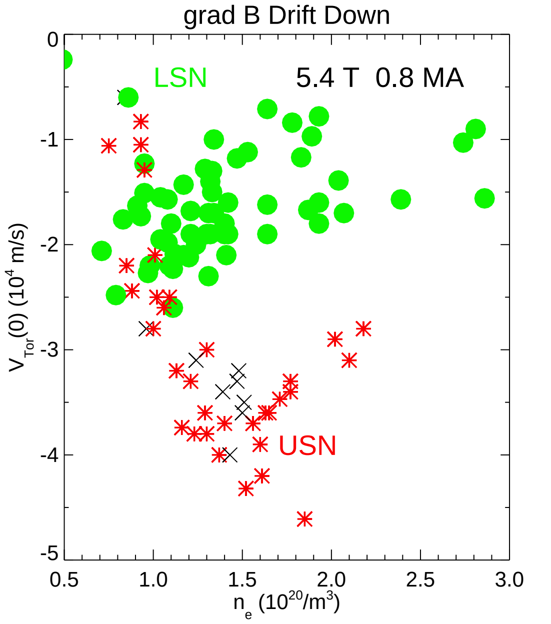

Fig.2 The ambient core (r/a = 0) toroidal rotation velocity as a function of average electron density for 5.4 T, 0.8 MA plasmas with the ion Bx ∇B drift downward. Green dots are for lower single null and red asterisks are for upper single null. The black Xs are from limited discharges.

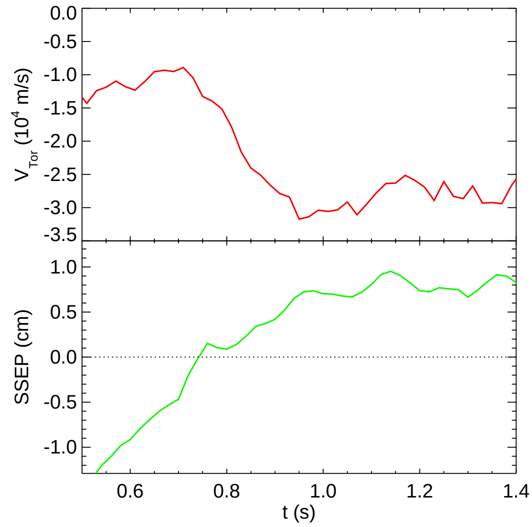

Fig.3 The core rotation velocity (top) for a discharge which changed from LSN to USN near 0.75 s. In the bottom frame is the distance between the primary and secondary separatrices, with negative for LSN and positive for USN.

This difference in the rotation velocity for LSN and USN can be seen dynamically in a single discharge, as shown in Fig.3. For this plasma, the magnetic configuration was

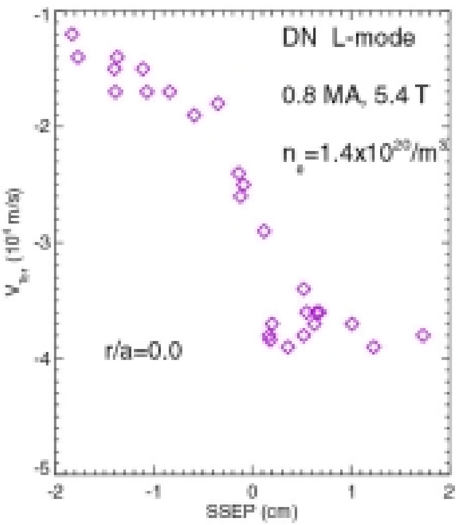

Fig.4 The central rotation velocity as a function of SSEP for near double null, 5.4 T, 0.8 MA discharges.

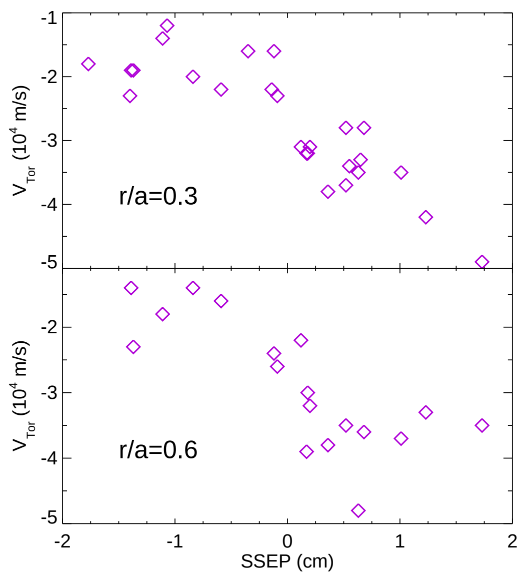

Fig.5 The rotation velocity as a function of SSEP at r/a = 0.3 and 0.6, for the near double null discharges of Fig.4.

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 [7]. The L-mode rotation velocity has been found to be extremely sensitive to SSEP, as suggested in Fig.3, and is shown in Fig.4 for a series of near DN 5.4 T, 0.8 MA discharges with an electron density of 1.4 x $10^{20}/m^3$. The core rotation velocity falls by 25 km/s with an SSEP variation of a few mm. This behavior persists out to r/a = 0.6, as demonstrated in Fig.5. These points are for the same discharges as shown in Fig.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 center. Similar observations have been made in the SOL [8]. This sensitivity suggests that care must be taken in defining what is considered to be the double null configuration.

4. Rotation and the H-mode Power Threshold

Application of ICRF power allows access to H-mode in C-Mod [15]. 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 [13,14,16]. Time histories for a LSN H-mode discharge are shown in Fig.6. The ICRF power was initiated at 0.7 s, but at a level

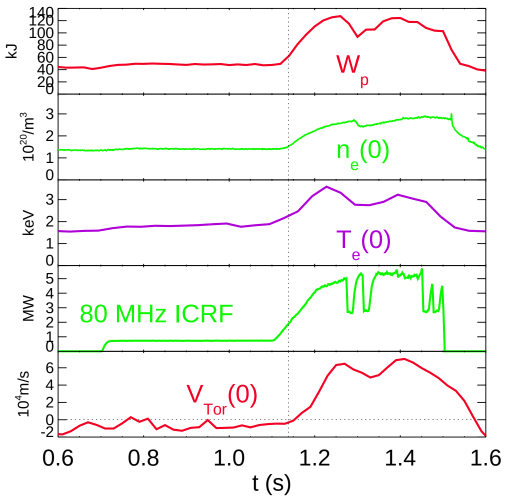

Fig.6 Time histories of (from top to bottom) the plasma stored energy, the central electron density, the central electron temperature, total ICRF power and the core toroidal rotation velocity for a LSN discharge. The H-mode transition time was at 1.139 s.

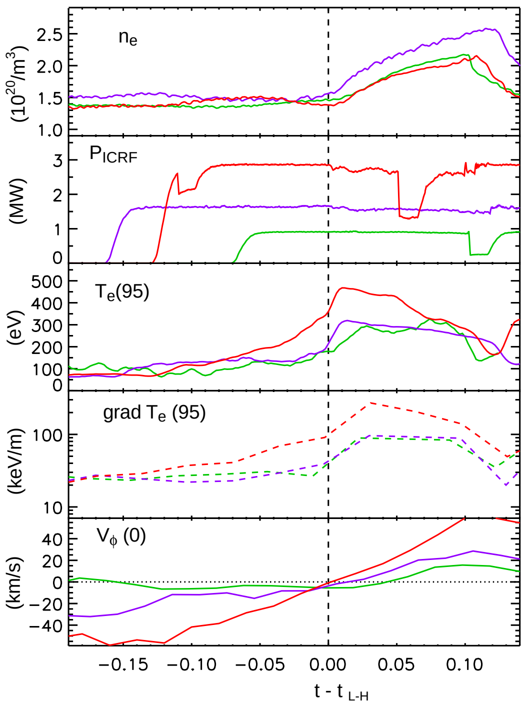

Fig.7 Time histories of (from top to bottom) the electron density, ICRF power, electron temperature at the Ψ=0.95 surface, electron temperature gradient at the Ψ=0.95 surface and the core toroidal rotation velocity for discharges with LSN (green), DN (purple) and USN (red).

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. Similar results have been found in JET [17] and Tore Supra [18] plasmas. The increase in the central toroidal rotation velocity is also found to be inversely proportional to the plasma current [14,16,18]. 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 Fig.7. 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 [16,19,20].) During this time the electron density and gradient remained constant. In all three cases the H-mode transition occurred about when the core rotation velocity crossed through 0 km/s. This does not imply that the core rotation velocity passing through 0 km/s is a condition for the transition; it is more likely the edge velocity or gradient (or E_r gradient) which must reach a certain value. The edge rotation velocity and gradient are not routinely measured 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 in to the center following the EDA H-mode transition with a momentum diffusion time scale similar to the energy confinement time [21,7]. For the particular set of conditions for the target plasmas in Fig.7, 0.8 MA, 5.4 T and average electron density of 1.4 x $10^{20}/m^3$, the H-mode transition occurs when the core velocity passes through 0. 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 km/s to 0 km/s.
The H-mode power threshold has been carefully determined as a function of SSEP.

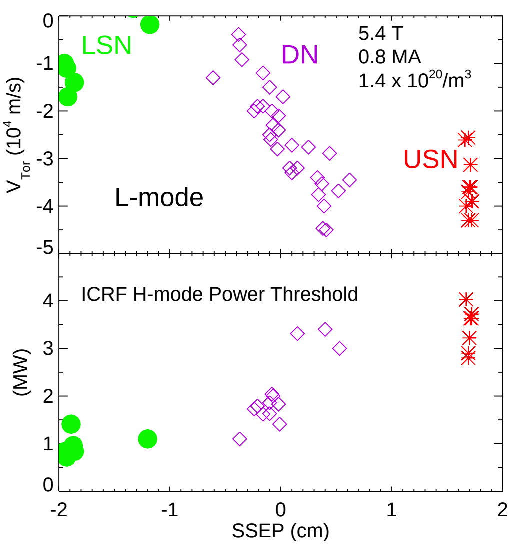

Fig.8 The central toroidal rotation velocity during the L-mode portion of LSN (green dots), DN (purple diamonds) and USN (red asterisks) 0.8 MA, 5.4 T discharges with n_e = 1.4 x $10^{20}/m^3$ as a function of SSEP is shown in the top frame. In the bottom is the minimum ICRF power required to induce the L-H transition as a function of SSEP, for several of these same discharges.

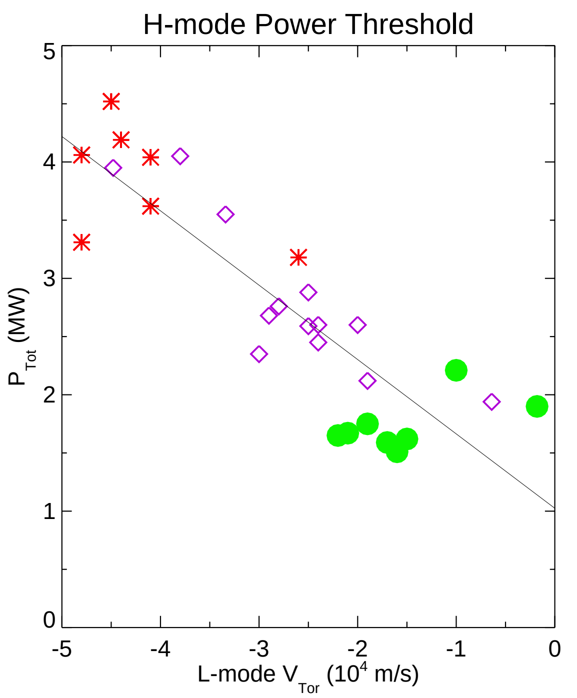

Fig.9 The total power level (ICRF and Ohmic) required to enter H-mode as a function of the central L-mode toroidal rotation velocity of the target plasma for LSN (green dots), DN (purple diamonds) and USN (red asterisks) 0.8 MA, 5.4 T discharges.

Shown in Fig.8 are the ambient L-mode central rotation velocities as a function of SSEP (similar to Fig.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. The parameter SSEP has been eliminated between the two panels in Fig.8 and the total H-mode threshold power (ICRF plus Ohmic) as a function of the central L-mode target plasma rotation velocity is shown in Fig.9. This figure emphasizes that the effect of the upper/lower null balance on the power threshold may well be due to the ambient rotation velocity. Points from all three discharge types are well mixed.

5. Discussion and Conclusions

The ambient L-mode rotation velocity, both in the plasma center and the scrape off layer, has been found to depend strongly on the magnetic topology. With the ion $B\times\nabla B$ drift direction downward, upper single null and inner wall limited discharges have significantly stronger counter current rotation than do discharges with a lower single null. 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 in near double null configurations. 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 transition to H-mode has been found to occur when the core rotation velocity becomes co-current, and the H-mode power threshold decreases with the ambient rotation velocity of the target L-mode plasma, regardless of magnetic configuration. Any model of the H-mode power threshold should take into account the dependence of the rotation velocity on the magnetic topology.

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