Observations of anomalous momentum transport in Alcator C-Mod plasmas with no momentum input

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Abstract

Anomalous momentum transport has been observed in Alcator C-Mod tokamak plasmas. The time evolution of core impurity toroidal rotation velocity profiles has been measured with a tangentially viewing crystal x-ray spectrometer array. Following the L-mode to EDA (enhanced Dα) H-mode transition in both Ohmic and ion cyclotron range of frequencies heated discharges, the ensuing co-current toroidal rotation velocity, which is generated in the absence of any external momentum source, is observed to propagate in from the edge plasma to the core with a timescale of the order of the observed energy confinement time, but much less than the neo-classical momentum confinement time. The ensuing steady state toroidal rotation velocity profiles in EDA H-mode plasmas are relatively flat, with $V_\phi \sim 50 \text{ km s}^{-1}$, and the momentum transport can be simulated using a simple diffusion model. Assuming that the L–H transition produces an instantaneous edge source of toroidal torque (which disappears at the H- to L-mode transition), the momentum transport may be characterized by a diffusivity, with values of $\sim 0.07 \text{ m}^2 \text{s}^{-1}$ during EDA H-mode and $\sim 0.2 \text{ m}^2 \text{s}^{-1}$ in L-mode. These values are large compared to the calculated neo-classical momentum diffusivities, which are of the order of $0.003 \text{ m}^2 \text{s}^{-1}$. Velocity profiles of ELM-free H-mode plasmas are centrally peaked (with $V_\phi(0)$ exceeding $100 \text{ km s}^{-1}$ in some cases), which suggests the presence of an inward momentum pinch; the observed profiles are consistent with simulations including an edge inward convection velocity of $\sim 10 \text{ m s}^{-1}$. In EDA H-mode discharges which develop internal transport barriers, the velocity profiles become hollow in the centre, indicating the presence of a negative radial electric field well in the vicinity of the barrier foot. Upper single null diverted and inner wall limited L-mode discharges exhibit strong counter-current rotation (with $V_\phi(0) \sim -60 \text{ km s}^{-1}$ in some cases), which may be related to the observed higher H-mode power threshold in these configurations. For plasmas with locked modes, the toroidal rotation is observed to cease ($V_\phi \lesssim 5 \text{ km s}^{-1}$).

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1. Introduction

Rotation and velocity shear play important roles in the transition to high confinement mode (H-mode) [1–5], in the formation of internal transport barriers (ITBs) [6] and in the suppression of resistive wall modes [7] in tokamak discharges. Compared to energy and particle transport, however, there has been considerably less effort addressing momentum transport. In a majority of tokamak plasmas, the toroidal rotation is generated externally by neutral beam injection. By measuring the rotation profiles from the associated beam diagnostics, and calculating the input torque profiles from the beam injection, momentum transport may be characterized [8–15]. Momentum confinement is generally found to be anomalous, with a diffusivity, $\chi_\phi$, similar to the ion thermal conductivity, $\chi_i$, but much larger than the neo-classical diffusivity (viscosity). The reliability of this type of analysis relies on the accuracy of the input torque calculations, and the inherent assumption that there is no additional source of momentum when the plasma enters H-mode. Alcator C-Mod ion cyclotron range of frequencies (ICRF) heated [16, 17] and Ohmic [16, 18, 19] H-mode discharges are found to have substantial spontaneous co-current toroidal impurity rotation (as high as $100 \text{ km s}^{-1}$, Mach number 0.3) in spite of the fact that there is no momentum input. Similar observations have been made on other devices such as JET [20, 21], COMPASS [22] and Tore Supra [23–25]. Several attempts to explain the observed rotation in C-Mod have been made, based on...
ICRF wave driven fast particle orbit shift mechanisms [26–29], turbulence [30, 31] and sub-neo-classical [32] effects. The similarity of the rotation observed in ICRF and purely Ohmic plasmas suggests that it is not due to ICRF wave or fast particle effects. The prediction of reversal of the rotation direction with high magnetic field side (HFS) off-axis ICRF absorption [27, 29] has not been observed in the experiments [33]. For the turbulence driven theories [30, 31], the sign of the rotation is correct, but the magnitude cannot be tested because the turbulence fluctuation levels are not measured. The predictions of the rotation magnitude and direction from the sub-neo-classical theory agree with the measurements [32], but this may be fortuitous since the calculated momentum diffusion timescale is two orders of magnitude larger than what is observed.

In order to gain a better understanding of the mechanism generating the rotation in the absence of an external source, and to characterize momentum transport, in general, temporally resolved velocity profiles are needed. In the absence of neutral beam based diagnostics, a new tangentially viewing x-ray spectrometer array has been installed on Alcator C-Mod in order to provide this information. An outline of this paper is as follows: a brief description of the experiment and the spectrometer array is provided in section 2. Observed rotation profile evolution in H-mode plasmas is presented in section 3, along with modelling in section 4. Rotation profiles for L-mode discharges in a variety of magnetic configurations are given in section 5. A discussion placing momentum transport in the context of previously measured particle, impurity and energy transport is given in section 6, with conclusions presented in section 7.

2. Experiment and spectrometer description

The rotation observations were obtained from the Alcator C-Mod tokamak, a compact (major radius 0.67 m, typical minor radius 0.21 m), high magnetic field ($B_T \leq 8$ T) device with strong shaping capabilities and all metal plasma facing components. Auxiliary heating is available with 4 MW of ICRF heating power at 80 MHz, which is coupled to the plasma by 2 two-strap antennae. For the plasmas described here, the hydrogen minority heating was with a $0 - \pi$ phasing, and there was no momentum input. An additional 4 MW of ICRF power is available at 78 MHz from a variable phase four-strap antenna; for the cases described here, this antenna was operated with a $0 - \pi - 0 - \pi$ phasing, again with no momentum input. Previous off-axis toroidal rotation measurements from the Doppler shifts of argon x-ray lines on Alcator C-Mod were from x-ray spectrometers with only a slight toroidal view [16], so only large rotation velocities could be seen, and even then, only with poor time resolution. The von Hamos type x-ray crystal spectrometer system has now been modified with three fully tangential views, vertically displaced to provide three points on the rotation profile. The spectrometer arrangement around the device is shown in figure 1. The three spectrometers at C, F and K ports have views which are tangential to $R = 0.685$ m; the C port spectrometer is on the mid-plane while the F and K port spectrometers are vertically displaced by 0.09 m and 0.18 m, respectively. The tangency points of these views superimposed on a (typical) magnetic flux plot are shown in figure 2, along with the mapping to the outboard horizontal mid-plane, which demonstrates the profile coverage at $r/a = 0.0, 0.3$ and 0.6. The spatial resolution of these spectrometers is 1.5 cm, determined by the slit, crystal and detector heights. The central chord spectrometer observes the Ar$^{17+} \text{Ly}_\alpha$ doublet while the off-axis spectrometers monitor the Ar$^{16+}$ forbidden line, $z$ [16]. These three rotation measurements are augmented by the velocity of magnetic perturbations associated with sawtooth oscillations recorded with an array of fast pickup coils [18]. This provides rotation information at the $q = 1$ surface,
which is typically near $r/a \sim 0.2$. For all the discharges presented here, the observed sawtooth inversion radii were in the range of $0.17 \leq r/a \leq 0.23$. Electron density profiles were determined by Thomson scattering and from the visible continuum using a high spatial resolution imaging CCD system [34]. Electron temperature profiles were determined from Thomson scattering and from electron cyclotron emission (ECE). Magnetic flux surface reconstructions were provided from the EFIT code [35].

3. Observed rotation profile evolution in H-mode plasmas

Previous measurements of toroidal rotation velocities in Alcator C-Mod H-mode plasmas, in the co-current direction and in the range of 20–120 mm s$^{-1}$, have been largely restricted to the plasma centre [16, 17, 33]. In going from L-mode to both Ohmic and ICRF H-mode, the change in the core rotation velocity was found to be proportional to the increase in the plasma stored energy normalized to the plasma current. Reversing the plasma current direction reverses the toroidal rotation direction. With the new tangential spectrometer array, a variety of different velocity profile shapes has been revealed. Shown in figure 3 are the time histories of the impurity toroidal rotation velocities at three radii and the rotation of magnetic perturbations in pre- and post-cursors of sawtooth oscillations, for a 2.0 MW ICRF heated EDA H-mode plasma [36]. This 0.8 MA, 5.3 T discharge entered EDA H-mode at 0.655 s, as indicated by the drop in the $D_\alpha$ signal, with a subsequent increase in the plasma stored energy and toroidal rotation velocity [16, 17]. The velocity increase was first seen on the outermost spectrometer ($r/a = 0.6$), sequentially moving inwards, suggesting an edge source of toroidal momentum which propagated in towards the centre, with a timescale somewhat longer than $\tau_E$, the energy confinement time. Typical error bars are shown in figure 3, which are determined largely by statistical variation in the fit to the line shapes [16]. After about 150 ms (at 0.8 s), the rotation settled to a value of $\sim 50$ mm s$^{-1}$ (in the co-current direction), with a flat profile. The fact that the rotation velocities for argon ions and $m = 1$ perturbations are the same in the steady state bolsters the argument that it is the bulk plasma rotation being measured [16, 18]. During this steady phase of the discharge, the central electron density was $2.8 \times 10^{20}$ m$^{-3}$ and the central electron temperature was 2.1 keV. A similar velocity profile evolution has been seen in purely Ohmic EDA H-mode plasmas. This time evolution and flat steady state rotation profile suggest that the momentum transport in EDA H-mode plasmas may be characterized by a purely diffusive process. The situation is different in ELM-free H-mode plasmas, as can be seen in figure 4. This 0.8 MA, 4.6 T discharge entered ELM-free H-mode at 0.624 s, reverted to L-mode at 0.834 s, then re-entered ELM-free H-mode at 0.871 s. Following both L–H transitions, there was a rapid increase in the core rotation velocity and stored energy. In contrast to the EDA H-mode case, these rotation profiles are highly peaked (as in figure 11 of [16]), reaching $\sim 70$ mm s$^{-1}$ in the core (again in the absence of external momentum input) and $\sim 15$ mm s$^{-1}$ at $r/a = 0.6$. For such a profile to be sustained in steady state, in the presence of momentum diffusion without a central momentum source, a mechanism of inward momentum transport up the velocity gradient, an inward momentum pinch is required [13]. During the first ELM-free period, the electron temperature was relatively constant at 1750 eV, while the electron density rose continuously from 1.1 to $2.9 \times 10^{20}$ m$^{-3}$, but maintaining a flat profile. Improved energy, particle and impurity confinement is a characteristic of ELM-free discharges; whether this momentum peaking is related is an open question. In contrast to these peaked rotation profiles are the hollow profiles which develop in ITB plasmas. ITB discharges can be produced with off-axis ICRF heating [33, 37, 38], provided the resonance location is outside of

![Figure 3](image1.png)  
**Figure 3.** The plasma stored energy, impurity toroidal rotation velocity at three radii (red dots, green asterisks and purple diamonds for $r/a = 0.0, 0.3$ and 0.6, respectively), magnetic perturbation rotation (black $x$'s) at the sawtooth inversion radius ($r/a \sim 0.2$), and the edge $D_\alpha$ brightness for an ICRF heated EDA H-mode discharge.

![Figure 4](image2.png)  
**Figure 4.** The plasma stored energy, impurity toroidal rotation velocity at three radii, magnetic perturbation rotation at the sawtooth inversion radius and the edge $D_\alpha$ brightness for an ICRF heated ELM-free H-mode discharge.
$r/a = 0.5$, and the plasma first enters the EDA H-mode. These ITBs are characterized by a strong peaking of the core electron density, which evolves in conjunction with a decrease and reversal of the core toroidal rotation velocity \cite{33,37}. Shown in figure 5 are the rotation time histories for a 4.5 T, 0.8 MA EDA H-mode plasma produced with 2.2 MW of off-axis ICRF heating power at 80 MHz. Up to 0.85 s, this discharge exhibited the normal EDA H-mode rotation characteristics (figure 3) with the rotation propagating in from the outside, and the profile becoming flat across most of the plasma. After 0.85 s, the core rotation inside $r/a = 0.5$ (the location of the barrier foot) dropped and reversed direction (similar to figure 7 of \cite{40}). A positive velocity gradient in the vicinity of the barrier foot, decreased more slowly and not so far, indicating a positive velocity gradient in the vicinity of the ITB foot. The radial electric field, $E_r$, determined from the force balance equation and from calculations of the poloidal magnetic field (using equation (37) of \cite{39}), which is rewritten as equation (1) in \cite{17}), was found to be $-8 \text{kV m}^{-1}$ at $r/a = 0.3$ (inside of the ITB foot) and $8 \text{kV m}^{-1}$ at $r/a = 0.6$ (outside of the foot), and a lower limit of the $E_r$ gradient is $\sim 250 \text{kV m}^{-2}$ at 1.1 s (see figure 7 of \cite{40}). A positive $E_r$ gradient at the barrier foot is a common characteristic of ITB discharges. The toroidal rotation velocity profiles for the previously described variety of H-mode plasmas are summarized in figure 6. In the top frame are profiles from two different ELM-free H-mode discharges demonstrating the central peaking; the green points are from figure 4 at 0.77 s. In the middle frame are profiles from two different EDA H-mode plasmas exhibiting flat shapes, at least up to $r/a = 0.6$; the green points are from figure 3 at 0.9 s and the red asterisks are from figure 5 at 0.85 s. In the bottom frame is the hollow profile from the ITB discharge of figure 5 at 1.07 s.

4. Modelling of rotation in H-mode plasmas

The evolution of the toroidal rotation velocity profiles has been simulated using a simple source-free momentum transport model \cite{41}

$$\frac{\partial}{\partial t} P + \text{grad} \left( -D_\phi \frac{\partial}{\partial r} P - v_\phi P \right) = 0$$ \hspace{1cm} (1)

with $P = n_i m_i V_\phi$ and $v_\phi = v_c r/a$, where $a$ is the minor radius and where the momentum diffusivity, $D_\phi$, and the momentum convection velocity, $v_c$, are free parameters to be determined. Positive $v_c$ indicates inward convection. Subject to the boundary conditions of an edge rotation, $V_\phi$, which is present only during H-mode

$$V_\phi(a, t) = \begin{cases} 0, & t < t_{L \rightarrow H} \\ V_0, & t_{L \rightarrow H} \leq t \leq t_{H \rightarrow L} \\ 0, & t > t_{H \rightarrow L} \end{cases} \hspace{1cm} (2)$$

and with the assumptions (observed in the electrons) of a flat ion density profile and constant (spatially and temporally) $D_\phi$ and $v_c$, the toroidal rotation velocity, $V_\phi$, profile evolution may be determined (in cylindrical coordinates) from a solution of the equation

$$\frac{\partial}{\partial t} V_\phi - D_\phi \left[ \frac{\partial^2}{\partial r^2} V_\phi + \left( \frac{1}{r} + \frac{v_c r}{a D_\phi} \right) \frac{\partial}{\partial r} V_\phi + \frac{2 v_c}{a D_\phi} V_\phi \right] = 0$$ \hspace{1cm} (3)

via an expansion in confluent hypergeometric functions.

An example of a comparison of this model to the observed velocity time evolution in an EDA H-mode plasma similar to that presented in figure 3 is shown in the top frame of figure 7. The time of the L- to H-mode transition was 1.11 s. The three curves represent the simulated rotation velocities at the radii of the three spectrometer views. For this case, $D_\phi$ was
spatially constant with a value of 0.05 m² s⁻¹, and \( v_c \approx 0 \), which corresponds to a momentum confinement time, \( \tau_0 \), of 150 ms, and \( V_0 \) was 65 km s⁻¹, compared to −5 km s⁻¹ during L-mode. This momentum diffusivity is much greater than the neo-classical viscosity [42], \( \chi_0 \sim \rho_i^2/\tau_{ii} \sim 0.003 \) m² s⁻¹ for this case, and the momentum transport may be characterized as anomalous. The momentum diffusivity may also be determined for L-mode from the decay of the rotation velocity after the H- to L-mode transition at 1.53 s; \( D_\phi \) for the L-mode portion of this discharge was 0.20 m² s⁻¹, with \( \tau_0 \sim 35 \) ms.

From the modelling of several ICRF and Ohmic EDA H-mode plasmas, \( D_\phi \) was found to be in the range from 0.05 to 0.10 m² s⁻¹, with \( v_c \approx 0 \), and \( \tau_0 \) in the range from 70 to 150 ms. The simulations for the ELM-free discharge from figure 4 are shown in the bottom frame of figure 7, which is on the same timescale as the top frame for comparison. In this instance \( D_\phi \) was 0.40 m² s⁻¹ with \( v_c = 12 \) m s⁻¹ and \( \tau_0 \approx 70 \) ms and with \( V_0 = 85 \) km s⁻¹, compared to −10 km s⁻¹ during L-mode. This value of the pinch velocity was necessary to match the quasi-steady peaked profile shape at 0.8 s (shown in figure 6), with a ‘peaking factor’ [43], \( S \equiv a v_c/2D_\phi = 3.2 \), along with the overall rise time of the rotation. From the rotation decay after the H- to L-mode transition (from 0.82 to 0.88 s), a value of \( D_\phi \sim 0.25 \) m² s⁻¹ was determined. From the rotation decays in many discharges after the H- to L-mode transition (both EDA and ELM-free), \( D_\phi \) for L-mode was determined to be in the range from 0.20 to 0.25 m² s⁻¹, with \( v_c = 0 \).

The model of equation (3) cannot be strictly applied to the ITB case in figure 5 because the electron (ion) and argon density profiles [37] were peaking in the core during the barrier evolution. However, along with the negative rotation velocity inside of the barrier foot, this implies a negative momentum density in the core, which would require an outward momentum convection in the core in the ITB phase.

5. Rotation in Ohmic L-mode plasmas

In the two previous sections, the toroidal rotation velocity profiles in H-mode plasmas were characterized. L-mode discharges also display a wide variety of behaviour, although mostly in the counter-current direction. Earlier rotation observations of C-Mod discharges documented the counter-current rotation in Ohmic L-mode plasmas [44]. During the steady state phase of lower single null (LSN) diverted plasmas, the central rotation velocity was found to be in the range of −5 to −20 km s⁻¹ [16, 17, 44]. (Here, the minus sign indicates counter-current rotation.) This range in velocities is largely due to electron density variation. The magnetic configuration also has a strong effect on the magnitude of the counter-current rotation. This is demonstrated in figure 8, which shows a comparison of two otherwise similar discharges which began with a LSN then switched to upper single null (USN). In the bottom frame is the distance between the primary and secondary separatrices (SSEP), mapped to the midplane. When SSEP is negative, the plasma has a LSN; when SSEP is 0, the discharge has a double null (DN); and when SSEP is positive, there is an USN. The only difference between these two discharges was the timing of the USN transition. When each plasma switched to USN, there was a significant drop (an increase in the counter-current direction) in the central rotation velocity. These discharges both had the ion grad B drift downward. Presumably, the change of ion orbits at the edge of the USN configuration led to a negative core \( E_r \) and stronger counter-current rotation. Strong counter-current rotation is also observed in the inner wall limited configuration. Shown in figure 9 is a comparison of parameter time histories for similar successive discharges, in green for a LSN discharge and in red for an inner wall limited plasma. The plasma parameters were similar, the inner wall limited discharge was rotating at −40 km s⁻¹. The electron density also has a strong effect on the observed rotation velocity in L-mode discharges. Shown in figure 10 are electron density and toroidal rotation...
velocity profiles for two successive 6.2 T, 0.8 MA inner wall limited discharges. The higher density plasma (green) had a flat velocity profile ($\sim-20$ km s$^{-1}$) while the lower density discharge (red) had a strongly peaked profile with a central value of $-55$ km s$^{-1}$. The profile shown in red is nearly opposite to the peaked profiles in ELM-free H-modes shown in figure 6 and is suggestive of a momentum pinch, albeit in the counter-current direction. This larger counter-current rotation at the centre of lower density Ohmic L-mode discharges is in qualitative agreement with the predictions of neo-classical theory (equation (56) of [39]).

One feature of C-Mod H-mode plasmas is the co-current toroidal rotation associated with the stored energy increase after the L–H transition. In fact there is a strong correlation between rotation velocity and H-factor (figure 10 of [16]). It is possible that for limited and USN diverted discharges, which exhibit significant counter-current rotation, the rotation increase which ensues after ICRF injection is not enough to be significantly co-current, so the plasma remains in L-mode. This notion is demonstrated in figure 11, which shows a comparison between parameters in two similar discharges, one with a DN and the other an USN. The target parameters and ICRF power (1.5 MW) were the same in both these 5.4 T, 0.8 MA deuterium plasmas. The DN discharge (green, with SSEP near 0) entered EDA H-mode at 0.85 s with the usual increases in stored energy, electron density and toroidal rotation velocity (which was strongly co-current). The USN discharge (red, with SSEP positive) exhibited an increase in the rotation velocity, but since the target plasma was rotating at $-40$ km s$^{-1}$, the final level was barely co-current. If a large enough edge velocity gradient is required to be present to make the transition, apparently it was not enough for this plasma to enter H-mode. The strong counter-current rotation observed in USN and limited discharges may be related to the higher power threshold for plasmas in these configurations to make the L–H transition.

In discharges with locked modes, the toroidal rotation has been observed to stop [45, 46]. Similar behaviour has also been seen in C-Mod plasmas. Shown in figure 12 are parameter time histories for an Ohmic L-mode discharge, which developed a locked mode at $\sim$0.96 s. The locked mode formation was accompanied by a drop in stored energy and electron temperature, disappearance of sawtooth oscillations and a braking of the toroidal rotation velocity. These modes occur in C-Mod plasmas with low density and high plasma current. In this particular case, all these events occurred at about the same time. Another example of a locked mode plasma is shown in figure 13. In this instance, the central rotation ceased before the disappearance of the sawtooth oscillations. The rotation stopped in less than 20 ms, which, interestingly, is shorter than the L-mode momentum confinement time. The evolution of most C-Mod locked modes includes a double sawtooth event (1.15 s) followed by an increase in the sawtooth event.
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Figure 12. The plasma stored energy (top frame), electron temperature (middle frame) at the centre (red) and $r/a = 0.3$ (green) and the toroidal rotation velocity (bottom frame) at $r/a = 0.0$ (red) and $r/a = 0.3$ (green) for a discharge which developed a locked mode.

Figure 13. A locked mode plasma (same legend as figure 12).

period (after 1.20 s) and eventual loss of sawtooth oscillations (1.37 s). In this case, the drop in stored energy and the halt in the rotation were correlated with the sawtooth period increase. Part of the temperature profile was eroded at this time as the $q = 1$ surface moved inwards, as seen in the inversion of sawteeth at $r/a \sim 0.3$ (green).

6. Discussion

The presentation of the characteristics of momentum transport in the preceding sections may be put in context with previously measured particle, impurity and energy transport. In the progression from L-mode to EDA H-mode to ELM-free H-mode to ITB discharges, the particle diffusivity steadily drops (particle confinement increases), approaching neo-classical levels in the core in ITB plasmas. Electron density profiles in L-mode discharges are centrally peaked (with no edge pedestal), EDA H-mode plasmas have temporally and spatially constant electron density profiles inside of the edge pedestal, ELM-free H-mode plasmas exhibit steadily rising electron density profiles which maintain a flat shape and ITB discharges show a central peaking of the density profile [33,37] consistent with the neo-classical Ware pinch velocity. The same sequence of impurity confinement may be characterized as highly anomalous in L-mode, with an impurity diffusivity $D_I \sim 0.5$ m$^2$ s$^{-1}$ ($\tau_I \sim 15–25$ ms) and $D_I \sim 0.1–0.3$ m$^2$ s$^{-1}$ in EDA H-mode with $\tau_I \sim 50–150$ ms [47]. For ELM-free H-mode plasmas, the impurity confinement is long ($\tau_I \sim 1$ s) with reduced $D_I \sim 0.05$ m$^2$ s$^{-1}$) and substantial inward convection (10–100 m s$^{-1}$) at the edge [47]. In ITB discharges there is strong core impurity accumulation [37] with $D_I \sim 0.02$ m$^2$ s$^{-1}$) and $v_I \sim 100$ m s$^{-1}$ inward) close to the neo-classical values in the core plasma. Energy confinement exhibits a somewhat similar progression with $\chi_{\text{eff}}$ dropping from $\sim 1$ m$^2$ s$^{-1}$ in L-mode, to $\sim 0.5$ m$^2$ s$^{-1}$ in H-mode [36] and then as far as $\sim 0.1$ m$^2$ s$^{-1}$ (near the neo-classical level) in the core plasma during ITB operation [37]. Momentum confinement demonstrates some similarities in behaviour; there is a decrease in the momentum diffusivity from 0.20 to 0.25 m$^2$ s$^{-1}$ in L-mode to the range 0.05–0.10 m$^2$ s$^{-1}$ in EDA H-mode. Also, in ELM-free H-mode there is a strong momentum pinch, with $v_c \sim 10$ m s$^{-1}$, analogous to the observations of impurity transport. With such a large value of the inward pinch, an increase in the momentum diffusivity was required to match the profile shape and velocity rise timescale. In ITB discharges, particle, impurity and energy confinement may be characterized by transport coefficients with values similar to neo-classical levels in the core. For these discharges, however, the momentum seems to be expelled from the plasma centre, rather than having increased confinement. From a fit to the hollow ITB velocity profile in figure 6, a value of $-2.3$ is found for the peaking factor $S$. From the decay time of the core velocity in the ITB phase, $D_p$ is determined [43] to be $\sim 0.05$ m$^2$ s$^{-1}$, if the ITB foot radius is used (so these results only apply inside of the ITB), and $v_c$ is $\sim 2$ m s$^{-1}$. Due to uncertainties in the applicability of this model in the ITB case, these values may be regarded as estimates. The reason that the momentum transport in ITB discharges does not follow the behaviour of particle and energy confinement may be because these plasmas have a negative $E_i$ well in the core, and may be influenced by the fact that momentum is an odd moment of the distribution function, with directionality. The momentum transport in ITB discharges does not seem to be tied to energy confinement. A similar difference in behaviour is seen in discharges with locked modes, where the energy confinement is slightly degraded, but the momentum is lost from the plasma [45]. Representative values for the particle, impurity, momentum and thermal diffusivities in the various confinement modes are summarized in table 1, with the convection velocities (here, positive values indicate inward directed velocities) in table 2.

7. Conclusions

The time evolution of core impurity toroidal rotation velocity profiles has been measured with a tangentially viewing crystal x-ray spectrometer array. Following the L-mode to
EDA H-mode transition in both Ohmic and ICRF heated discharges, the ensuing co-current toroidal rotation velocity is observed to propagate in from the edge plasma to the core with a timescale of the order of the observed energy confinement time. The ensuing steady state toroidal rotation velocity profiles are relatively flat, with $v_\phi \sim 50 \text{ km s}^{-1}$, and the momentum transport can be simulated with a simple diffusion model, with diffusivities of $\sim 0.07 \text{ m}^2 \text{s}^{-1}$ during EDA H-mode and $\sim 0.2 \text{ m}^2 \text{s}^{-1}$ in L-mode. Velocity profiles of ELM-free H-mode plasmas are centrally peaked, which suggests the presence of an inward momentum pinch; the observed profiles are consistent with simulations including an edge inward convection velocity of $\sim 10 \text{ m s}^{-1}$. In EDA H-mode discharges which develop ITBs, the velocity profiles become hollow in the centre, indicating the presence of a negative radial electric field well in the vicinity of the barrier foot.

The momentum transport may be characterized as anomalous, with momentum diffusivities much larger than neo-classical levels. The cause of the toroidal rotation, which appears to propagate in from the plasma edge, and is generated in the absence of a momentum source, remains unexplained.

L-mode plasmas generally exhibit counter-current rotation. Inner wall limited and USN discharges have stronger counter-current rotation than lower single or DN plasmas, which may be related to their observed higher H-mode power threshold. For L-mode plasmas which develop locked modes, the rotation is seen to cease.

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