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Abstract. Recently there has been widespread attention paid to rotation and momentum transport in tokamak plasmas. Of particular interest is spontaneous (intrinsic) toroidal rotation in plasmas without external momentum input. The strong co-current spontaneous rotation in enhanced confinement regimes, with ion thermal Mach numbers up to 0.3, may allow for resistive wall mode suppression in high-pressure ITER discharges, without requiring the use of neutral beam injection. Spontaneous rotation in L-mode discharges exhibits a complex dependence on plasma parameters and magnetic configuration compared to the relatively simple scaling of Alfven Mach number $M_A \sim \beta_N$ observed in enhanced confinement plasmas. There is currently no comprehensive, quantitative explanation of this phenomenon. An accurate prediction of the expected rotation velocity profile from whatever neutral beam injection is available on ITER requires a detailed understanding of momentum transport. There have been extensive investigations into correlations between energy and momentum diffusivities, and whether there are systematic trends of the Prandtl number with plasma parameters. Of late, there has been vigorous theoretical activity regarding a possible momentum pinch that could help enhance the rotation in the plasma interior. There has been a renewed interest in poloidal rotation, especially in ITB discharges, which is generally found to be at odds with the predictions of neo-classical theory. This calls into question the common practice of the determination of E_r from toroidal rotation measurements with the assumption of neo-classical poloidal rotation.

1. Introduction

Plasma rotation and velocity shear play important roles in the transition to high confinement mode (H-mode) [1-6], in the formation of internal transport barriers (ITBs) [7-10] and in suppression of resistive wall modes (RWMs) [11,12] in tokamak discharges. Rotation is usually externally provided by the momentum input from neutral beam injection in the current generation of tokamaks. This may not be available in future reactor-grade devices due to the large machine sizes, high densities and the limitations of beam current. It has been estimated that an Alfven Mach number $M_A = 0.02$ will be required for RWM stabilization in certain ITER operational scenarii, [13,14], depending on the velocity profile and normalized pressure, β_N. This corresponds to a rotation speed of 200 km/s (30 kRad/s) in a particular ITER case with $B_T = 5.2$ T and $n_e = 6.7 \times 10^{19}/m^3$, and it is unknown whether this level of rotation will be generated from neutral beams. There are currently two approaches to this problem. The first is to utilize the best estimates of anticipated neutral beam injection for ITER and to

calculate the expected rotation velocity profile assuming a particular form for the momentum diffusivity, χ_ϕ. The usual assumption is that momentum diffusivity is equal to the ion thermal conductivity, χ_i, which has been observed in several experiments. However, since the expected beam power is possibly marginal for RWM suppression, a more accurate knowledge of χ_ϕ is desirable. There also exists evidence for an inward momentum pinch in some experiments that could enhance the internal rotation for a given input torque. In either case, a better understanding of momentum transport is necessary for an accurate evaluation of the rotation velocity in ITER from neutral beam injection. The other approach is to take advantage of the spontaneous (intrinsic) rotation observed in many tokamaks without external momentum input to provide the necessary velocity. This relies on the accuracy of extrapolation of the current observations to the ITER plasma and machine parameters. To this end a database of spontaneous rotation has been recently been assembled [15]. In section 2 observations of spontaneous rotation in a wide variety of operational scenarii will be summarized and the results of the database will be presented. In section 3 the current understanding of momentum transport will be reviewed.

2. Spontaneous Rotation

Spontaneous rotation (in the absence of external momentum input) in low confinement mode (L-mode) plasmas is often directed counter-current, and depends very sensitively on the magnetic configuration [16-18] and in a complicated fashion on other parameters, such as the plasma current, electron density and ion temperature [17-20]. While the study of spontaneous rotation in L-mode discharges is of interest in its own right (e.g. for its relation to the H-mode power threshold [17,18]), these plasmas will not be considered here, since most ignition scenarii in future devices require H-mode confinement. The spontaneous toroidal rotation in H-mode or in other enhanced confinement regimes is generally in the co-current direction [17,21-36] and has been observed on many devices and produced with a wide variety of techniques (ICRF, Ohmic, ECH), demonstrating its fundamental nature.

Substantial rotation velocities have been obtained in ion cyclotron range of frequencies (ICRF) heated plasmas on JET [22,32], Alcator C-Mod [23,24,29,30,33,17] and Tore Supra [25,28,31]. Co-current spontaneous rotation during H-mode operation was first observed in JET ICRF heated plasmas [22], where a strong correlation was found between the local angular momentum density and the ion pressure for low recycling discharges (figure 10 of Ref.[22]). Intrinsic rotation velocities as high as 60 km/s (20 kRad/s) were measured using passive x-ray spectroscopy, viewing the plasma at r/a ~ 0.35. Spontaneous rotation in ICRF heated H-mode plasmas has been studied extensively in Alcator C-Mod [37], with velocities up to 130 km/s (200 kRad/s, thermal ion Mach number M_i = 0.3) measured in discharges with no direct momentum input, also utilizing passive x-ray spectroscopy. The main C-Mod results are summarized as follows: the rotation during H-mode is in the co-current direction, changing direction, but remaining co-current when the current direction is reversed. The time histories of two discharges, with forward and reversed current, are shown in figure 1. Both plasmas enter H-mode after 0.7 s with noticeable increases in the stored energy; at the same time, the rotation switches from slightly counter-current in both cases to substantially co-current. The time history of the rotation velocity tracks the time evolution of the plasma stored energy, W_p, and not the electron density or ion temperature independently. It was not possible to change the magnetic field and plasma current directions separately. The change in the rotation velocity between L- and H-mode increases with the change in the plasma stored energy during ICRF heating and decreases with the magnitude of the plasma current, which is demonstrated in figure 2. This appears to be a common feature of spontaneous rotation in enhanced confinement regimes. The intrinsic rotation is seen to propagate in from the plasma boundary following the H-mode transition, with a momentum confinement time similar to the energy confinement time [30,17], and highly anomalous compared to neo-classical theory. This is demonstrated in the top of figure 3, which shows the velocity profile evolution at three different radii for an EDA H-mode (transition time 1.11 s) plasma. The solid curves are from a simple

momentum diffusion model with a diffusivity of 0.05 m^2/s. The rotation velocity profiles are flat in EDA H-mode and
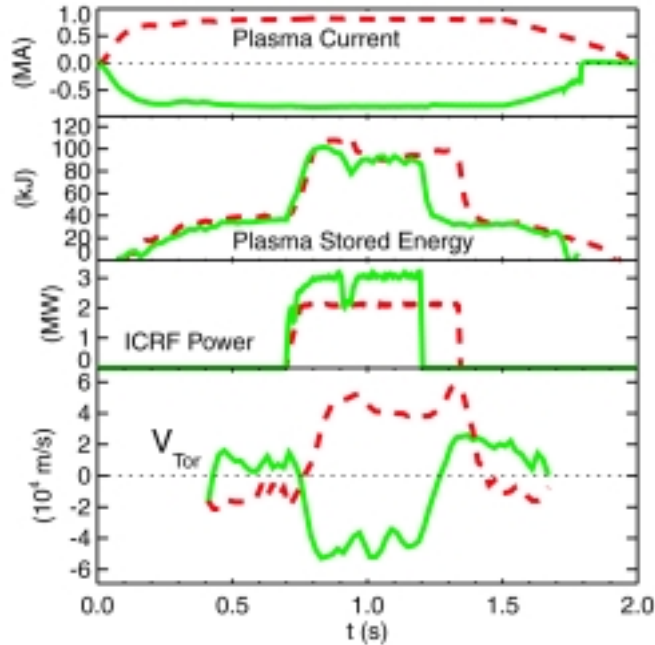

Figure 1. Time histories of the plasma current, stored energy, ICRF power and central rotation velocity for forward (red dashed) and reversed (green) current H-mode discharges.

centrally peaked in ELM-free H-mode (bottom of figure 3), implying the presence of an inward momentum pinch in the latter case of ~ 10 m/s (see next section). In Tore Supra, strong co-current toroidal rotation, with velocities reaching 80 km/s (35 kRad/s), has similarly been observed in ICRF heated enhanced confinement regimes [25,28,31], also using passive x-ray spectroscopy. A scaling similar to the C-Mod results, with the change in the rotation velocity increasing with the change in the stored energy normalized to the plasma current, has been observed (figure 3 of Ref.[31]). In this case the slope of a line through the data points is a little over a factor of two less than in C-Mod, and this presumably contains some machine size scaling information. The best correlation of the intrinsic rotation velocity in Tore Supra is with the ion pressure [25].

Co-current rotation has been seen in Ohmic H-mode discharges in COMPASS-D [27], Alcator C-Mod [24,26,27], DIII-D [34,35] and TCV. Spontaneous rotation in Ohmic H-mode plasmas has been studied extensively in C-Mod [26,27], and the observations are essentially identical to those in ICRF H-modes in terms of the scaling with W_p/I_p (see figure 2), and in the overall rotation time histories, as shown in figure 4. This is suggestive of a common driving mechanism not involving energetic ions [33]. The rotation velocity profiles during Ohmic H-modes in C-Mod and DIII-D are flat.

Similarly, co-current rotation has been observed in the outer regions (r/a~0.8) of electron cyclotron heated (ECH) H-mode plasmas on DIII-D [34,35], on JT-60U [36] with a combination of lower hybrid (LH) waves and ECH, and in TCV with core ECH [37]. In DIII-D ECH H-modes, rotation velocities as high as 30 km/s (20 kRad/s) at r/a = 0.8 have been measured. The profile shape depends on the ECH resonance location, with hollow profiles occurring under on-axis heating; no velocity increase in the plasma center over the L-mode background value is seen. Off-axis ECH leads to relatively flat (see figure 5)
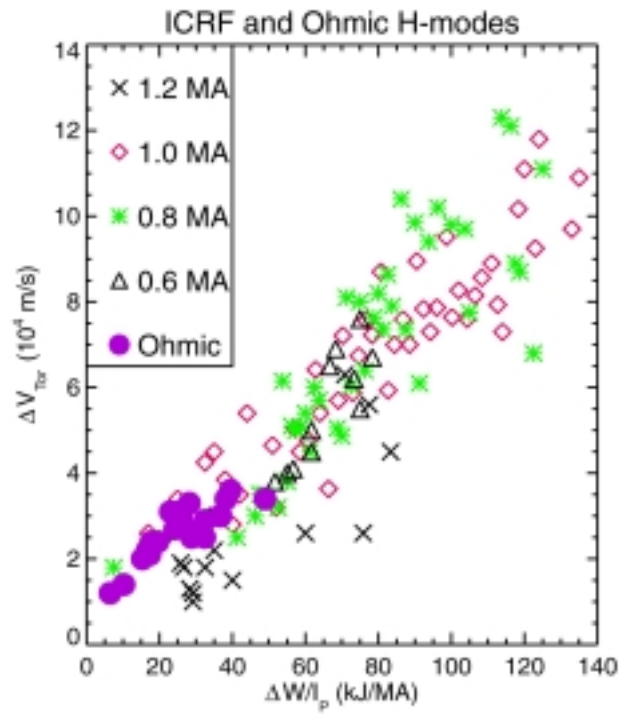
Figure 2. The change in the central rotation velocity between L- and H-mode as a function of the change in the stored energy normalized to the plasma current, for ICRF and Ohmic plasmas.
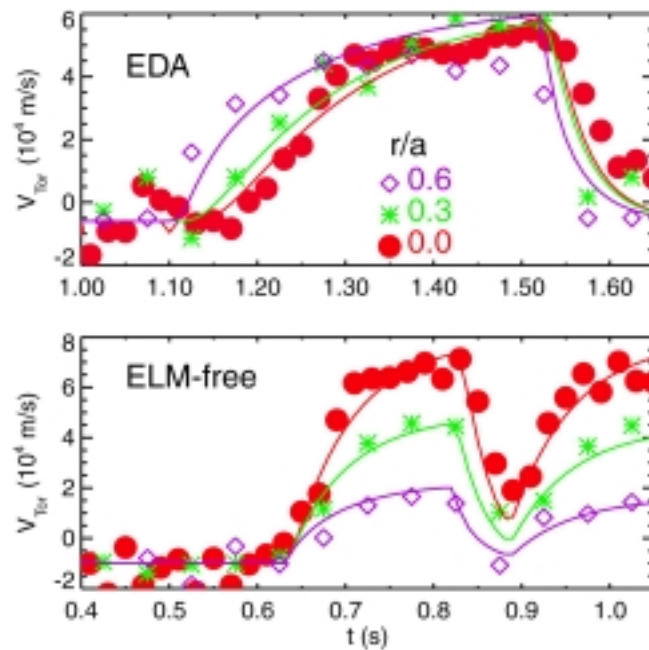

Figure 3. The rotation velocity profile evolution at three different radii for EDA (top) and ELM-free (bottom) H-mode discharges.
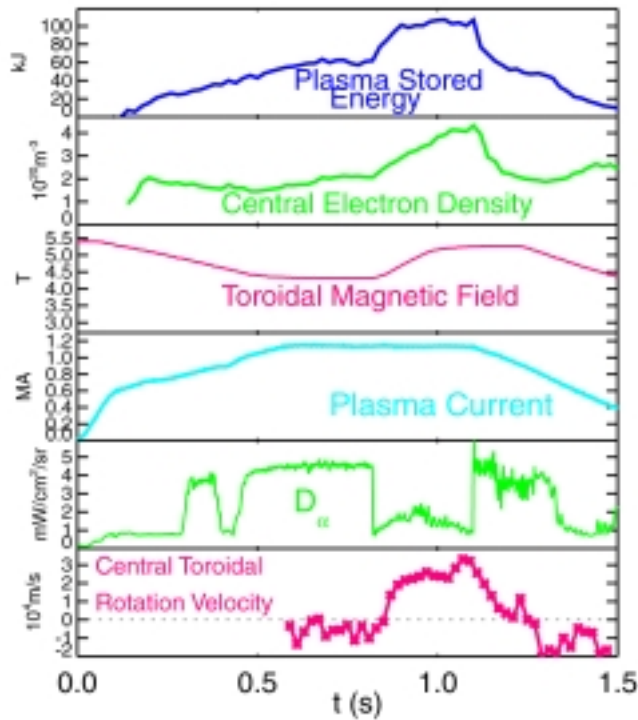
Figure 4. The time histories of plasma parameters for a C-Mod Ohmic H-mode discharge, with the transition time at 0.82 s.

velocity profiles. Regardless of the resonance location, the maximum co-current velocity increase is near r/a = 0.8. A scaling of the rotation velocity near r/a = 0.8 as a function of the plasma stored energy normalized to the plasma current in DIII-D ECH and Ohmic H-modes shows a very similar scaling to those seen in C-Mod and Tore Supra (see figure 6 top), suggesting a fundamental connection between observations of intrinsic rotation, regardless of the production technique. A slightly better fit to the DIII-D data was found multiplying W_p/I_p by $T_e(0)/T_i(0)$, as shown in figure 6 bottom. The slope of the fit is lower than that found in C-Mod and Tore Supra. Strong co-current intrinsic rotation, with velocities as high as 120 km/s (35 kRad/s), has been observed in JT-60U plasmas with a combination of LH and ECH [36], utilizing the very beginning of the heating neutral beam pulse. These discharges were at low electron density ($n_e = 4 \times 10^{18}/m^3$ and $T_e \gg T_i$), had electron temperature ITBs and exhibited slightly peaked velocity profiles. Similar to the scalings described above, there was a strong correlation between the rotation velocity and the electron pressure. Co-current spontaneous rotation has also been observed in TCV ECH H-mode [37] plasmas, with velocities up to 35 km/s (40 kRad/s) at r/a ~ 0.6 - 0.7.

Co-current spontaneous rotation has also been revealed in DIII-D neutral beam heated H-mode plasmas [35]. Using careful tuning of co- and counter-current directed neutral beam injection, H-mode plasmas have been produced which have near zero input torque profiles. These plasmas exhibit a net co-current toroidal rotation consistent with the scalings of figure 6.

A common feature of all of these observations, regardless of the heating method, is a strong correlation between the toroidal rotation velocity and the plasma pressure or stored energy. In experiments that can operate with a large range of plasma current, the rotation velocity is found to be inversely proportional to I_p. The coefficient of this scaling is different on different devices, and probably includes some machine size scaling information. In order to unify the various observations from the different tokamaks, with an eye towards extrapolation to future devices and to assist in a
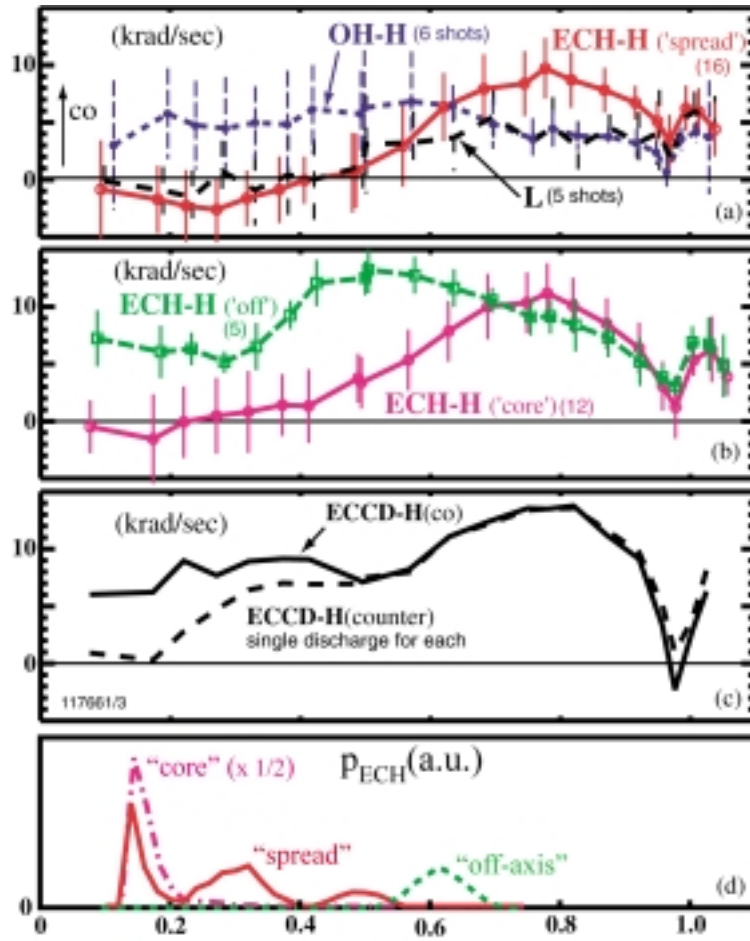
Figure 5. Rotation and ECH power deposition profiles in DIII-D.

better theoretical understanding of the process(es) driving spontaneous rotation, the approach of utilizing dimensionless parameters has been followed [15]. For the normalized velocities, the ion thermal and Alfven Mach numbers have been considered. A parameter that captures the ratio of the stored energy to the plasma current, and includes some size scaling is the normalized pressure, β_N. The scaling of M_A as a function of β_N is shown in figure 7 [15], depicting co-current toroidal rotation in H-mode and enhanced confinement regimes in C-Mod, DIII-D, JET, JT-60U, TCV and Tore Supra. (The top axis is $\beta_N/40\pi$, which is truly dimensionless.) This scaling seems to unify the results fairly well and extrapolates to $M_A \sim 3\%$ for ITER with β_N of 2.6, high enough for RWM suppression. Whether this scaling indicates that an MHD process is driving spontaneous rotation is not known. In contrast, there is no correlation of Mach number with normalized gyro-radius, as shown in figure 8; points from various machines are arranged in vertical strips. If this implies that certain turbulence effects are not involved in generating the spontaneous rotation is an open question. Similarly, there is no correlation found with collisionality [15]. A proper regression analysis has been performed with dimensionless parameters and the result is shown in figure 9 [15]; the best fit has $M_A = 0.65 \, \beta_T^{1.4} q^{*2.3}$, which has a stronger plasma current dependence than $1/I_p$. This scaling also bodes well for ITER with regard to RWM suppression. In line with this dimensionless scaling approach, a series of dimensionless similarity experiments has been undertaken between C-Mod and DIII-D [35]. In these experiments,
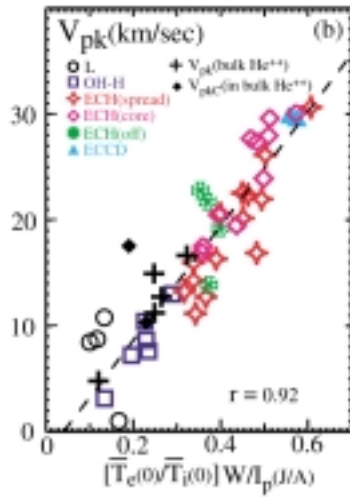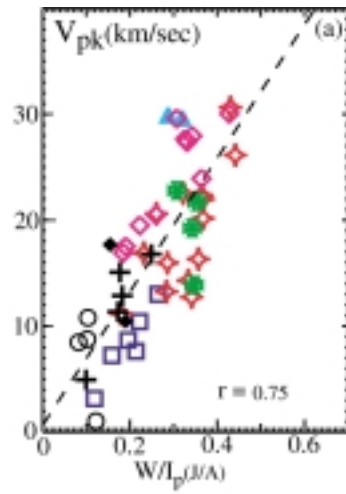
Figure 6. Rotation in DIII-D plasmas as a function of stored energy normalized to the plasma current (top) and with a factor $T_e(0)/T_i(0)$ (bottom).
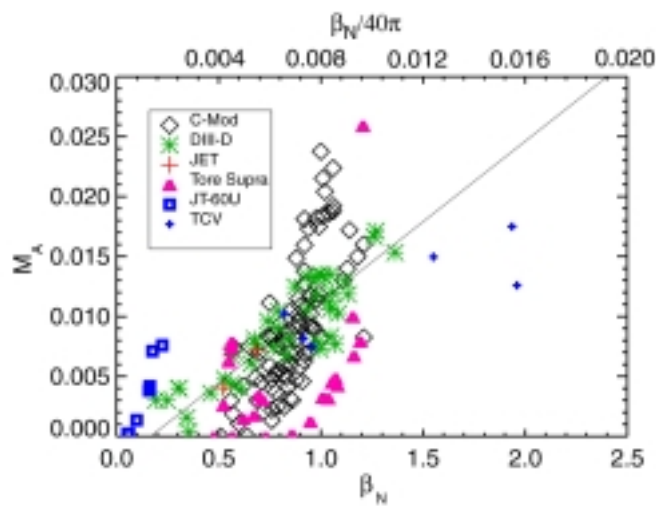

Figure 7. Alfven Mach number as a function of β_N for six devices.
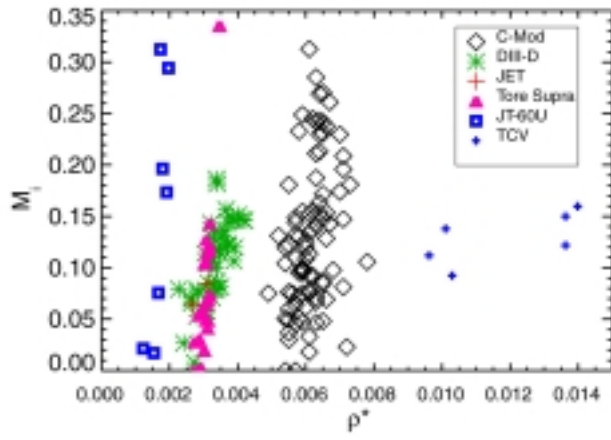
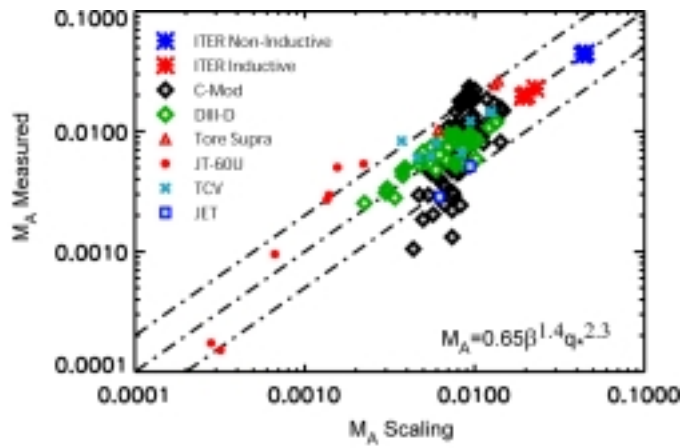**Figure 8.** Thermal Mach number as a function of $\rho*$.

Figure 9. The measured Alfven Mach number as a function of dimensionless scaling.
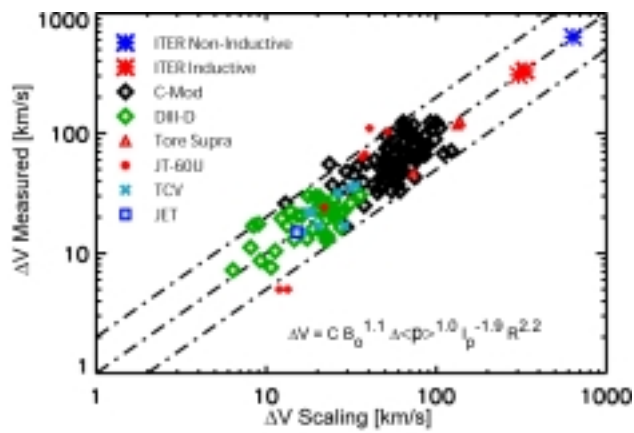

Figure 10. The measured rotation velocity as a function of the machine parameter scaling.

several different values of the dimensionless parameters q, β, $\rho*$ and $\nu*$ have been matched in discharges on both devices and the thermal Mach numbers were also found to match. The scaling from a regression analysis using dimensional machine parameters [15] is shown in figure 10, and an extrapolation to ITER predicts rotation velocities in the 100s of km/s range.

Several approaches toward an explanation of the observed intrinsic/spontaneous rotation have been undertaken. An obvious starting point is a comparison with the predictions of neo-classical theory. Using a moment formulation [38] in conjunction with radial force balance, the impurity toroidal rotation has been determined as a function of plasma parameters [39], with the toroidal rotation velocity proportional to the pressure gradient and radial electric field, and inversely proportional to the poloidal magnetic field. This captures some of the general features of the observed intrinsic rotation velocity scaling shown in figure 2: the plasma pressure or stored energy is widely found to increase with the pedestal pressure gradient, and the plasma current is directly related to the poloidal magnetic field. Unfortunately, the radial electric field is rarely measured directly (in practice it is inferred from the routinely available rotation velocity [40]) and remains largely an unknown, yet dominant, parameter. Furthermore, the standard neo-classical theory may not be valid at the edge of some H-mode discharges because the normal ordering, that the ion gyro-radius is small compared to the ion temperature gradient scale length, is violated. The sub-neo-classical theory [41,42] properly treats this situation, and has the added benefit of providing E_r from an ambipolarity constraint. The predicted toroidal rotation velocity is in reasonable quantitative agreement with observations on C-Mod [43] under certain operating conditions [33]. However, a fundamental problem with neo-classical and sub-neo-classical theory is that the momentum diffusivity [44] (viscosity) is orders of magnitude smaller than that observed in experiments [30 and references therein] (see next section).

Since the early observations of intrinsic rotation were in ICRF heated discharges, it is natural to consider models based on energetic ion orbit shift mechanisms [45-49]. However, the similarity of the intrinsic rotation observed in ICRF, ECH and purely Ohmic plasmas suggests that it is not due to ICRF wave or fast ion orbit effects. The prediction of reversal of the rotation direction with high magnetic field side off-axis ICRF absorption [46,48] has not been observed in the C-Mod experiments [36]. Energetic ion orbit effects have also been ruled out as a source of rotation in JET [22] and Tore Supra [28].

An alternative approach to explain the spontaneous generation of rotation is based on turbulence [50]. Fluctuation induced toroidal stress [51] can give rise to toroidal rotation where the direction of the rotation depends upon the mode frequency spectrum, and may explain the reversal of the observed rotation in going from L- to H-mode. A quantitative comparison with experimental results is not yet possible since the calculated magnitude of the rotation is a function of the level of the turbulence, which is not routinely measured. A comparison of predicted velocity profile shapes in C-Mod plasmas has produced mixed results [33]. A similar model [52] of electrostatic modes driven by the ion pressure gradient is in qualitative agreement with many of the features observed in the C-Mod experiment: direction of rotation in L- and H-mode, scaling with W_P/I_P in H-mode and the drop in the rotation observed in ITB plasmas. However, there are no quantitative predictions about the magnitude of the rotation or the size of the momentum diffusivity for further comparison with the experimental results. Furthermore, these turbulence-based theories do not provide a scaling of the turbulence levels with plasma parameters that would allow a direct comparison. A recent model of turbulence driven transport of toroidal momentum [53], which includes a momentum convection related to the particle pinch and an off-diagnoal fluctuation-induced torque density enabled by the symmetry breaking provided by radially sheared poloidal **ExB** flow, looks promising. It has recently been suggested [54] that the blob transport at the edge of C-Mod plasmas could possibly drive the rotation if the blobs exit the plasma at some toroidal angle. Whether the total momentum of blobs leaving the plasma edge is enough to spin the plasma in the opposite direction remains an open question for future work.

As discussed above, it is difficult to make quantitative comparisons of the measured toroidal rotation with the predictions of neo-classical theory, largely because the radial electric field is very rarely independently measured. The expression for the neo-classical poloidal rotation velocity [39] is relatively simple, proportional to the ion temperature gradient with a coefficient depending on the collisionality regime. Recent measurements of poloidal rotation velocities are at odds with neo-classical predictions, quantitatively and even in direction. In JET ITB plasmas [55], the measured poloidal rotation velocity profiles in the vicinity of the ITB foot substantially disagree with the calculated neo-classical values. Similarly, the measured poloidal rotation velocity profiles of H-mode plasmas in DIII-D [56] can differ in sign and by an order of magnitude quantitatively when compared to neo-classical calculations. This certainly calls into question the common practice of determining E_r from the measured toroidal rotation velocity profile and using the calculated neo-classical poloidal profile in the absence of direct measurements of the latter. One possible contribution to poloidal rotation could come from poloidal viscous stresses due to drift waves [57]. The generation of poloidal rotation from ITG and TEM turbulence has been simulated in JET plasmas [58].

3. Momentum Transport

In a majority of tokamak plasmas, the toroidal rotation is generated externally by neutral beam injection. Momentum transport may then be characterized [59-71,30,58] with various levels of sophistication. The global momentum confinement time, τ_ϕ, can be determined from the ratio of the total plasma angular momentum to the input torque. This type of analysis has been performed on many devices [60,62,63,66,68,70,58] and it has been generally found that τ_ϕ is very close to the energy confinement time, with some systematic trends in the ratio between τ_ϕ and τ_E as a function of electron density in JET [70,58], as shown in figure 11. By measuring the steady state rotation velocity profiles, either from the associated beam diagnostics or by passive techniques, and calculating the input torque profiles from the beam injection, momentum transport coefficient profiles may be evaluated. Momentum diffusivity profiles have been obtained on many devices [61-64,69,70,58]; momentum confinement is generally found to be anomalous [59-71,30,58], with a diffusivity, χ_ϕ, similar to the ion thermal conductivity, χ_i, but much larger than the neo-classical [44,72-74,41] diffusivity (viscosity). Prandtl numbers between 0.1 and 2 have been observed, depending on radial location and plasma parameters; some systematic trends have been seen in this ratio with plasma parameters [69-71,58]. Evidence for a momentum pinch (off diagonal transport) has been clearly demonstrated using off-axis beam injection [64,67], utilizing co-counter beam modulation [65] and from the time evolution of spontaneous rotation, as shown in the bottom of figure 3 [30]. Analysis of steady state velocity profiles does not allow a unique determination of the pinch velocity; transient analysis from beam modulation experiments is necessary [65,71]. An inward pinch velocity of ~ 10 m/s has been inferred from JT-60U measurements [71] in this way, as shown in figure 12.

It is generally believed that the source of anomalous momentum transport is turbulence. It has been found that for diffusive momentum transport driven by ITG turbulence [75], χ_ϕ is of order χ_i, similar to what has been observed in most experiments. Viscous stress due to ITG modes has been considered in Ref.[76]. Anomalous viscosity from Reynolds stress has been calculated from a non-linear electro-magnetic gyro-kinetic equation [77] and the effects of fluctuation-induced stress have been included in a neo-classical quasi-linear treatment of momentum confinement [78]. Anomalous toroidal viscosity has been included in transport codes such as GYRO [79], GLF23 [80] and LINART [81]. Recently, there have been explanations put forward for a toroidal momentum pinch, due to the Coriolis drift effect [82] and from symmetry breaking due to magnetic field curvature [83].
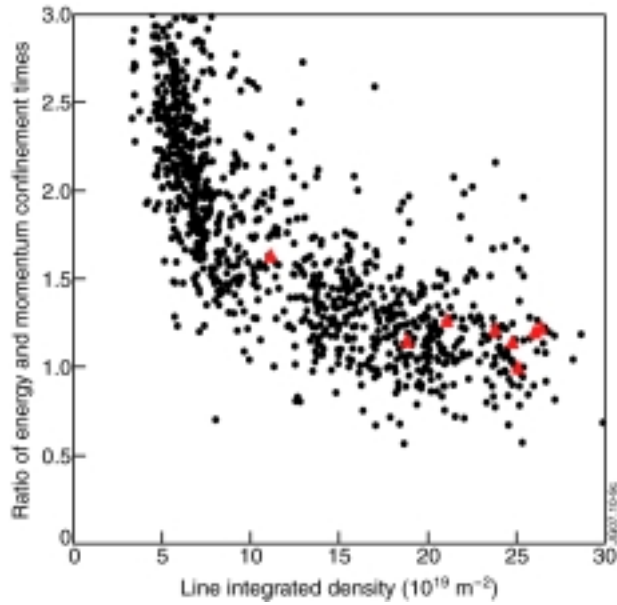
Figure 11. The ratio of the energy and momentum confinement times as a function of density for JET discharges.
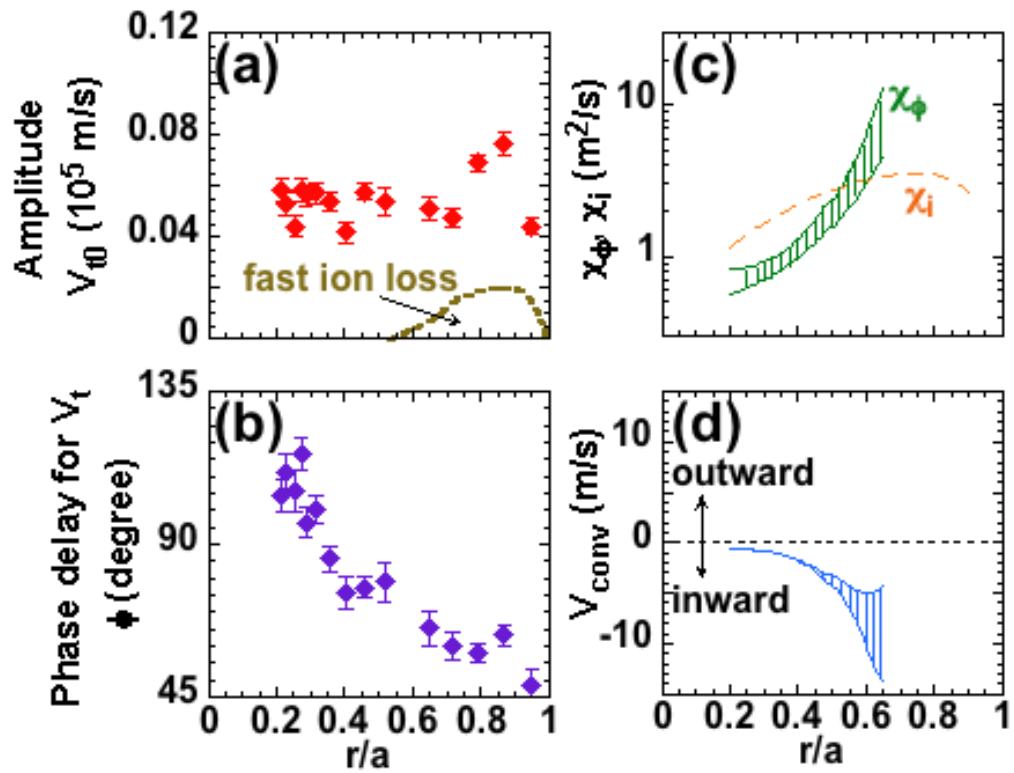

Figure 12. Profiles of the modulated amplitude (a), phase delay (b), momentum diffusivity (c) and momentum convection velocity (d) obtained from transient momentum balance analysis in JT-60U.

4. Conclusions

Spontaneous (in the absence of external momentum input) co-current toroidal rotation has been observed on many tokamaks in H-mode and other enhanced confinement regimes, produced by a variety of different methods: ICRH, ECH, Ohmic heating, ECH with LHH and balanced neutral beam injection. A common feature of these observations is that the rotation velocity increases with the plasma pressure or stored energy. A simple dimensionless scaling, with the Alfven Mach number proportional to the normalized pressure ($M_A = \beta_N/40\pi$), unifies the results. No dependence is found with normalized gyro-radius or collisionality. A more rigorous regression yields $M_A = 0.65\ \beta^{1.4}\ q*^{2.3}$ for dimensionless parameters and $\Delta V = C\ B^{1.1}\ \Delta<P>^{1.0}\ I_p^{-1.9}\ R^{2.2}$ for machine variables. All of these scalings predict rotation velocities for ITER high enough for RWM suppression without external momentum input. At present there is no comprehensive, quantitative explanation for spontaneous rotation. Some recent observations of poloidal rotation are inconsistent with the predictions of neo-classical theory.

Momentum transport has been found to be closely coupled to energy transport, and with momentum diffusivities much higher than neo-classical values. These results are consistent with diffusive momentum transport driven by ITG turbulence. Evidence for an inward momentum pinch has also been observed, which could be due to the Coriolis drift effect or from symmetry breaking due to magnetic field curvature

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