Overview of Tokamak Rotation and Momentum Transport Phenomenology and Motivations

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Abstract

Toroidal rotation is a key part of the design of ITER because of its ability to stabilize resistive wall modes. Understanding of the intrinsic rotation drive in plasmas is important because it will be difficult to externally torque a plasma the size of ITER.

This section will cover phenomenology of the toroidal rotation and momentum transport processes. First, a historial understanding of heat and particle transport process will be described, with descriptions of turbulent diffusion and a nondiffusive pinches which can cause up-gradient transport. The motivated understandings and shortcomings of the heat and particle transport on determining rotation (and specifically intrinsic rotation) will then be discussed, with the introduction of a residual, turbulence driven, stress to drive the plasma rotation. Finally some ongoing observations regarding the role of turbulence, and the species of turbulence, in plasma rotation will be briefly discussed.

1 Historical overview

A classic problem of interest has been evaluating plasma heat and density profiles, given a source of heat and particles. This requires an understanding of the transport processes that carry the fueling out of (or into) the core of the plasma. Profile resiliency for a variety of fueling techniques and locations has been key to uncovering new mechanisms at play in the plasma.

1.1 Temperature profiles and heat transport

Given that most heat deposition occurs at the core of the plasma, the plasma profiles are accounted for by an outward heat flux Q. This has typically been modeled as a diffusive process, and attributed to turbulence,

$$Q = -\chi \nabla T.$$

Relaxation of temperature gradients and the subsequent outgoing heat fluxcan drive other phenomena in the plasma, and an analogy has been made of the plasma as a heat engine converting free energy into bulk behavior.

Profile resiliency found significance in the 80s. Profiles similar to those of core deposition were obtained for plasmas heated off axis. This led to questions about the presence inward pinch in heat maintaining the profiles, or of the role of sawtooth oscillations in setting the core profiles.

1.2 Density profiles and particle pinch

In contrast to heat fueling, which takes place primarily at the core of the plasma, particle fueling typically occurs via gas puffing at the edge. The fact that peaked density profiles can be maintained with edge particle fueling is a fortunate reality, and implies the presence of an inward particle pinch in addition to diffusive particle transport,

$$\Gamma_n = -D\nabla n + V_{pinch}\, n, \quad \text{with}\, V_{pinch} < 0.$$

The existence of an inward pinch was verified experimentally during modulated intense gas puffing (Strachan, NF 1982). Measurements indicated that the rise in central density due to edge fueling occured 10-100 times faster that would be accounted for using neoclassical theory.

The particle pinch comes from two sources: $V_{pinch} = V_{thermo} + V_{TEP}$

1. The thermodynamic pinch comes from off diagonal elements from the transport matrix, but is seen to be highly parameter sensitive. In certain cases, a downgradient heat flux is accompanied by an upgradient particle flux, i.e. an upgradient particle flux has as destabilizing effect on the instability. This was shown for the ion-mixing mode (ITG with nonadiabatic electrons) by Coppi (PRL 1978).

   $$V_{thermo} \sim \sum |\phi_k|^2 (-\nabla T_i)\tau_{c_k}$$

   The thermodynamic pinch is expected to be highly parameter dependent.

2. The TEP pinch is a non thermodynamic, threshold effect due to magnetic geometry, specifically the compressibility of the $E \times B$ drift in nonuniform field. This is easily seen in the following argument.

   $$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = 0 \qquad\qquad \mathbf{v} = \mathbf{v}_{E\times B} = -\frac{c}{B(x)}\nabla\phi \times \hat{z}$$

   $$\nabla \cdot \mathbf{v}_{E\times B} \neq 0$$

   n/B is now the quantity that is conserved along particle trajectories,

   $$\frac{d}{dt}\left(\frac{n}{B}\right) = \frac{\partial}{\partial t}\left(\frac{n}{B}\right) + \mathbf{v}_{E\times B} \cdot \left(\frac{n}{B}\right) = 0$$

The turbulent heat flux is given by,

$$\Gamma_n = \langle \tilde{n}\, \tilde{v}_{E\times B}\rangle = -D\nabla\left(\frac{n}{B}\right) = -\frac{D}{B}\nabla n + Dn\nabla\left(\frac{1}{B}\right).$$

The first term is set by the density profile and is of the order $\sim 1/L_n$, while the second term is fixed by the magnetic geometry and is of the order $\sim 1/R$. Therefore, the TEP pinch is expected to be weak.

2 Rotation

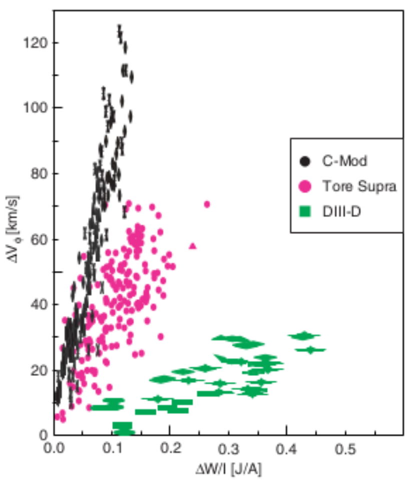
2.1 Importance of rotation to ITER

ITER is expected to be sensitive to resistive wall modes, which are large MHD instabilities. Plasma rotation can help to stabilize wall modes. However, externally torquing a plasma (e.g. via neutral beams) the size of ITER will be very difficult. Therefore, it is important to understand the drive for intrinsic rotation of of the plasma, and whether the intrinsic rotation on its own will be sufficient to stabilize resistive wall modes in ITER.

2.2 Rotation phenomenology

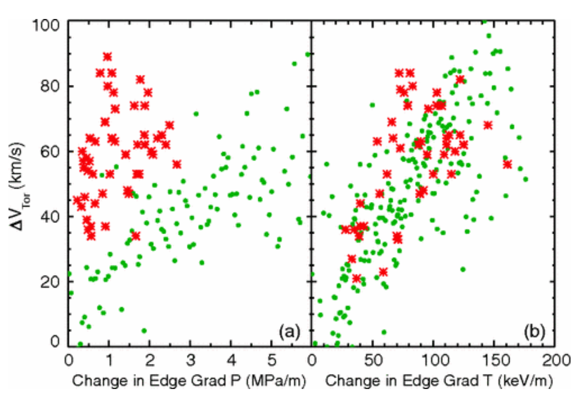
- *Intrinsic rotation as fundamental plasma phenomenon:*
  With the introduction of neutral beam injection (NBI) heating, toroidal rotation began to be universally observed. The injection of neutral beams into the plasma provided an external source of torque. Subsequently, strong rotation was observed in the H-mode at C-Mod, which had high power density from RF heating but no external sources of torque. This showed that rotation was a fundamental plasma phenomenon, and was not due to external torquing or specifics of heating sources. Rotation was also observed in ohmic heated plasmas and outside of H-mode. Thus, the phenomenon was dubbed intrinsic rotation.

- *Relation to L-H transition:*
  The Rice scaling (NF 2007) is a cross machine scaling of central rotation velocity across the L-H transition that shows a linear relation between the rise in central rotation velocity $\Delta V_\phi(0)$ and the change in stored energy normalized to the plasma current $\Delta W/I_P$ across the L-H transition. The rise in stored energy across the L-H transition is due to the formation of the edge pedestal, thus pointing strongly at the influence of edge physics on plasma rotation.



from Rice et. al, 2011

The Rice scaling indicated the role of the edge pedestal in driving intrinsic rotation, but was a scaling of bulk characteristics. The edge temperature gradients were directly measured on C-Mod in 2011 (NF 2011), and a linear scaling was observed between $\Delta V_{\phi,edge}$ and $\nabla T/B_\theta$. Furthermore, the scaling was identical between H-mode and I-mode plasmas.

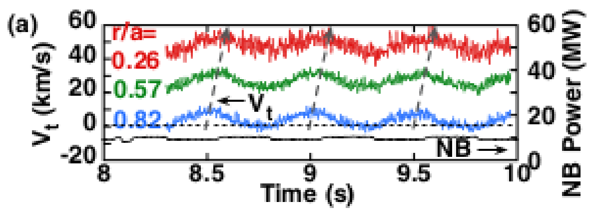


from Rice et. al, 2011

The messages from this experiment are that intrinsic rotation is fundamental to tokamak plasmas (i.e. not just an H-mode phenomenon) and that the edge ion temperature gradient is the key player. Since turbulence is driven by temperature gradients, this points to the role of turbulence in driving intrinsic rotation.

- *Studies on direction/asymmetry of rotation:*
  Studies in the mid-90s to early-2000s showed that the direction of rotation (i.e. co-current vs. counter-current) depended in the direction of beam injection. The notion of an intrinsic source of torque spinning up the plasma was pinned down by Solomon in experiments on DIII-D in H-mode with NBI, where the external torque was controlled. The plasma rotation was completely stopped, i.e. $V_\phi = 0$, for a given amount of counter-current beam injection. This corresponds to a state where the intrinsic torques $\tau_{intr.}$ are exactly balanced by external torque input τ_{NBI}, and allows measurement of the torques intrinsic to the plasma.

- *Turbulently driven residual stress as rotation drive:*
  Experiments on JT-60U transiently torqued the plasma edge using NBI, and measured the core rotation. The results showed an inward flux of momentum (Yoshida et al. NF, 2009),

  from Yoshida et al., 2009

  The colored traces show the rotation at different plasma radii, and depict the inward propagation of the response of rotation to the pulsed external torque. Yoshida et al. attributed the inward flux to a momentum pinch, in direct analogy to the phenomenology of particle transport

  However, the momentum pinch expression cannot explain plasma spin-up in steady state experiments. Furthermore, the pinch expression fails at high power, as the two contributions to the pinch (TEP and thermodynamic) are expected to weak and highly parameter-dependent. This suggested the presence of an intrinsic torque in the plasma, driven by non-diffusive, non-convective, turbulence-driven stress, dubbed the residual stress.

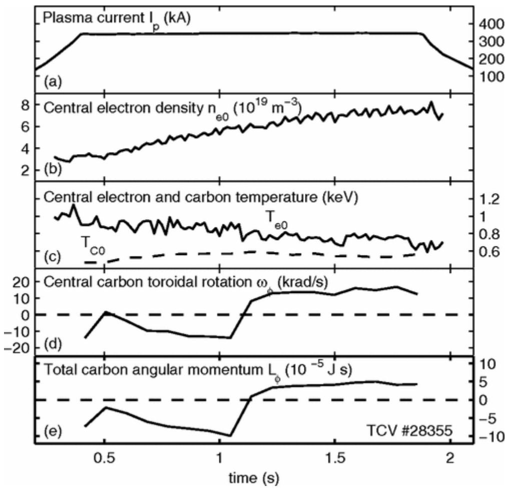
  $$\Pi = -\chi_\phi \nabla V_\phi + V_{pinch} V_\phi + \Pi_{resid}$$

  Both the pinch and residual stress terms are dependent on the temperature gradient, i.e.

  $$V_{pinch} = V_{pinch}(\nabla T)$$
  $$\Pi_{resid} = \Pi_{resid}(\nabla T).$$

  Thus, the plasma can be looked at as a heat engine, where relaxation of temperature gradients (i.e. heat transport) drives the bulk motion of the plasma, among other effects.

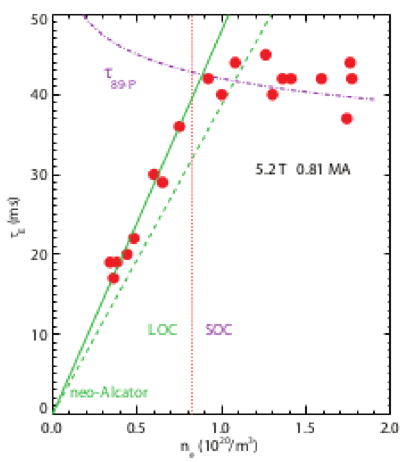
- *Rotation reversals:*
  The direction of rotation was observed to abruptly and spontaneously flip at a critical density in Ohmic-heated L-mode plasmas. This was observed dynamically in TCV in 2006 (Bortolon et al. PRL, 2006), and more characterized in more detail on C-Mod (Rice et al. NF, 2012).



from: Bortolon et al., 2006

The abrupt rotation reversal can be seen in the lower two traces, while the density steadily increases through the discharge, as shown in the second trace.

The energy confinement scaling with density in low density Ohmic plasmas, neo-Alcator scaling, is not fully understood, and is shown in the figure below.



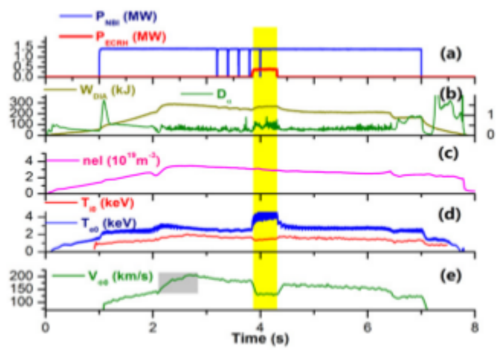
from: Rice et al., 2012

The energy confinement time increases linearly with density at low densities; this is the linear Ohmic confinement (LOC) regime. Above a critical density, the confinement curve flattens; this is the saturated Ohmic confinement (SOC) regime. Ohmic heating predominantly heats the electrons, and the confinement in the LOC is expected to be controlled by electron drift waves and TEM modes. At higher densities, heat is collisionally transferred to ions, and ITG modes are expected to control the confinement in the SOC regime. Therefore, the crossover point between LOC and SOC is a transition point between a electron transport dominated regime to an ion transport dominated regime.

It was observed on C-Mod that the rotation reversal occurs exactly at the crossover point between LOC and SOC, flipping from co-current in the LOC to counter-current in the SOC. These results point to the significance of the type of turbulence in driving rotation. It was also noted that the rotation reversal can be used as an indicator of the change in regime between LOC and SOC, and may aid understanding of the physics behind neo-Alcator scaling.

- *Effect of ECH on rotation:*
  Dramatic decreases in the core toroidal rotation were observed when electron cycling resonant heating (ECH) was applied to neutral beam heated plasmas in ASDEX (McDermott et al. PPCF, 2011) and KSTAR (Shi et al. NF, 2013).

In the absence of ECH, peaked co-current rotation profiles were observed, due to external torque by NBI, and intrinsic torques originating at the edge pedestal. When ECH was transiently applied, the rotation was observed to drop in a large range of the interior of the plasma, from the core to near the edge pedestal. In contrast to NBI, ECH carries no momentum and cannot be an external source of torque. ECH also predominantly heats electrons in the core of the plasma and $T_e > T_i$ during the periods of ECH heating.

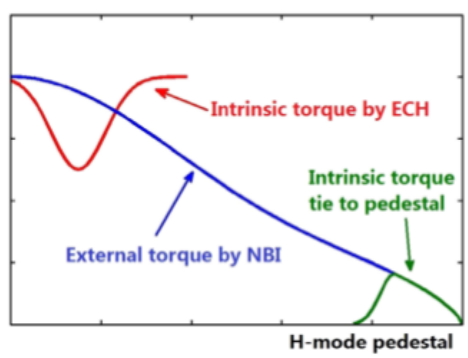


from: Shi et al., 2013

The shaded region is the time when the ECH is applied. From the trace second to the bottom, the electron temperature is seen to significantly jump during this period. From the bottom trace, the central toroidal rotation is seen to significantly decrease during this period.

This could not be explained by a simple increase in the core momentum diffusivity, and suggested the presence of an intrinsic torque brought on by ECH, opposite in direction to the external torque due to NBI and the preexisting intrinsic torques. The total torque on the plasma was now the sum of the three pieces, all of which are spatially dependent on plasma properties,

$$\tau = \tau_{ext,NBI} + \tau_{int,pedestal} + \tau_{int,ECH-driven}$$



from: Shi et al., 2013

Because ECH increases the electron temperature, electron transport is expected to become more significant during periods of ECH. Similarly to the story of rotation reversals in Ohmic L-mode, the rotation profiles are seen to be sensitive to the channel of heat transport, and very likely to plasma profiles and turbulence.

It was proposed that ECH excites TEM modes in the core of the plasma, which in turn drive a counter-current intrinsic torque. Shi et al. noted that this requires a better understanding of the physics of TEM in the plasma core, specifically the source of symmetry breaking. Furthermore, they observed that the TEM is only unstable deep in the core, while the intrinsic torque is affected over a much wider region of the plasma, suggesting the effect of turbulence spreading and non-local effects due to ECH.

- *Effect of lower hybrid (LH) current drive on rotation:*
  Lower hybrid current drive was observed to change the rotation profile, in both co-current and counter-current directions, depending on the change in q-profile of the plasma. The change in the shear

parameter $\hat{s}$ is expected to significantly affect the structure of the residual stress by affecting the mode structure, symmetry breaking mechanisms, and other characteristics of the turbulence.

3 Summary

In summary, some phenomenological observations about toroidal rotation in plasmas, and emerging understanding have been presented. Rotation was first treated as an oddity in tokamak plasmas, but understanding and predicting rotation has become important in the design of ITER as rotation can stabilize disruption-inducing resistive wall modes (RWM). Since the ITER plasma cannot be effectively externally torqued, it is essential for the intrinsic rotation to be strong enough to stabilize RWM in ITER.

Rotation was first observed in the H-mode on neutral beam heated plasmas, as the injection of neutral beams into the plasma is an external source of torque. However, rotation was subsequently observed in RF heated plasmas with no external torque input, and in operating scenarios other than H-mode, showing that rotation is an intrinsic, universal plasma phenomenon.

The Rice scaling showed a cross-device jump in central rotation across the L-H transition, directly proportional to the jump in stored plasma energy. This pointed at the edge pedestal as a key player in driving intrinsic rotation. The effect of torque on rotation were observed to propagate inward from the plasma edge, and could not be attributed to pinches. This motivated the understanding of the source of intrinsic rotation as due to turbulently-driven "residual" stresses. Since the intrinsic rotation appears to be sensitive to the temperature gradient and outgoing heat fluxes, this motivated the analogy of the plasma as a heat engine converting relaxation of temperature gradients into bulk motion.

Recently, the direction of rotation was observed to spontaneously and abruptly reverse on Ohmic heated L-mode plasmas, with no change in heating. This occured at the crossover point between the linear Ohmic confinement and saturated Ohmic confinement regimes, suggesting that the channel of heat flux (i.e. electron dominated vs. ion dominated) is a major player in intrinsic rotation drive.

Transient electron cyclotron resonance heating was observed to slow the rotation profiles of NBI heated H-mode plasmas. This is in agreement with rotation reversal, in that the transport of heat via the electron channel produces an intrinsic torque that is counter in direction to the intrinsic rotation in the otherwise ion dominated transport regime.

Last, lower hybrid current drive was observed to change the rotation profile in both co-current and counter-current directions, depending on how it changed the magnetic structure. The change in magnetic shear, is expected to strongly affect the residual stress by affecting the types of turbulence, mode structures, and symmetry breaking mechanisms.

4 References

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