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Abstract

Intrinsic core toroidal rotation has been observed in I-mode plasmas from the Alcator C-Mod tokamak, and is found to be very similar to the rotation in H-mode discharges, both in its edge origin, profile shape and in the scaling with global plasma pressure. Since I- and H-mode plasmas have similar pedestal temperature gradients, but completely different edge density profiles, it may be concluded that the drive of the intrinsic rotation is the edge temperature gradient rather than the pressure gradient. Evidence suggests that the connection between gradients and rotation is the residual stress, and a scaling for the intrinsic rotation from the conversion of thermodynamic free energy to macroscopic flow is calculated.

Understanding the mechanism whereby turbulence drives a macroscopic sheared flow is a classical problem in the physics of self-organization. A notable example of this is the origin of solar differential rotation, *i.e.* how convection zone Rayleigh-Benard turbulence drives latitudinally and radially sheared flows [1] in the sun. Efforts to understand this self-acceleration phenomenon have motivated development of mean field theory Reynolds stress closure models for convective and MHD turbulence [2]. In tokamaks, sheared toroidal rotation appears spontaneously, seemingly as a result of turbulence driven self acceleration.

Rotation and velocity shear play important roles in the suppression of deleterious MHD modes [3] and drift wave turbulence [4] in tokamak plasmas. Toroidal rotation is predominantly driven by neutral beam injection in present day tokamaks, but this method will be much less effective in future large scale devices and reactors. An alternative approach is to take advantage of the self-driven flows (intrinsic rotation) which have been widely observed in plasmas without external momentum input [5]. A fundamental understanding of this curious phenomenon is necessary in order to extrapolate confidently to reactors. Since the transport and relaxation of toroidal momentum is due to turbulence (with a Prandtl number $\chi_\phi/\chi_i \sim 1$), intrinsic rotation necessarily implies the existence of an agent or element of the momentum flux which can oppose turbulent viscosity. This off-diagonal flux, the residual stress Π^{res}, is likely responsible for the self-acceleration of intrinsic flow [6]. The connection between observed intrinsic rotation and directly measured turbulent residual stress has been demonstrated in CSDX plasmas [7]. The residual stress has also been isolated in DIII-D plasmas by adjusting the input torque from neutral beam injection to produce a null velocity profile with no velocity gradient [8]. Residual stress may be understood as a momentum flux driven by macroscopic gradients which produces a directed bulk flow by converting radial inhomogeneity to broken $k_\parallel$ symmetry of the fluctuation spectrum. This process resembles an engine, in that the turbulence converts thermodynamic free energy to macroscopic flow, just as a heat engine converts a temperature difference to useful work [9].

Several questions arise, the first of which is concerned with the driving gradient. This is a subtle question, since the pressure gradient ∇P can drive instabilities, break $k_\parallel$ symmetry [10] by its contribution to the zonal flow shear $\langle V_E \rangle'$, and also quench turbulence [11] via $\langle V_E \rangle'$. Other possibilities include ∇T and ∇n. Here, comparison studies of different confinement regimes (H-mode and I-mode plasmas) are used to isolate the driving gradient. The link between this gradient and the macroscopic flow is the residual stress. A simple theory of the intrinsic rotation engine, based on entropy dynamics, is described. This theory yields a scaling for the intrinsic rotation velocity.

The core intrinsic toroidal rotation has been found to be well correlated with the plasma stored energy (volume averaged pressure) in H-mode plasmas [12] in Alcator C-Mod (R $\sim$ 0.67 m,a $\sim$ 0.21 m) and many other devices [5]. This effect is demonstrated in Fig.1, where H-mode (green dashed curves) was accessed using 2 MW of ICRF minority heating (zero momentum input) power in Alcator C-Mod. Following the L-mode to H-mode transition ($\sim$0.62 s) there were increases in the electron density and temperature, plasma stored energy and core toroidal rotation velocity (increment in the co-current direction), the latter determined from the Doppler shifts of core x-ray lines. Shown for comparison are the time histories for an I-mode plasma (solid red curves). Both discharges had a magnetic field of 5.4 T and plasma current of 0.8 MA,

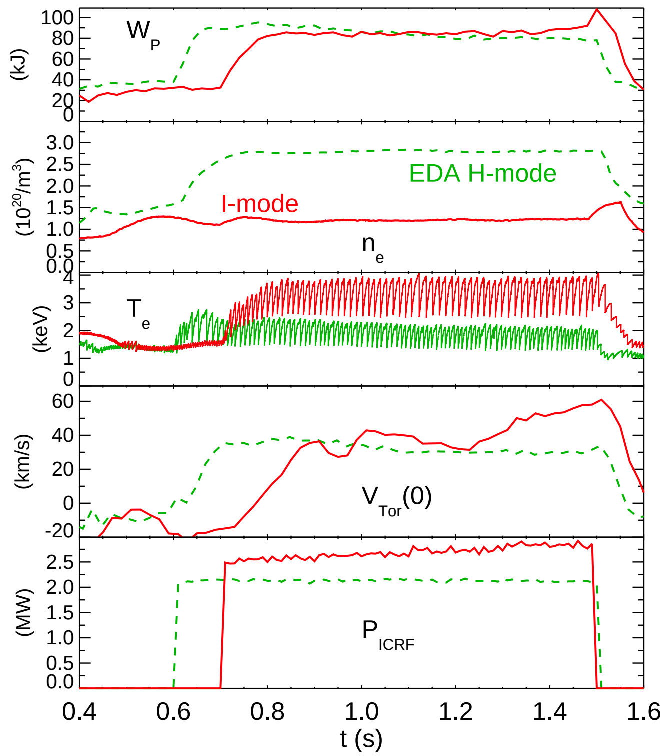

Figure 1: Time histories, from top to bottom, of the plasma stored energy, average electron density, central electron temperature, central rotation velocity (positive denotes co-current) and ICRF power, for an EDA H-mode (green dashed) and an I-mode (red) plasma.

with similar target densities and ICRF hydrogen minority heating power. The main difference was that the I-mode plasma was formed with the unfavorable ion $\mathbf{B}\times\nabla\mathbf{B}$ drift direction, in this case with an upper single null magnetic configuration. There was very little change in the electron density in the I-mode case, and a larger increase in the electron temperature. The stored energy in these two discharges was very similar, as was the magnitude of the core toroidal rotation velocity and velocity profile shape.

I-mode is an operational regime [13] which exhibits H-mode energy confinement with L-mode particle confinement. Shown in Fig.2 is a comparison of edge profiles from the EDA H-mode [14] and I-mode plasmas of Fig.1. These profiles are from Thomson scattering, and are averaged over the steady portion of the discharges. Both

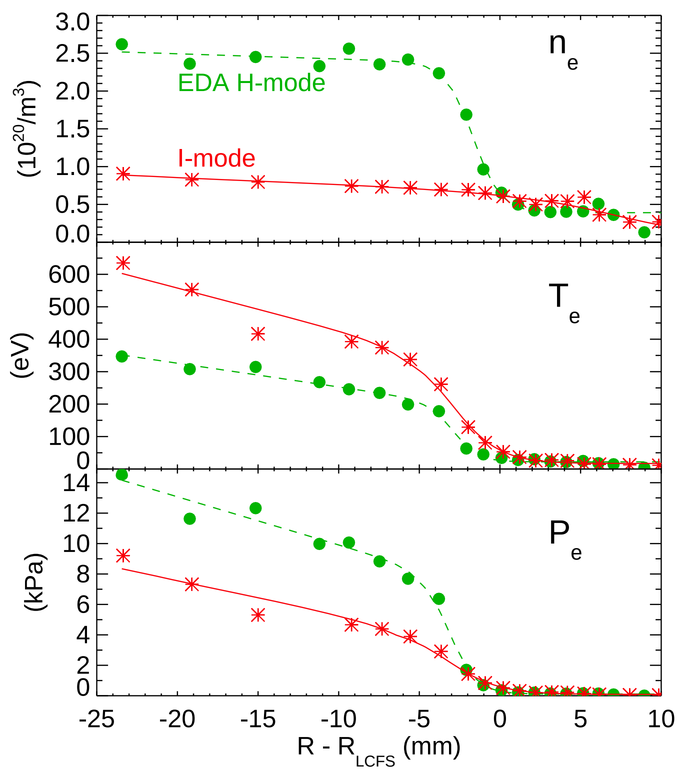

Figure 2: Edge profiles of the electron density (top frame), electron temperature (middle frame) and electron pressure (bottom frame) from the EDA H-mode (green dots) and the I-mode (red asterisks) discharges of Fig.1. The curves are hyperbolic tangent fits.

plasmas display an edge energy transport barrier, as manifested by the pedestals in the electron temperature at 3 mm inside of the last closed flux surfaces. The temperature gradient at this location is the same for both plasmas, about 70 keV/m. Only the EDA H-mode discharge has a pedestal in the electron density, however; in I-mode the edge density profile is similar to that in L-mode. This demonstrates a favorable attribute of I-mode: good energy confinement with poor particle confinement. That heat and particle transport is decoupled in I-mode allows a unique opportunity for energy barriers to be studied separately; in H-mode both transport channels are usually linked. Since there is no particle barrier in I-mode, the edge pressure gradient is considerably lower (∼0.7 MPa/m, about a factor of three in this comparison) compared to EDA H-mode. The pedestal radial electric field well depth is also shallower in I-mode compared to H-mode [15].

For H-mode plasmas, it has been established that the intrinsic rotation originates at the plasma edge, and propagates in to the core on a momentum confinement time scale [16]. Similar behavior is seen in I-mode plasmas, as shown in Fig.3. Following the

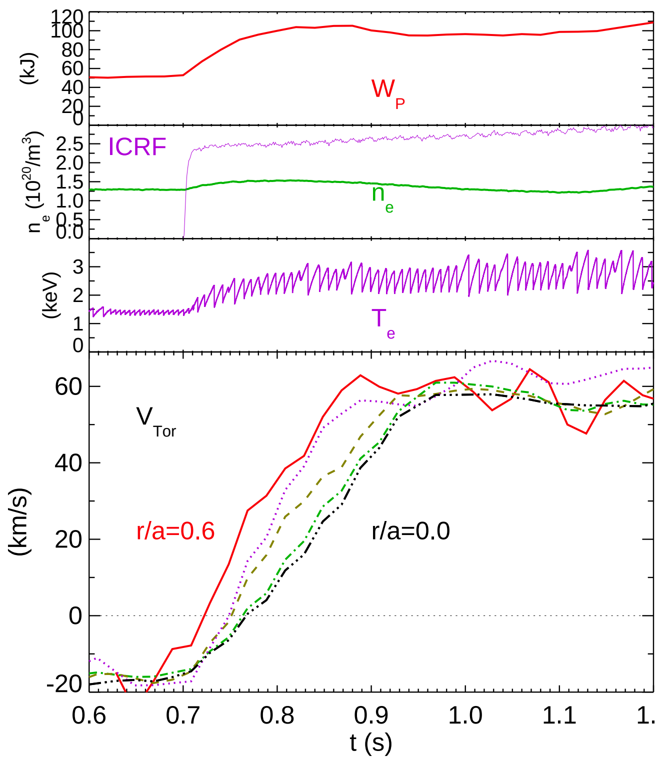

Figure 3: Parameter time histories for an I-mode discharge. In the bottom frame is the normalized chord-averaged toroidal rotation velocity at several radial locations, evenly spaced from r/a=0.6 to r/a=0.0.

transition to I-mode (0.7 s), the rotation velocity first appears at the plasma edge, then propagates in to the plasma center. The pedestal rotation velocity was not available for this discharge, but in previous studies has been shown to develop immediately after the I-mode transition [15].

It is well documented that the change in the toroidal rotation velocity between L- and H-mode is proportional to the change in the plasma stored energy (normalized to the plasma current) [12, 5], which is evident in Fig.1. Similar behavior is apparent in I-mode as well; the changes in rotation and stored energy are very similar in the two plasmas of Fig.1. This scaling holds over a large range of plasma parameters (density, plasma current, magnetic field, ICRF power), as can be seen in Fig.4. The I-mode points (red asterisks) overlay the H-mode points (green dots) from a large database,

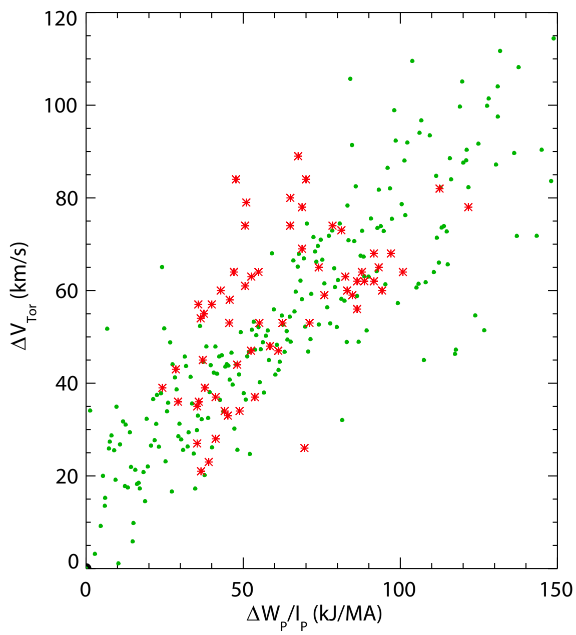

Figure 4: The change in the core toroidal rotation from L-mode to I-mode (red asterisks) and to H-mode (green dots) as a function of the change in the stored energy normalized to the plasma current.

suggesting a common phenomenology giving rise to the rotation.

Given the evidence that the origin for the intrinsic rotation is in the pedestal region ([16] and Fig.3), it would be natural to seek a local edge gradient rather than the global stored energy as relevant to the rotation drive. Intrinsic rotation in JT-60U plasmas has been linked to the ion pressure gradient [17]. Shown in Fig.5a is the change in the rotation velocity as a function of the change in the pedestal electron pressure gradient. (In C-Mod plasmas, the edge ion and electron pressure profiles are the same [15].) For the H-mode points, there is a very good correlation between the core rotation velocity

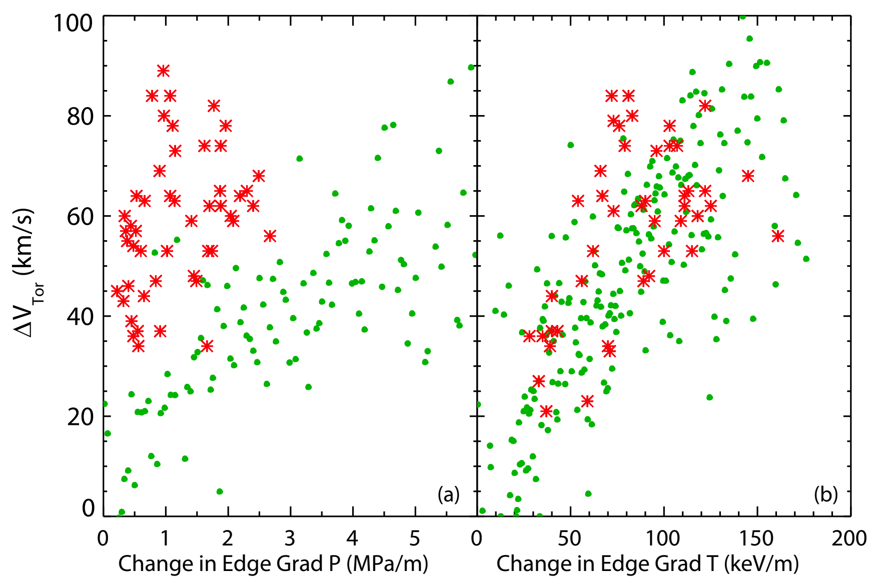

Figure 5: The change in the core rotation velocity as a function of the change in the pedestal electron pressure gradient (a) and pedestal electron temperature gradient (b) for H-mode (green dots) and I-mode (red asterisks) plasmas.

and edge pressure gradient. However, the I-mode points do not coincide, because the rotation is the same while the pressure gradients are lower than in H-mode (as seen in Fig.2). The two sets of points overlay very well for the pedestal temperature gradient, as demonstrated in Fig.5b, suggesting that it is ∇T which is key in driving intrinsic rotation. The association of intrinsic rotation with the ion temperature gradient has been demonstrated in LHD ITB plasmas [18].

Ongoing work is focused on a study of the relation $\Delta V_T(0) \sim \nabla T/B_\theta|_{edge}$ as an alternative scaling expressed in terms of local quantities, and on the correlation of edge electric field shear with $\Delta V_T(0)$. The high density regime of C-Mod makes it difficult to separate T_e from T_i. Thus, the driving gradient could be either ∇T_e or ∇T_i, depending on the nature of the turbulence (i.e. CTEM or ITG). To this end, it's useful to recall that gyrokinetic particle simulations [19] have shown that intrinsic rotation in ITG turbulence correlates with ∇T_i while in CTEM turbulence, it correlates with ∇T_e. Either is possible in C-Mod, and the ultimate resolution of the question requires detailed edge fluctuation measurements.

The approach for addressing the origin of intrinsic flow may be cast in terms of fluctuation entropy and describes intrinsic rotation as a thermodynamic engine. In the framework of residual stress, the generation process of flows can be understood as a conversion of thermal energy, which is injected into a system by heating, into kinetic energy of macroscopic flow by drift wave turbulence excited by ∇T, ∇n, etc. Using the physical picture of flow generation as an energy conversion, an explicit expression for the efficiency of the conversion process may be formulated by comparing rates of entropy production/destruction due to thermal relaxation/flow generation [20].

For a simple model with drift kinetic ions and adiabatic electrons, the time evolution of entropy or δf^2 is given by

$$\partial_t \int d\Gamma \frac{\langle \delta f^2 \rangle}{\langle f \rangle} = \int d^3x \left\{ -\frac{n}{T_i L_T} Q^i_{turb} - \frac{n}{v^2_{thi}} \langle V_\perp \rangle' \langle \tilde{V}_r \tilde{V}_\perp \rangle - \frac{n}{v^2_{thi}} \langle V_\parallel \rangle' \langle \tilde{V}_r \tilde{V}_\parallel \rangle + \frac{1}{T_i} \langle \tilde{J}^i_\parallel \tilde{E}_\parallel \rangle \right\} \quad (1)$$

apart from collisional dissipation and boundary terms. Here the notation is standard. The right hand side can be further simplified for a stationary state. Using a simple model for turbulent flux and neglecting the pinch, the entropy production rate, P, becomes

$$P \equiv \int d^3x \left\{ n\chi_i \left(\frac{\nabla T}{T} \right)^2 - nK \left(\frac{\langle V_E \rangle'}{v_{thi}} \right)^2 + n\chi_\phi \left(\frac{\langle V_\parallel \rangle'}{v_{thi}} \right)^2 - n \frac{\Pi^{res2}_{r\parallel}}{v^2_{thi}\chi_\phi} \right\} \quad (2)$$

where $K \equiv \sum_k c_s^2 \tau_{ZF} (\rho_s^2 k_\theta^2)/(1+k_\perp^2\rho_s^2)^2 \{-k_r \partial\eta_k/\partial k_r\}$, $\eta_k \equiv (1+k_\perp^2\rho_s^2)^2 |\hat{\phi}_k)|^2$. The first term in the right hand side is the entropy production rate due to thermal relaxation. The second term is the entropy destruction rate due to zonal flow generation. Note that this term destroys entropy only when zonal flow grows, i.e. $\gamma_{ZF} \propto K > 0$. The third term is the entropy production rate due to the relaxation of the velocity gradient. The last term is the entropy destruction rate due to the generation of intrinsic toroidal rotation.

The production rate P contains terms with a definite order. The last two terms are smaller than the first two terms by the order of $O(k_\parallel/k_\perp)$ where k is a representative of the mode number of drift waves. Hence a stationary state is achieved by balancing the production and destruction rates order by order. To the lowest order, the balance is between the production rate from thermal relaxation and the destruction rate from zonal flow growth. The balance yields $\langle V_E\rangle'^2 = (\chi_i/K)(v_{thi}^2/L_T^2)$ which relates zonal flow strength to the temperature gradient directly. To the next order, the third and the fourth terms in Eq. 2 cancel since the total parallel momentum vanishes for a stationary state as $\langle \tilde{V}_r\tilde{V}_\parallel\rangle = -\chi_\phi\langle V_\parallel\rangle' + \Pi_{r\parallel}^{res} = 0$.

To calculate $\langle V_\parallel\rangle$, a model of the residual stress is required. Here, a case is considered where toroidal rotation is driven by a two step process: first, a stationary state is achieved by balancing the entropy production rate due to thermal relaxation by the entropy destruction due to zonal flow growth. Secondly, the zonal flow $E\times B$ shear set by the dominant balance gives rise to symmetry breaking and momentum flux via k space scattering. In such a process, the residual stress is calculated as [10, 6]

$$\Pi_{r\parallel}^{res} = -\rho_*\frac{L_s}{2c_s}K\langle V_E\rangle'^2 = -\rho_*\frac{L_s}{2c_s}\chi_i\left(\frac{\nabla T}{T}\right)^2 v_{thi}^2. \tag{3}$$

It is worthwhile to comment that the strong scaling of the residual stress with $\nabla T/T$ is entirely consistent with the observed $\Delta V_T(0)$ vs $\nabla T|_{ped}$ correlation discussed earlier. The condition $\langle \tilde{V}_r\tilde{V}_\parallel\rangle = 0$ implies a strongly nonlinear relation between $\nabla V_\parallel$ and $\nabla T/T$, i.e.

$$\langle V_\parallel\rangle' = \frac{\Pi_{r\parallel}^{res}}{\chi_\phi} = -\frac{1}{2}\rho_*\frac{\chi_i}{\chi_\phi}\frac{L_s}{c_s}\left(\frac{\nabla T}{T}\right)^2 v_{thi}^2. \tag{4}$$

Simple integration then establishes the relation between edge ∇T and the flow velocity,

$$\frac{\langle V_\parallel\rangle}{v_{thi}} \cong \frac{1}{2}\rho_*\frac{\chi_i}{\chi_\phi}\frac{L_s}{L_T}\sqrt{\frac{T_i}{T_e}} \tag{5}$$

where $(T'/T)' = -(T'/T)^2 + T''/T \cong -(T'/T)^2$ has been used. The sign conventions here are such that the rotation is predicted to be co-current. For typical H- and I-mode discharges in C-Mod, $\rho_* \sim 0.006$, $T_e \sim T_i$, Prandtl number ~ 1, $L_s \sim 0.6$ m and $L_T \sim 0.01$ m, Eq.5 yields a thermal Mach number of 0.18, which is also typical [5]. Eq.5 captures the ∇T scaling of Fig.5 (and in LHD [18]) from 1 / L_T and the 1 / I_p scaling of Fig.4 from $L_s \propto q/\hat{s} \propto 1 / I_p$.

In this paper, progress toward a physics based phenomenology of intrinsic rotation in H-mode and I-mode has been described. The principal results of this paper are as follows.

1. studies in Alcator C-Mod indicate a close correlation between change in central velocity $\Delta V_T(0)$ and $\nabla T|_{edge}$, both in H-mode and I-mode. This, in turn, suggests that the macroscopic scaling $\Delta V_T(0) \sim \Delta W_p/I_p$ may be replaced by a relation expressed in terms of *local* parameters i.e. $\Delta V_T(0) \sim \nabla T/B_\theta$. The central velocity does not correlate with edge ∇P in I-mode.

2. a theory of the entropy balance for a turbulent plasma is presented, which yields a scaling for the residual stress and the toroidal rotation velocity. The theory predicts that $V_{\parallel}$ scales with ∇T and q.

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