

Plasma Rotation and Momentum Transport, and Their Relations to Transport Barriers

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The studies of plasma rotation and momentum transport are the most-watched core-transport topics over the last few years. It is well known that plasma rotation can play an important role to achieve high confinement and high beta. The large rotational shear can produce an internal transport barrier (ITB) by suppression of turbulence, and the enough rotation speed can suppress resistive wall modes. Although fast toroidal rotation and its large shear can be obtained in present devices thanks to large toroidal momentum input from neutral beams, slow plasma rotation is foreseen in burning plasmas under the conditions of low momentum input and dominant alpha heating. Therefore it is important to accurately predict plasma rotation profile in ITER and DEMO reactor. In this paper, recent progresses in the studies of plasma rotation and momentum transport are reviewed especially in spontaneous or intrinsic toroidal rotation, momentum pinch, and their relations to transport barriers.

Spontaneous toroidal rotation in the absence of external momentum input has been observed in many tokamaks with several heating methods, such as ICRF (ASDEX-U, C-Mod, JET), ECRF (DIII-D, JT-60U, TCV) and LHCD (C-Mod, JT-60U). Since even the direction of spontaneous rotation is different in some cases, the understanding of the source of spontaneous rotation is important to predict the toroidal rotation profile in the burning plasmas. Several theoretical models are proposed as the source of spontaneous rotation.

An inward momentum pinch is evaluated in many tokamaks (C-Mod, DIII-D, JET, JT-60U, NSTX) by the transient analysis and the perturbative experiments such as NBI modulation and non-resonant magnetic perturbation. Several theoretical models are also proposed as the mechanism of momentum pinch.

There is also progress with respect to the effect of rotation on transport properties. For example, the effects of the modified rotation profile by TF ripple on ITBs, and the influence of the momentum pinch on the movement of ITB of ion temperature and toroidal rotation, and the impact of toroidal rotation on resilient profile of ion temperature.

Mach probe measurement of peripheral plasma rotation evolution during LH transition and ITB decay in the TUMAN-3M tokamak

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Radial electric field and associated sheared plasma rotation is known to play crucial role in the turbulent transport suppression and improved confinement development.

Toroidal and poloidal rotation velocity at the plasma edge was studied on the TUMAN-3M tokamak using four-tip movable Mach probe. Measurements were performed in two modes of plasma confinement: H-mode transition (featured by peripheral transport barrier formation), and transient ITB formation; both in ohmic heating scenario. The measurements were performed in a vicinity of the LCFS, both in core and SOL plasmas. In ohmic H-mode, virtually no perturbation of toroidal rotation velocity was observed, whereas poloidal rotation velocity profile underwent substantial evolution – mostly after the transition. Contrary, in transient ITB scenario, a noticeable perturbation of toroidal rotation velocity was observed just after the ITB decay, indicating, probably, the outflux of the toroidal momentum due to confinement degradation.

The Mach probe data obtained in the both scenarios are compared to available data on radial electric field and impurity ion's rotation velocity, and speculations are done on the possible drive forces of the rotation, taking into account radial force balance equation.

Radial Current, Residual Stress and Intrinsic Rotation

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We present a novel mechanism for self-acceleration and intrinsic rotation driven by microturbulence, and show that ambipolarity breaking by polarization currents and radially propagating waves drives a *mean radial current* $\langle J_r \rangle$, which in turn exerts a toroidal force $F_\phi = \langle J_r \rangle B_\theta / c$. We prove that $F_\phi = (B_\theta / B_T) \partial_r \pi_{r,\theta}^w$, where $\pi_{r,\theta}^w$ is the radial flux of poloidal wave momentum density[1], and then extend previous work on wave momentum transport[2] to explicitly calculate $\pi_{r,\theta}^w$ for a system of *interacting* drift waves. The principal results of this study are:

- i.) the wave momentum density flux is calculated and demonstrated to consist of a diffusive contribution, driven by the gradient of the *pseudomomentum* (i.e. *wave momentum density*) and a non-diffusive term related to $E \times B$ shearing, which drives flow formation.
- ii.) the non-diffusive effect is the same as zonal flow drive, so the *overall mechanism is one which converts poloidal wave momentum to toroidal plasma flow*.
- iii.) the wave momentum density is unambiguously identified as $\langle \tilde{q}^2 \rangle / v_*$, where $\langle \tilde{q}^2 \rangle$ is the potential enstrophy and v_* is the diamagnetic velocity. The latter sets the pseudomomentum direction and provides the requisite symmetry breaking.
- iv.) the non-diffusive $\langle V_E \rangle'$ driven effect is typically *stronger* and *more robust* than that due to $\langle V_E \rangle'$ breaking of k_{\parallel} symmetry, which has been extensively studied.
- v.) the net flow direction (co vs. counter) is determined by the wave propagation direction (electron vs. ion diamagnetic) and the turbulence intensity profile.

The relevance of these results to the phenomenology of intrinsic rotation will be discussed. This material is based upon work supported by the Department of Energy under Award Numbers DE-FG02-04ER54738, DE-FC02-08ER54959 and DE-FC02-08ER54983.

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Rotation and Transport in Alcator CMod ITB Plasmas

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The transport barriers that arise in the core of C-Mod plasmas display common features despite the means used to induce their formation. Typically, ITB's are triggered with off-axis ICRF power, but they commonly arise spontaneously in Ohmic H-mode plasmas. Independent of the trigger, they typically persist tens of energy confinement times until the plasma is terminated or a disruption occurs. Short-lived (1 energy confinement time) ITBs are usually observed following the H to L-mode transition as well. All C-Mod core barriers exhibit strongly-peaked density and pressure profiles, unchanged or peaking temperature profiles, peaking impurity density profiles, and thermal transport coefficients that approach neoclassical values in the core. As the central density peaks during the evolution of the ITB, the intrinsic central plasma rotation develops a central well that becomes more distinct as the density peaking increases. This rotation profile well is relatively flat in the center then rises steeply in the region where the foot in the ITB density profile is observed. Gyrokinetic analyses of ITB onset conditions [1] points to the broadening of the T_i profile with off-axis ICRF to reduce the ion temperature gradient and suppress the ion temperature gradient (ITG) instability driven particle fluxes as the primary mechanism for ITB formation. However, experimental verification of this scenario remains elusive[2]. Recent work indicates that changes in the q-profile may also play a role in ITB formation in these plasmas. The role of the rotation with respect to plasma transport in this region will be explored. In addition a summary of current research will be presented.

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Two-dimensional simulations of time-dependent poloidal flow.

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Poloidal flows in tokamaks are receiving an increasing amount of consideration, as newer and better flow measurements keep increasing the amount of available experimental information. In particular, finite poloidal flows are routinely observed in experiments in the edge region of the plasma. MHD theory predicts that when the poloidal velocity is transonic with respect to the poloidal sound speed ($c_{sp} \equiv c_s B_p / B$, where B_p is the poloidal field) shocks will develop in the transonic region. Such shocks will then move in the poloidal direction and disappear once they reach the location of the minimum transverse flow cross section (typically the inboard midplane in a low- β plasma). In the aftermath of the shock disappearance, a pedestal in plasma density and pressure is left, with the height of the pedestal depending on the poloidal location. In this work, we present the result of time-dependent simulations aimed at reproducing the theoretical prediction. Simulations are performed with a finite-difference predictor-corrector code, solving the conservative form of the equations of motion. Simulation results show how an initial condition with transonic flow evolves, creating a train of shocks near the transonic surface, which eventually result in sharp transitions in (e.g.) density profiles, not dissimilar from what is predicted by theory. This work was supported by the US Department of Energy under Contract No. DE-FG02-93ER54215

Toroidal and poloidal flow evolution

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We present recent results in the theory of turbulent momentum transport pertinent to the description of intrinsic rotation. Emphasis is placed on the self-consistent evolution of poloidal and toroidal flows. Both turbulent and neo-classical stresses are considered, allowing for the recovery of purely neo-classical flows, as well as the description of deviations induced by the background turbulence. Along with radial force balance, toroidal and parallel force balance are utilized to constrain the evolution of poloidal and toroidal momentum. Within the turbulent toroidal momentum flux, in the limit of small but finite inverse aspect ratio, two distinct non-diffusive contributions capable of spinning up a plasma from rest are identified. The first results from $\mathbf{E} \times \mathbf{B}$ shear induced symmetry breaking of the underlying wave population, whereas the second follows from charge separation induced by the polarization drift. While both mechanisms are found to provide robust means of driving toroidal rotation in the absence of external momentum sources, the magnitude of the former is found to be closely coupled to the poloidal rotation. An expression for the poloidal flow, including both neo-classical and turbulent stresses, is obtained from parallel force balance. Potentially significant deviations from neo-classical poloidal rotation are found, which are in turn seen to provide a robust means of enhancing toroidal flow generation. Ongoing work is devoted to the development of a self-consistent model describing the coupled poloidal and toroidal flow evolution, with particular emphasis placed on recovering empirical scaling laws.

Recent Progress in Rotation and Momentum Transport by the ITPA Transport and Confinement Group

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There has been substantial progress recently in the understanding of momentum transport and intrinsic rotation in tokamak plasmas. From beam modulation experiments on JET, JT-60U, DIII-D, NSTX (others?), profiles of the momentum diffusivity and pinch velocity have been determined under a wide range of operating conditions. Related results have been obtained from C-Mod following the H-mode transition. Momentum diffusivity is generally found to be anomalous, and similar in magnitude to the ion thermal diffusivity (Prandtl number of order unity). There is also evidence for inward momentum convection. These observations have been compared to several recent theories, in particular models of the turbulent equipartition and thermoelectric pinches. Under construction is a momentum transport profile database which will allow systematic characterization momentum confinement for comparison with theory and extrapolation to future devices. (Problematic coordinate transformation properties of the momentum pinch portion of the momentum flux proportional to the velocity may lead to a different characterization of momentum transport.) An extended database of intrinsic/spontaneous rotation in H-mode and other enhanced confinement regimes from JET, C-Mod, Tore Supra, DIII-D, JT-60U, TCV and ASDEX Upgrade has been compiled and a universal scaling has been developed. Some generic features have been captured in recent theories of the residual stress. The more complex intrinsic rotation in L-mode plasmas, including rotation inversions, is also an area of vigorous activity on TCV, C-Mod and JET. RF driven rotation by ICRF mode conversion has been demonstrated on C-Mod and will be explored in JET. Rotation in LHCD plasmas is also under investigation.

ITB Formation in Alcator C-Mod ICRF Mode Conversion Flow Drive Plasmas

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ICRF mode conversion flow drive has been recently demonstrated in Alcator C-Mod plasmas [1,2], manifested by large (up to 80 km/s) toroidal rotation in the plasma interior, in addition to spatially localized poloidal rotation near $r/a = 0.45$. The toroidal rotation exceeds by a factor of two the intrinsic rotation scaling. The peak of the poloidal rotation velocity profile is close to the location of the calculated power deposition to ^3He ions by the mode converted ion cyclotron wave. Also observed at this position is an increase in the ion temperature gradient, which is suggestive of ITB formation. The deduced ExB shearing rate at this location, $2 \times 10^5/\text{s}$, exceeds the calculated maximum linear growth rate for ITG turbulence.

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Angular momentum in wall-bounded MHD turbulence

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In fusion plasmas, large-scale spontaneous toroidal rotation is beneficial for the confinement as it may suppress turbulence. This effect may be related to the transition to an improved confinement state (L-H transition) [1]. The absence of this transition might jeopardize the success of the ITER project. The understanding of spontaneous toroidal plasma flow dynamics is therefore of considerable interest in order to regulate the L-H transition.

The spontaneous generation of angular momentum in two-dimensional turbulence in non-axisymmetric domains was discovered by Clercx *et al.* [2]. In a recent work, [3], it was shown that this effect is enhanced in magnetohydrodynamics. The shape of the boundary which contains a plasma may be very important in determining the dynamics of close to two-dimensional plasma flow. In two dimensions, the importance of the shape of the plasma container was shown to be far from trivial. Indeed, while in infinite cylinders plasma can be retained in a static, quiescent state by the Lorentz force, toroidal geometries are shown to induce non-zero velocities due to visco-resistive effects [4]. It is reasonable to expect that the same statement will be true in fully three-dimensional MHD.

In the present communication we will present results of two and three dimensional MHD simulations in differently shaped geometries to study spontaneous generation of velocity. The effect on a net current on the generation of angular momentum will also be addressed.

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Transport dependence of high performance operation on ExB shear and momentum

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Effects of ExB shear and momentum on confinement/transport have been investigated in high performance plasmas under the framework of the ITPA multi-machines joint experiments. Momentum scans were performed by using RF (ICRF, ECH, etc), tangential-NB (co or ctr.), magnetic breaking and/or intrinsic rotation in JT-60U, JET, DIII-D, AUG, NSTX, TCV and C-Mod. In JT-60U weak shear plasmas (hybrid target plasmas), highest confinement was achieved with co-rotation. The rotation direction seemed to be important rather than the ExB shear. On the other hand, decreased ExB shear reduced the confinement in DIII-D hybrid scenario plasmas and enhanced the transport in NSTX H-mode plasmas, where high confinement or reduced transport was observed with a large co-rotation. In C-Mod, high confinement was also obtained with a large co-rotation and strong ExB shear. In AUG, additional electron heating by ECH in low density NBI heated plasmas led a significant reduction of confinement and toroidal rotation, while additional RF ion heating did not reduce as much confinement, but had similar effect on the toroidal rotation. This result indicated that T_e/T_i seemed to be important rather than the ExB shear. In TCV, high confinement was obtained with a large reversed shear with low momentum input, indicating that magnetic shear was important rather than rotation. In JET, T_i -ITB trigger events were investigated with very low levels of injected momentum using ICRH. The evidence indicated that ExB shear driven by toroidal rotation was not important with a shear-reversed target q -profile. In JT-60U reversed shear plasmas, confinement and rotation were strongly linked with each other. When the transport significantly decreased in the ITB region, a notch structure was formed in the toroidal rotation profile and strong ExB shear was produced. The experimental results obtained in multi-machines will be systematically discussed to elucidate physics underlying various observations.

NBI Modulation Experiments to Study Momentum Transport on JET

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*See Appendix of F. Romanelli et al., paper OV/1-2, IAEA 2009, Geneva

Plasma rotation can have a major influence on the dynamics of transport barriers. In particular the sustainment of Internal Transport Barriers (ITBs) is affected by the gradient of the toroidal rotation [1,2]. Therefore, understanding of momentum transport is crucial, not only for well-known beneficial effects of toroidal rotation on both stability and confinement, but also from the ITB sustainment point of view.

In this paper, momentum transport is studied using the Neutral Beam Injection (NBI) modulation technique. Earlier results using this technique have demonstrated the existence of a significant inward momentum pinch and Prandtl numbers between 0.5 and 1.5 [3]. Here, the parametric dependencies of the pinch and Prandtl numbers are reported. The momentum transport theory also predicts a large inward momentum pinch [4,5] where the pinch depends most strongly on density gradient length R/L_n and q -profile [4]. The preliminary experimental results show that indeed in plasmas with larger R/L_n the pinch is also larger, well in accordance with theory. However, no clear dependence of the magnitude of pinch on q -profile was found in the experiments.

The experimental results, both the profiles of the pinch and Prandtl number, are compared with simulation results from GKW gyro-kinetic code [6]. The comparison shows that the agreement between the simulations and experiments, both for Prandtl number and pinch number $Rv_{\text{pinch}}/\chi_\phi$ is well within a factor of 2 and in most cases, the discrepancy is much less than a factor of 2.

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Effect of Trapped Electrons on Nonlinear Residual Stress Generation and Toroidal Momentum Transport

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Global quasi-stationary zonal flow structure along with a toroidal zonal component is observed in global gyrokinetic simulations of ion temperature gradient (ITG) turbulence. A residual stress is found to be generated nonlinearly by the zonal flow shear via the symmetry breaking in the parallel wavenumber k_{\parallel} spectrum. This residual stress drives an inward flux of toroidal momentum robustly observed in the post-saturation phase of ITG turbulence, leading to core plasma rotation spin-up. A finer radial scale of zonal flow is introduced by trapped electron dynamics. Trapped electrons are shown to largely enhance the residual stress generation particularly in ITG marginality regime. A momentum pinch is shown via simulations using different rigid rotation. Further, trapped electrons do not considerably change the phase space structure of momentum flux for ITG turbulence. Compared to ITG case, momentum transport driven by trapped electron modes (TEM) is made by ions from different regions and in a different way. Determination of non-diffusive momentum transport direction (inward or outward) is also examined in connection with the characteristic of turbulence spectrum. Work supported by U.S. DOE Contract DE-AC02-76-CH03073 and the SciDAC GPS-TTBP project.

Transport of Parallel Momentum by Drift Resonance of Toroidal Ion Temperature Gradient Instability near Marginality

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With recognition of importance of momentum transport, there has been lots of progress in identifying underlying mechanisms for momentum pinch in toroidal geometry. While both TEP pinch [1] and thermodynamic pinch [2] were studied in toroidal geometry, simple analytic expressions were only available in the fluid regime which is strictly valid well above ITG marginality [1, 3]. However, it is well known that the plasma profile is often near threshold of ion temperature gradient (ITG) instability in experiments [4]. With this motivation, we calculate transport of parallel momentum carried by drift resonance of toroidal ITG instability near marginality using quasilinear theory starting from a phase space conserving gyrokinetic equation [5] for ions. The principal results are: TEP pinch remains inward as the most robust term of pinch. In addition, ion temperature gradient driven pinch is inward for typical parameters. Interestingly, density gradient driven pinch is outward as in the previous kinetic results in slab geometry [6], but opposite to the results in the fluid regime [3]. Parameter dependency of momentum diffusivity and pinch velocity on the electron to ion temperature ratio ($\tau = T_e / T_i$) has been examined over a wide range of density profiles.

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