Physics of Flows and Turbulence in Fusion Plasmas

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Results on flows and turbulent transport as obtained from stellarators, tokamaks and non-fusion devices are highlighted to discuss the complex interaction between them. Both neoclassical and turbulent transport processes are needed to cover the rich spectrum of experimental observations. The magnetic configuration plays an important role for both processes. Therefore, a better understanding of this important field could lead – after the first neoclassical optimisation of stellarators – to a second optimisation step which envisages improved control on turbulent transport.

Keywords: Plasma confinement, turbulence, rotation, zonal flows

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1 Introduction

The interplay between flows and turbulence is a fascinating and rich topic of fusion research. Background flows aligned with the flux surfaces are a prerequisite for confinement of high-temperature plasmas. But even in globally stable plasmas, micro-instabilities lead to the development of turbulence. The interaction between flows and turbulence is twofold. Sheared flows can reduce turbulence and trigger the development of transport barriers while turbulence is able to power large scale zonal flows in a self-adjusting manner.

The physical description of flows and turbulence depends on details of the magnetic configuration used to confine the plasma: Magnetic curvature and trapped-particle drifts enter the calculation of growth rates and determine the character of turbulence. The topology of magnetic ripples not only defines the trapped-particle populations but also the parallel viscosity and hence the damping of the flows. Rational values of the rotational transform, magnetic islands and magnetic shear are further configurational elements with relevance for both flows and turbulent transport.

2 Physics of flows

In a simple magnetised torus, the physics of flows is relatively straightforward. The toroidal coordinate is identical with the symmetry axis and the plasma can flow freely parallel to the magnetic field $\mathbf{B}$. The poloidal plasma flow is decoupled from the poloidal one. It can only be generated by the diamagnetic and the $E{\times}B$ Drift. Even in a tokamak with ideal toroidal symmetry, due to the helical field lines the parallel flow is coupled to the poloidal one. The toroidal flow now is a superposition of a parallel flow and drifts due to the poloidal magnetic field component B_θ. Furthermore, due to the toroidal magnetic field ripple, poloidal flows are damped by a viscous force.

Equilibrium flows in toroidal geometry follow from the condition $\boldsymbol{\nabla} p = \mathbf{j}^{dia} \times \mathbf{B}$. As it can be seen in Fig. 1, diamagnetic flows have poloidal and toroidal components. Due to their mass, the ions are the relevant species for momentum studies. The toroidal component of the ion diamagnetic flow points into the same direction a plasma current has to flow in order to generate the rotational transform (call *co-direction*).

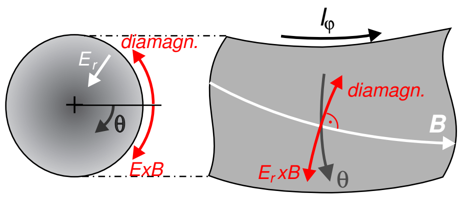

Fig. 1 Ion flows in toroidal geometry.

The poloidal flow u_θ is subject to a viscous force which, for qualitative studies, can be approximated by $F_\theta^{visc} \approx \sqrt{m}\hat{\mu}_\theta u_\theta$. The force depends on the mass m of the species and the parallel viscosity coefficient $\hat{\mu}_\theta$. The neoclassical transport can be understood as a radial drift $v_D = \mathbf{F}^{visc} \times \mathbf{B}/qB^2$ in response to the viscous force. Since the ion viscosity is higher, ion losses would be stronger than electron losses (assuming the same pressure gradient). This results in non-ambipolar radial transport and thus a negative radial electric field. This process goes on until the $E{\times}B$ drift, which slows down the poloidal ion flow and increases the electron flow, is strong enough to make the viscous forces on the two species equal and therefore transport ambipolar. What remains is a slow poloidal ion flow into the ion-diamagnetic direction, which has a small component into the toroidal co-direction. Even for a complex stellarator field as the one of W7-AS, the thus

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estimated ambipolar radial electric field

$$E_r^{amb} \approx \nabla_r p_i / en \tag{1}$$

agrees rather well with measurements and fully neoclassical calculations [1, 2].

Experiments on plasma rotation rely on measurements on impurities and not the mains ions. The impurity ion pressure p_I, their density n_I and flow velocity perpendicular to the magnetic field $u_{I\perp}$ have to be measured to allow for the calculation of the radial electric field according to the radial force balance for the impurity ions

$$\frac{E_r}{B} + u_{I\perp} - \frac{p_I'}{ZenB} = 0. \tag{2}$$

With expression (1) inserted for ambipolar electric field one finds

$$u_{I\perp} = -E_r/B + \partial_r p_I / Z_I e n_I. \tag{3}$$

E_r is set by the main ions. Since the pressure gradient of the impurities is in general smaller than the one of the main ions, the impurity-ion flow points into the $E \times B$ (ctr.) direction.

very fast

$$r\colon \quad nm\dot{u}_r = qnE_r + qn\left(u_\theta B_\varphi - u_\varphi B_\theta\right) - \nabla_r p$$

fast

$$\theta\colon \quad nm\dot{u}_\theta = -qnu_r B_\varphi - n\hat{\mu}_\theta \sqrt{m} u_\theta$$

slow

$$\varphi\colon \quad nm\dot{u}_\varphi = +qnu_r B_\theta - n\hat{\mu}_\varphi \sqrt{m} u_\varphi + F_\varphi$$

Fig. 2 Components of the ion-momentum equation.

The equilibrium flows can be modified by external and internal torques. As shown in Fig. 2, forces F_θ and F_φ act through the ion momentum equation on the ion flow. The ion and electron equations are coupled through the radial electric field. External momentum input can stem from neutral-beam injection (NBI), ion or electron-cyclotron-resonance heating (ICRH and ECRH). Momentum can also be redistributed internally by Reynolds stress. Locally this can be treated as a force. Furthermore, radial momentum transport is also a local source or sink of momentum, which can be represented by the forces in Fig. 2. The characteristic response time of flows to toroidal and poloidal forces are $\tau_\varphi = \hat{\mu}_\varphi/\sqrt{m} \gg \hat{\mu}_\theta/\sqrt{m} = \tau_\theta$. Since $\hat{\mu}_\varphi$ is small, the toroidal flows adjust rather slowly to equilibrium changes. Furthermore, due to their small mass electrons react much faster than ions. If the collisionality changes with time, the viscosities can also be modified leading to a distortion of the equilibrium and changes in flows and radial electric field. These changes happen on a fast time scale as far as the electron viscosity is concerned. Otherwise, the modifications in the flows should happen slower.

Modifications in the equilibrium act on the ambipolarity condition through the Lorentz force (indicated by arrows). Due to the fast reaction of the electrons, the reconstitution of ambipolarity through the radial component is a very fast process, too. Slow changes are also connected to the pressure gradient, which can only be modified on the confinement-time scales. A more direct manipulation of the radial electric field occurs if radial losses of fast electrons or ions are generated by e.g. ECRH or ICRH.

3 Toroidal flows

The recent interest in toroidal flows arises from their stabilising influence on MHD modes like the resistive wall modes in tokamaks [3]. In present day devices, toroidal plasma flows can readily be driven by NBI heating. In a fusion reactor, however, external momentum sources will be absent or insufficient. Hence, it is worthwhile to study the possibilities of an intrinsic generation of toroidal flows. In principle, there are two mechanisms which can drive core plasma rotation: a momentum inward pinch with the momentum source located at the plasma edge, and the toroidal component of the turbulent Reynolds stress. While the existence of a momentum pinch can be shown in transient phases of the plasma, the turbulent drive can only be assessed if all neoclassical effects are taken into account correctly. Alternatively, it can be attempted to measure the Reynolds stress directly.

In order to asses the importance of pinches or turbulent drives, the measured flow velocities have to be carefully compared to the neoclassical predictions addressed above. In Ohmically heated (OH) discharges on Alcator C-mod [4], the impurity ions flow into the direction opposite to the plasma current and the flow reverses sign with plasma current. The same is true for Ohmic plasmas in TCV [5]. The measured toroidal flow of C^{6+} in the core is into the ctr-direction, too. Little flow was observed close to the separatrix. These results agree with the expectations from neoclassical theory. The scaling of core flow velocity is $u_\varphi \sim T_i(0)/I_p$ [5]. The dependence on the central ion temperature can be understood in terms of the simple estimate of Eq. (1). Surprising is the spontaneous change in flow direction observed in TCV [6]: at a critical density, the flow changes from ctr to co-direction. This could be an effect of changing collisionality or due to the onset of a pinch or a turbulent drive.

On the DIII-D tokamak, a comparison of the rotation profiles with neoclassical theory has been carried out, too. Ohmic and ECRH H-mode discharges have been analysed [7]. In OH discharges, slow impurity core rotation was found. In the H-mode edge, where the impurity pressure gradient might become strong, the flow was stronger and co-directed. When ECRH was added leading to $T_e > T_i$, ctr-rotation became evident in the plasma core. The strong rotation coincided with the ECRH deposition profile. The comparison with neoclassical theory points to an additional toroidal torque.

Externally driven radial currents e.g. due to fast electron losses generated by ECRH must lead to a fast change in the ambipolar electric field. If electrons are lost, E_r becomes less negative and impurity rotation should become more co-directed. Ion losses, on the other hand, would lead to faster impurity rotation into the ctr-direction. A study of the effect of ion-ripple losses on toroidal rotation has been carried in JT-60U [8]. Although the plasma was heated with co-NBI, the impurity rotation at the plasma edge was into the ctr-direction. This is consistent with the the expected effect of ion losses due to the toroidal field ripple at the plasma edge. Consequently, a reduction of the magnetic ripple due to the insertion of ferritic steel tiles changed the edge rotation into the co-direction. Also in Alcator C-mod, a change of the toroidal rotation from ctr to co was observed, when ICRH was added onto Ohmic plasmas [9]. Although this behaviour is qualitatively consistent with neoclassical theory, a detailed analyses revealed that a momentum pinch is required to explain the data. Similar experiments carried out in ASDEX Upgrade, where ICRH was added to NBI discharges, yielded a reduction of the rotation velocity in both cases, with co and ctr-NBI. Here confinement changes were made responsible for the reduction in toroidal momentum [10].

If additional torques are applied due to NBI or wave momentum input parallel to the magnetic field, the ambipolar electric field is going to change on the slow time scale. The parallel flow contributes an additional flow component into the poloidal direction which now reads

$$u_\theta = (|u_{E\times B}| - |u_{dia}|)\cos\alpha \pm u_\parallel \sin\alpha \qquad (4)$$

Here α is the pitch angle of the field lines. If the arguments from above still apply and neglecting changes in the pressure profiles, the poloidal ion flow must remain unchanged. Consequently according to the discussion of Fig. 1, an external co-torque must lead to a reduction of the radial electric field, while a ctr-torque makes E_r more negative. The change happens slowly as plasma speeds up. The resulting electric field will be such that the flow mainly aligns with the direction of symmetry.

Here differences between stellarators and tokamaks can be expected. In an ideal tokamak the driven flow will align with the toroidal direction. Since the viscosity in this direction is small, neoclassical transport will not change substantially. In case of a stellarator, the resulting direction of rotation will depend on the specific magnetic configuration. In quasi-symmetric devices, strong flows can be driven without strongly increasing neoclassical transport. In the absence of symmetry, the momentum input will not drive the same rotation velocity and the influence on neoclassical transport will be more important.

In the CHS heliotron, the alignment of the flows with the direction of minimum ∇B was experimentally demonstrated [11]. In discharges with combined ECRH and NBI, an internal electron-transport barrier with positive radial electric field developed. The measured impurity flow pointed opposite to the direction NBI. It was shown that the net flow of the main ions is such that it aligns with the direction of minimum ∇B.

The presented survey shows that there exists no uniform picture of toroidal momentum transport yet . To disentangle neoclassical effects from turbulent ones is not simple. But it has to be done properly in order to conclude on spontaneous turbulent drives. Clearer than steady state analyses are transient transport experiments. They have already been successfully applied to particle transport, where an anomalous pinch has been observed in tokamak [12, 13] and stellarator experiments [14, 15]. Recently, a pinch has also been discovered in the momentum transport channel [16] and for the explanation, theoretical models related to symmetry breaking of turbulence [17] and a inwards drift due to the Coriolis force [18] have been put forward. If momentum is generated at the plasma edge, the pinch can transport it to the core. Hence the momentum pinch is one possible source of toroidal rotation for the plasma core. However, the momentum source needed for a complete model remains still unexplained.

Furthermore, there exists also first direct evidence for a turbulent drive of toroidal rotation. Measurement of the parallel Reynolds stress have been carried out in TJ-II [19]. Above a critical density, net energy transfer from turbulence to parallel flows has been found by means of probe measurements in the plasma edge.

4 Poloidal flows

Sheared poloidal flows are widely accepted to be beneficial for the reduction of turbulent transport. Of special interest are zonal flows, which are radially localised $E\times B$ flows with poloidal and toroidal mode numbers $m = n = 0$. Recent reviews of the vast experimental and theoretical work can be found in Refs. [20, 21, 22]. Still open are questions addressing the nature of the momentum sources, which can have neoclassical and turbulent elements, and the detailed mechanism of turbulence reduction. It is also well known, that the zonal flow couples to the Geodesic Acoustic Mode (GAM) [23], which appears at the characteristic frequency $f_{\text{GAM}} \sim c_s/R$. Hence, zonal flows mostly appear in the form of GAMs as it has been demonstrated in many devices using heavy-ion beam probes, beam emission spectroscopy and Doppler reflectometry (see Ref. [24] for a survey).

Zonal flows are also observed in fluid and gyro-fluid turbulence simulations. In the numerical models, the generation of zonal flows is clearly due to the turbulent Reynolds stress $\partial_r \langle \tilde{v}_\theta \tilde{v}_r \rangle$. Also in simulations they are oscillatory (GAMs) and radially localised. If interchange turbulence with radially elongated streamers is dominant, one can visually observe the decorrelation of the large turbulent structures [25]. Fluid simulations using the drift-Alfvén turbulence code DALF3 [26] have been carried out [27] to test analyses techniques for the study of the turbulent drive of zonal flows. The averaged poloidal flow from the simulations exhibited typical GAM structures. Using a cross-bispectrum technique, evidence for Reynolds-stress drive of the flows was found and correlation analyses also showed the reduction of turbulence in regions of maximum flow shear.

In the TJ-II heliac, the Reynolds stress has been measured directly with a probe array [28]. Gradients in the Reynolds stress were found in the vicinity of a shear layer. Also in linear devices, evidence for turbulent flow drive was found [29]. Poloidal rotation was observed in a plasma without net momentum input. The poloidal momentum balance was successfully checked using measured flow and Reynolds stress profiles. The generation of a zonal flow can also be interpreted as sign of an inverse turbulent cascade, which is expected to be active in magnetised plasmas. First direct evidence for the inverse cascade were was obtained from the TJ-K torsatron applying bispectral analyses methods on 2-dimensional probe data [30].

Hence there is ample evidence of the existence of poloidal flows and the importance of a turbulent drive.

5 Flows acting on turbulence

Zonal flows play a key role in the regulation of turbulent transport. Once generated through Reynolds stress, the flows can act back to reduce turbulence [20]. This interplay can be observed in turbulence simulations, but is rather difficult to be unambiguously demonstrated in experiment. Although the shear-decorrelation mechanism has been pointed out already in 1990 [31], there is still no clear experimental evidence on the reduction of the turbulent scales due to sheared flows.

Turbulent transport, which can be written as

$$\tilde{\Gamma} \sim |\tilde{n}| \left|\tilde{\phi}\right| \sin \delta_{n\phi}, \tag{5}$$

can be manipulated by different means. The density and potential fluctuation amplitudes $\tilde{n}$ and $\tilde{\phi}$ can be reduced. According to the mixing-length argument, this would be done by a reduction of the turbulent radial correlation length. On the other hand, a change in the cross phase $\delta_{n\phi}$ can influence transport, too. Which of the two effects is more important can sensitively depend on the dominant type of turbulence present in the plasma. While interchange turbulence is characterised by a cross phase of $\delta_{n\phi} \approx \pi/2$, the phase of drift-wave turbulence is close to zero. In the first case, a small change of $\delta_{n\phi}$ does not substantially alter transport while in the latter case small changes can already have strong influence on the its magnitude. Hence, in order to predict the role of shear flows in future devices, a knowledge of the expected dominant type of turbulence is of great importance. In Ion-Temperature-Gradient (ITG) or Trapped-Electron Modes (TEM), which both are of the interchange type, the characteristic streamer-like turbulent structures can efficiently be reduced by sheared flows while the effect of the cross phase might be negligible. This kind of turbulence is expected to be dominant in the core of tokamak plasmas. In the plasma edge of both stellarators and tokamaks, drift-wave turbulence might be more important. Drift waves do not show the radially elongated structures but they have small cross phases, hence the phase might be the key parameter to reduce transport at the plasma edge. Therefore related important questions are what is the character of turbulence in the core of stellarators and what is the dominant instability in the plasma edge of both stellarator and tokamak plasmas.

Already with the discovery of the H-mode in the ASDEX tokamak it was shown that the region of the transport barrier is related to reduced fluctuation amplitudes [32]. This has been confirmed in many different devices since where a edge transport barrier could be achieved. But sheared flows can also act on the cross phases as shown in biasing experiments on the small stellarator TJ-K, where drift waves have been shown to be the dominant instability [33, 34]. In this case no decorrelation of turbulent structures was detected. Confinement improvement happened rather due to cross-phase modifications [35].

Less is known about core transport in stellarators. In the core of larger tokamaks, ITG and TEM modes are likely to be dominant. This kind of turbulence can account for one major property of the temperature profiles, namely the profile resilience as, e.g. shown for the tokamak ASDEX Upgrade [36]. The fact that

$$\frac{1}{L_T} = \frac{\nabla T_e}{T_e} \approx \text{const.} \tag{6}$$

results in an offset-linear scaling of the electron heat flux vs. electron-temperature gradient as, e.g. shown for Tore Supra [37]. Although the electron temperature profiles in stellarators can become flat in the centre when ECRH is deposited off-axis, in the W7-AS stellarator there was also evidence for profile resilience when the central heating power was different from zero [38]. It should be stressed, that in a tokamak there is always residual Ohmic heating in the centre. Hence, similar concepts may also apply to stellarators plasmas and a quantitative comparison of the W7-AS results with tokamak models gave a quite good agreement, although the critical gradient in W7-AS is steeper [39].

If profile resilience is also present in stellarators, ITG and TEM turbulence may also be candidates to explain turbulent transport. Both instabilities are driven in the bad curvature regions of the plasma. Furthermore, to develop the TEM needs trapped particles in the region of bad curvature. Therefore, a optimisation of the magnetic configuration can also be carried out in view of a stabilisation of these modes. The W7-X stellarator has been optimised with respect to neoclassical properties. For neoclassical transport, the separation of curvature and trapped particles is also a criterium. In this respect, W7-X has also achieved some degree of optimisation against TEM turbulence.

First gyrokinetic simulations of TEM turbulence in W7-X geometry show [40] that the spatial distribution of local transport maxima reflects the fivefold symmetry of the magnetic configuration. The largest transport levels are found in regions where magnetic wells and bad curvature still overlap to some extent.

6 Summary and Conclusions

The paper intended to demonstrate the richness of the phenomena related to the interplay between flows and turbulence in toroidal plasmas and their importance for the development of future fusion devices. The importance arises from their ability to stabilise MHD modes and to reduce turbulent transport. Since future devices will not be equipped with sufficient means to drive strong flows, the spontaneous generation of flows is especially important.

The radial electric field, which is closely related to neoclassical transport, is the key player of the flow system. In plasmas without external momentum input, qualitative agreement with neoclassical expectations is found in many cases. But there also exist observations like the spontaneous flow reversal in TCV, that cannot readily be explained by neoclassical theory and need more sophisticated codes for interpretation. And there exists also clear evidence for momentum pinches which cannot be explained by standard neoclassical theory. The pinch can act as a momentum source in the plasma core, but a momentum source is still needed at the plasma edge. First evidence also exists that Reynolds stress can redistribute toroidal momentum to generate sheared toroidal flows.

Radially localised poloidal flows and their characteristics have been well documented in many experiments. There also exist strong indications for the importance of Reynolds-stress drive of these flows. Due to the toroidal field ripple, zonal flows also should interact with neoclassical transport. This aspect needs further attention and global turbulence simulations including neoclassical effects are desirable. There is also agreement that zonal flows have the ability to reduce turbulent transport. Details on the suppression mechanisms, however, are not yet fully understood and can be expected to depend on the type of the dominant instability.

The magnetic configuration enters in different aspects the flow-turbulence system. It sets the values of the different components of the parallel viscosity and therefore determines the amount of neoclassical transport for a given flow on the flux surface. In the same way the configuration determines the ability of the plasma to respond to torques and to develop zonal flows. On the other hand, curvature and trapped-particle populations are leading ingredients for driving turbulence. Both parameters are predefined by the magnetic configuration. A better understanding of the flow-turbulence system could therefore help to attempt an optimisation of the stellarator configuration with respect to both neoclassical and turbulent transport.

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