Particle and Momentum Transport in Tokamak Plasmas, the Complicated Path towards the Experimental Validation of the Theoretical Predictions of Transport in Fusion Plasmas*)

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Recent research on turbulent transport of particle and toroidal momentum in the core of tokamak plasmas is reviewed. Similarities and differences between these two transport channels are briefly presented, highlighting the common feature that both include large off-diagonal components in the radial flux. The main goal of the review is to provide selected recent examples of validation studies in these topical areas, and, thereby, to outline an efficient route to validation in the complex field of transport studies dedicated to transport channels which include important off-diagonal components.

Keywords: particle and toroidal momentum transport, tokamak plasma, off-diagonal turbulent transport, comparison between theory and experiment, validation

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1. Introduction and Motivation

The theoretical understanding of particle and momentum transport in tokamak plasmas plays an essential role in the design, the stable operation and the performance of a future tokamak fusion reactor, where possibilities of core particle fuelling and of external application of torque are limited. In recent years, large efforts have been made by the scientific community to develop and apply comprehensive theoretical models to the modeling of present experiments, in order to progress in the validation.

The main goal of this paper is not to provide a complete overview of the research on these transport channels, that is electron and impurity particle transport and toroidal and poloidal rotation, including both neoclassical and turbulent transport, from the core to the edge. The breadth of such a topic would be outside the scope of any possible review. Comprehensive overviews have been recently published on these areas, on the topic of particle transport [1], as well as on mostly experimental [2, 3] and theoretical [4] aspects of toroidal momentum transport. In addition, a very recent topical review compares the main aspects of these two transport channels [5]. The goal of the present paper is to be at least partly complementary to this recent topical review paper [5]. Selected aspects of the research on turbulent electron and impurity particle transport and toroidal momentum transport, mostly in the core of tokamak plasmas, will be described here, with the goal of defining an appropriate validation route to be undertaken for transport channels like particle and toroidal momentum transport, where large emphasis has to be given to the off-diagonal transport components. Examples from past and recent studies will be proposed, and will be presented outlining the historical development of the research, highlighting the approach to validation which has been followed by the scientific community. Under this viewpoint, this paper aims at describing specific aspects in the application of validation procedures, which have recently received large consideration in the magnetic fusion community at a more general level [6, 7].

A first important feature that particle and toroidal momentum transport have in common is that in future devices, like ITER, the sources of particle and momentum will be peripheral and/or are expected to have very limited impact. This implies that density and toroidal angular velocity profiles will be mainly determined by the balance between the usually outward diagonal diffusion, and the usually inward off-diagonal components of the radial fluxes. Thereby, the study of these off-diagonal contributions to the transport in addition of being of extreme physical interest, is also of high relevance for fusion applications.

An additional important aspect of turbulent transport in tokamak plasmas is that, particularly at ion Larmor radius scales, it is inherently multi-channel, that is turbulence usually produces transport in more than one transport channel. Thereby, an important element in the study of transport is the investigation of the mutual interactions among all the transport channels. These can be seen as different moments of the same distribution function, and the problem of transport has to be regarded in the form of a non-diagonal matrix. These considerations apply also to the multi-pronged approach to be used for model valida-

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tion, in order to assess the consistency of the predictions with respect to the observations in multiple channels.

While the connections between some transport channels have been realized since long (an example is the link between the ion heat and the toroidal momentum transport [8]), an aspect that has been realized only more recently is that there are physical processes which connect also particle and momentum transport (see [5] for a review), and thereby there are conditions in which these transport channels cannot be studied and understood separately. In this paper we shall analyze the main elements linking particle and momentum transport, and we shall emphasize which role they can play in the validation of theory models which aim to describe these channels. This will allow us to provide a description of the path that in our opinion can be followed to validate theoretical models for the description of complex transport channels (such as particle and momentum) where off-diagonal tranport plays an essential role.

2. Considerations on the Validation

It is the opinion of the Author that no validation can be achieved without physical understanding of the observations. Physical understanding, that is a consistent theoretical explanation of a class of phenomena and of the observed phenomenological dependences among the parameters involved, is an indispensable goal that a theoretical model has to achieve in order to be considered suited to describe that class of phenomena. A mere statistical validation over a even large data set and even adopting rigorous metrics over a well chosen set of figures of merit remains a sterile exercise which does not advance our knowledge of physics and which cannot be considered trustworthy, particularly in case of applications outside the domain over which the model has been tested.

A key element in the physical understanding of transport in the presence of off-diagonal components is to develop an appropriate decomposition of the fluxes, to be applied for the interpretation and theoretical explanation of the observations. Each off-diagonal component can have different dependences on plasma parameters, and project in different ways for the prediction of the behaviour of a burning plasma in a reactor. Thereby a critical step is to identify the correspondence among off-diagonal components which are theoretically predicted and those which are observed. To this end, a general and effective route can be outlined, which can be (and is usually) followed in investigations aiming at reaching a theoretical understanding of a class of observations and thereby the validation of a theoretical model.

a The first step is provided by a thorough characterization of the experimental observations in terms of theoretically relevant parameters, and the assessment of which theoretical model can be considered realistic and appropriate to describe the phenomenology under consideration. This analysis can allow the empirical determination of parameters which exhibit the highest correlations. In addition, through the analysis of time dependent evolution, one can gain indications about possible causality relationships through which some parameters can depend on others. The dependences which have been identified experimentally (and which can be expressed also in the form of statistical regressions), can be used to make projections for the parameters which will be reached in a reactor plasma. However, this should be considered just an empirical extrapolation, and not really a reliable prediction. A real prediction can be obtained only through a consistent (and "validated") theoretical model.

b To this end, the second step is to move to a comparison with theoretical predictions obtained from a theoretical model. Here the critical decision is about which model can be considered realistic enough to describe the observations, in particular whether a kinetic treatment is required, whether a local description is sufficient, whether a quasi-linear model is applicable and can be considered appropriate, and so on. The comparison between theoretical predictions and observations can be performed at different levels, and requires the definition of a hierarchy of observables which are easily measurable and which have a clear theoretical significance. They must enable as much as possible an unambiguous discrimination of whether the considered theoretical model is able to capture, or not, the correlation and dependences which are observed. The approach of plotting data by using theoretically relevant parameters is a main part of the approach adopted by the Author, under the idea that this allows the data to be organized in a physical way. However this approach increases error bars on the data, since theoretically relevant parameters are rarely directly accessed by diagnostics.

c The comparison between theoretical predictions and experimental observations can deliver a clear disagreement at the most basic qualitative level (e.g. theory predicts a dependence among parameters which is opposite to that which is experimentally observed, or theory predicts the same trend, but quantitatively off by more than one order of magnitude), which is the indication that something very fundamental is missing in the theoretical model. Or, the model can provide a qualitative, but not completely quantitative, agreement, which can be interpreted as the sign that the model might be only partly appropriate, but is incomplete, since it misses some elements which would allow a more accurate match. Finally, the model can give a quantitative agreement, that is the disagreement is below the uncertainties of the data (those which are predicted and those which are used as inputs to compute the prediction), and the experimentally observed dependences among parameters are quantitatively reproduced by the theoretical model. In this favorable condition, one receives indications that the model might be appropriate to describe the phenomenology. Then, by investigating theoretically which are the physical mechanisms which are responsible for reproducing the experimentally observed correlations and dependences, one can reach the conclusions that the same mechanisms are taking place in nature, and are responsible for the observed trends. Such a conclusion usually requires a large amount of confirmations, but it is clear that this is the critical step which increases our physical understanding, and allows a real validation to be achieved.

d As a final remark, with the goal of assessing the agreement between theoretical predictions and observations, the consistency of the predictions with all available measurements on different transport channels and with available fluctuations measurements plays an essential role. In many conditions, transport produced by turbulence is inherently multi-channel, and a multi-channel analysis can deliver a higher level of confidence in the assessment of the applicability of a theoretical model to the description of the observations. The availability of measurements of fluctuations and of other transport channels would also allow the validation procedure and the validation metrics to follow a more complete and consistent hierarchy [6].

In Sections 4 and 5, examples of validation processes carried out in the tokamak physics scientific community and dedicated to particle and toroidal momentum transport respectively are described. These examples are presented with the aim of gaining guidelines about how progress in this complicated field has been made and can be made in the future. In the next section (Section 3) a very general description of the main similarities and differences between particle and toroidal momentum transport is presented. In section 6, general conclusions are briefly drawn.

3. Radial Fluxes of Particle and Toroidal Momentum Transport

In the comparison between particle and toroidal momentum transport, the first consideration to be made is that density is a scalar, an even moment of the distribution function, whereas toroidal momentum is the component of a vector, and is an odd moment of the distribution function. The direct consequence is that while toroidal momentum can be zero in a plasma, it is clear that density, like energy, cannot be zero, since with zero density there is no plasma. Furthermore, while density is always positive, toroidal momentum can be positive or negative (and a sign convention must be defined). These different properties have a direct consequence on the most general expressions of radial particle and toroidal momentum fluxes. A general expression of the radial particle flux reads

$$\Gamma_n = n\left(-D_n \frac{\partial \ln n}{\partial r} + V_n\right), \quad (1)$$

where we observe that particle flux involves only off-diagonal terms which are proportional to density, and therefore can be decomposed in a diagonal diffusive term, with diffusion coefficient D_n, and in an off-diagonal convective term, with convection velocity V_n. In contrast, a general expression for the flux of toroidal momentum $nmR^2\Omega_\phi$, where Ω_ϕ is the toroidal angular velocity, reads

$$\Pi_\phi = nmR\left(-\chi_\phi R \frac{\partial \Omega_\phi}{\partial r} + V_\phi R \Omega_\phi\right) + \Pi_{RS}, \quad (2)$$

where, in addition to diagonal viscosity χ_ϕ and convection V_ϕ, additional terms, in Eq. (2) named Π_{RS}, cannot be excluded a priori. These terms cannot be described as diffusive, nor as convective, since they can be present even when rotation and rotation gradient are zero, and they are usually termed residual stresses. A further consequence is that, while the expression of the particle flux involves the logarithmic density gradient (containing a division by a strictly positive density), the expression of the toroidal momentum flux involves only the linear gradient, since a division by the toroidal velocity cannot be made, because it can be zero.

The expression of the particle flux has the interesting and experimentally testable consequences that stationary density profiles can develop in tokamaks which are centrally peaked, even in the absence of any central source, and that transient response of density profiles cannot be described by diffusion only. Demonstrations of both these properties have been obtained in tokamak experiments (e.g. [9] and [11] respectively). In particular, the fact that density profiles are centrally peaked even in the absence of a central particle source has been realized since the earliest observations in tokamaks [10].

The expression of the toroidal momentum flux includes an additional term at the right hand side, which has a larger variety of implications. In fact, not only in this case any transient response of the toroidal angular velocity cannot be described by simple diffusion, as several works have already demonstrated with transient momentum transport experiments (first in [12] and [13]), and the angular velocity profile can be non-zero even in the absence of an external torque (as observed first in [14] and [15]). In addition, the toroidal angular velocity profile can have whatever shape, even cross zero along the minor radius, which has been observed in several experiments (e.g. [16–18]), and in order to have a rotation profile equal to zero, with zero rotation gradient, an external torque has to be applied, which contrasts the residual stress [19]. Therefore, also in this case experimental demonstrations of all these general properties have been obtained, which provides an overall qualitative agreement between experimental observations and very general basic theoretical expectations. Of course, such an agreement is an indispensable first step in the process of validation of the theoretical models, but of course cannot be considered sufficient to gain a detailed physical understanding of the phenomena and the capability of making predictions for future devices.

As we described in detail in Section 2, more specific comparisons are required to make a step further, in which each theoretically predicted off-diagonal mechanism is experimentally identified and its dependence on parameters is experimentally demonstrated, possibly finding a quantitative agreement between theoretical predictions and experimental observations. This will be the topic of the next two sections, the first dedicated to particle and impurity transport, the second to toroidal momentum transport. The main lines of the historical development of research in these areas over the last decade will be described in order to present the progress in the validation which has been achieved recently by the scientific community. In addition, when applicable, the correspondences with the steps described in Section 2 are pointed out.

From the theoretical standpoint, it is of critical importance to develop complete theories where off-diagonal transport mechanisms are identified and decomposed in the expression of the radial fluxes. We remind that the decomposition is strictly applicable only in the local limit, where gradient lengths of kinetic profiles are large compared to the characteristics scales of the turbulent fluctuations. This allows us to identify an additional difference between particle and toroidal momentum transport, since the physical decomposition of off-diagonal transport mechanisms in particle and toroidal momentum transport cannot be performed applying the same physical arguments.

The decomposition of the radial electron and impurity particle flux can be directly obtained by considering a local limit, with a Maxwellian equilibrium distribution function, as given by usual orderings at the lowest order [20]. Then, considering the radial gradient of the Maxwellian distribution, one can decompose the particle flux in the following form

$$\frac{\Gamma_n}{n} = -D_n \frac{1}{n}\frac{\partial n}{\partial r} - D_T \frac{1}{T}\frac{\partial T}{\partial r} - D_u \frac{R}{v_{th}}\frac{\partial \Omega_\phi}{\partial r} + V_{pn}. \quad (3)$$

In this equation, on the right hand side, the usual diagonal diffusion appears first, then the thermo-diffusion, due to the presence of a (logarithmic) temperature gradient, the roto-diffusion, due to the presence of a toroidal angular velocity gradient, and finally a pure convection term, which exists also in the absence of any gradient of any kinetic profile (the reviews [1, 5] are suggested for a more complete description of the physical meaning of these terms). It is important to realize that while Eq. (3) has to be considered an appropriate physical decomposition, it does not describe a linear relationship. This is because the gradients affect the underlying turbulent plasma state, and therefore impact the transport coefficients, which are themselves a function of the gradients. This decomposition can be rigorously derived from the gyrokinetic equation, and a complete example of this derivation for the electron particle flux can be found in [21].

The same procedure cannot be applied to the decomposition of the toroidal momentum flux. Here the situation is made more involved by the fact that in the local limit, due to symmetry properties satisfied by the gyrokinetic equation [4, 22–25], the radial flux of toroidal momentum is zero unless the symmetry is broken by the presence of additional terms in the equation. The identification of symmetry breaking mechanisms provides a physical way to decompose the radial flux of toroidal momentum. Three main mechanisms can be identified which break the symmetry and deliver finite toroidal momentum flux. The first is connected with the presence of an equilibrium toroidal flow and/or its gradient. The gradient produces the diagonal term, whereas the flow itself is responsible for the turbulent convective term (in addition to and not to be confused with the regular convection which is produced by the presence of a particle flux). As already mentioned, in addition to diagonal and convective terms, the toroidal momentum flux has residual components of the Reynolds stress. These can be produced by two types of mechanisms. The most obvious one is associated with an up-down asymmetry of the magnetic equilibrium configuration. The other is related to the presence of any effect which leads to the development of finite average parallel and radial wave numbers, like for instance an equilibrium E × B sheared flow or several other mechanisms which can be identified when higher orders in the normalized ion Larmor radius parameter ρ_* are considered. In conclusion, a physical decomposition of the momentum flux can be obtained in this form [4, 5, 25]

$$\begin{aligned}\frac{\Pi_\phi}{nmR} &= -\chi_\phi R \frac{\partial \Omega_\phi}{\partial r} + V_\phi R \Omega_\phi + \frac{\Gamma_n}{n} R \Omega_\phi + \\ &\quad + \frac{\Pi_{FS}}{nmR} + M_\parallel \gamma_E + \rho_*^\alpha \frac{\Pi_*}{nmR}. \quad (4)\end{aligned}$$

At the right hand side, first appears the diagonal viscous term [8, 22], then the turbulent (Coriolis) pinch V_ϕ [26–28], then the regular particle convection term with the particle flux Γ_n. These are followed (2nd line in the equation) by the residual stress due to up-down asymmetry of the magnetic equilibrium [29, 30], the term produced by the presence of a shear of the $E \times B$ flow [31–35] and, finally, additional contributions to the residual stress which are connected with higher order ρ_* terms (e.g. reviewed in [4]). In contrast to particle transport, we observe that radial gradients of density and temperature do not appear in this expression, since these gradients to not lead to any symmetry breaking.

4. Validation of Theoretical Predictions of Turbulent Particle Transport

For many years the observation that density profiles are centrally peaked in tokamaks has remained unexplained [10]. Since the earliest observations, it was clear that the peaking could not be explained by neoclassical effects only [36]. From the theoretical standpoint, it has been realized that quasi-linear theories of turbulent transport predict the existence of off-diagonal convective particle (and heat) components [37], in particular connected with the curvature and the inhomogeneity of the confining magnetic field. In particle transport, this inward convection was also identified as a turbulent equipartition pinch [38, 39] through a complementary approach, in which turbulent fluxes are expressed in terms of adiabatic invariants. This convective mechanism, which is today often called "curvature" pinch [40, 41], is predicted to increase the peaking of the density profile with increasing magnetic shear (or increasing peaking of the current density profile). This predicted dependence has been observed in data bases from several experiments, (TFTR [39], DIII-D [42, 43], TCV [44], and JET [45]), and investigated in dedicated experiments in Tore Supra (TS) [46] and FTU [47]. However it appeared also clear that this dependence alone was not able to describe all the behaviors of the density profiles which were observed in tokamaks, because, in other conditions (and particularly in typical H-mode plasmas) this dependence was not observed [48,49]. Furthermore, the density peaking was observed to decrease in response to the application of central electron heating [50–53], but it was also realized that this behaviour was not universal [54, 55]. Finally, it was discovered that in usual H-mode plasmas, the density peaking was decreasing with increasing electron collisionality [48, 49, 56–58]. However, also this behaviour was not observed to be universal, since this behaviour was not observed in typical L-mode plasmas (e.g. in particular [49]). Altogether, these works allowed a fairly comprehensive empirical characterization of the observations, which can be considered to correspond to the step (a) of the validation procedure outlined in Section 2. This very complicated (and apparently contradictory) set of observations can be explained only by a set of theoretical predictions which exhibit a comparable level of complexity. A first general requirement for any theoretical model is to be at least qualitatively consistent with the entire set of these observations.

A long validation process has been carried out in the tokamak physics community over the last decade focusing on particle transport. These studies were dedicated to the investigation of all the convective mechanisms which are theoretically predicted and to their identification in the experimental observations. The theoretical treatment has been mainly based on a local description of the transport produced by ion Larmor radius scale instabilities, that is the ion temperature gradient (ITG) and trapped electron modes (TEM). By means of dedicated works, which is not the aim of the present paper to review in detail (see e.g. the recent review [1]), it has been eventually realized that also from the theoretical standpoint various off-diagonal mechanisms are predicted to occur. These off-diagoanal particle transport components depend critically on the turbulence regime, and can change direction or modify their dominant parametric dependences depending on whether the turbulence is TEM or ITG dominated [1]. Like in a puzzle game in which piece by piece the entire picture is recomposed, a large validation effort has been undertaken, in which at each experimentally observed dependence of the density peaking a corresponding consistent mechanism has been identified theoretically. This part of the validation procedure provides an example of step (b) outlined in Section 2. As already described above, first the consistency between the dependence of density peaking on the peaking of the current density profile was interpreted as the experimental counterpart of the theoretically predicted dependence of the collisionless curvature pinch on the magnetic shear. Then, it has been realized that collisions in ITG turbulence produce an additional contribution to the convection which is directed outward and which can explain the experimental observation that density peaking decreases with increasing collisionality [59]. It was also realized that the thermodiffusion process, which links particle transport to electron heat transport, reverses direction from inward to outward when moving from ITG to TEM. This theoretical prediction was found consistent with the observation that density peaking was responding in different ways to central electron heating depending on conditions [54, 55] and with the observed reversal of thermodiffusion [46]. At this point a critical question remained to clarify to prove a complete consistency between the theoretical picture and the full set of experimental results, namely why density peaking was observed in some conditions (typically in L-mode plasmas) to depend mainly on the peaking of the current density profiles (and not on collisionality) and why in other conditions (typically in H-mode plasmas) was observed to depend mainly on collisionality and not on the peaking of the current density profile. These different behaviours were understood more recently. It has been realized that the impact of collisions and of magnetic shear on the particle convection was also changing depending on the turbulence regime [1, 21, 60], and it has been clarified that the dependence of density peaking on magnetic shear vanishes for strong ITG turbulence, whereas the dependece of density peaking on collisionality vanishes in TEM turbulence (see Ref. [21] for a complete analytical derivation and related numerical results, and Ref. [1] for a more detailed description of the connections among experimental observations and theoretical predictions).

While such a consistency between the entire set of observations collected in different devices and the theoretical predctions was clarified at a general qualitative level, the need of a more specific quantitative validation of the theoretical models to describe the experimentally observed dependences arised. Of course, the dependence which has been considered first has been that which is the most relevant for the prediction of the density profile in the ITER standard scenario, that is the dependence of the density peaking as a function of collisionality, observed in typical H-mode plasmas. Therefore, in addition to the initial comparisons using fluid transport models [48,59], complementary and more complete studies have been performed later. A large set of linear gyrokinetic calculations has been compared with a large database of observations at JET [61] and specific nonlinear simulations of a AUG H-mode plasma at the same collisionality as that expected in the ITER standard scenario were performed [60]. In both studies, a satisfactory quantitative agreement has been found. More recently, also the role of central electron heating in typical H-mode plasma conditions has been more specifically investigated, and a quantitative agreement has been found between linear and nonlinear gyrokinetic simulations and experimental measurements [62], pointing out that, consistently with the experimental observations, central electron heating can increase the peaking of the density profiles in regimes which are dominated by ITG turbulence (this is in contrast to the flattening which is predicted in conditions dominated by TEM turbulence). These comparisons between theoretical predictions and experimental observations provide an example of step (c) presented in Section 2, where a quantitative agreement between theory and experiment has been found.

The predicted role of the turbulence regime in determining the behaviour of the density profile has strongly motivated a corresponding validation based on the direct identification of the turbulence regime by means of fluctuation measurements. This is a critical element of step (d) described in Section 2. The most direct microscopic observable to identify the type of turbulence, ITG or TEM, is the sign of the phase velocity of propagation of the turbulent eddies. While this quantity would allow a direct identification of the turbulence type, ion diamagnetic direction for ITG, electron diamagnetic direction for TEM, its measurement, for instance by Doppler reflectometry, turns out to be extremely challenging since it has been realized that even in the absence of an external torque, the measured perpendicular velocity is dominated by the plasma $E \times B$ rotation. Charge exchange spectroscopy measurements reveal that this is larger than the phase velocity by at least one order of magnitude [63]. Therefore, other diagnostic techniques have been devised in order to obtain an indication of the perpendicular velocity in the plasma frame. A possibility has been investigated in Alcator C-Mod with a phase contrast imaging (PCI) diagnostics, where a weight function to the PCI signal in the line integration is introduced in order to differentiate contributions from the top or the bottom, and by this enabling to resolve the direction of propagation [64]. Another option is given by the identification of a different microscopic observable, which is perhaps less directly connected with the identification of the turbulence type, but for which measurements are easier. A possibility which has been investigated in DIII-D is to measure the cross-phase angle between density and temperature fluctuations [65] by means of a system which combines reflectometry and correlation electron cyclotron emission radiometry. The cross-phase angle between density and temperature fluctuations is expected to decrease in size when moving from ITG turbulence to TEM turbulence, and by this it provides a useful additional information for the identification of the turbulence regimes, when compared with the results of gyrokinetic or gyrofluid simulations.

Of course, while the identification of the turbulence regime by means of the measurements of turbulence characteristics should be regarded as the most direct and conclusive approach, there are also macroscopic observables which can be considered in order to support the analysis of the particle transport behaviour in relationship with the type of turbulence. As we mentioned in the introduction, this is based on the fact that, particularly at ion Larmor radius scales, the transport produced by turbulence is naturally multi-channel, and therefore an important consistency check can be performed by examining the behaviour of other transport channels and in particular the heat fluxes. A clear example of inconsistency is given by a situation in which the presence of trapped electron mode turbulence has to be claimed to explain the behaviour of the density profiles, but the ion heat flux is significantly larger than the electron heat flux. Of course this is the sign of an inconsistency, and the explanation of the behaviour of the particle transport has to be revised. An additional interesting macroscopic observable which provides indications on the turbulent regime can be obtained considering heat modulation experiments, since by these experiments the main driving logarithmic temperature gradient can be identified. This is the electron temperature gradient for TEM, and in these conditions, consistently with the theoretical predictions, one expects the electron heat pulse (incremental) conductivity to be larger than the power balance electron conductivity. In contrast, in ITG turbulence, when the main drive of the transport is provided by the ion temperature gradient, the power balance electron conductivity can become as large or even larger than the incremental electron conductivity [66]. In conclusion, the ratio between the electorn heat pulse conductivity and the power balance electron heat conductivity can be used as an indicator of TEM or ITG turbulence.

Also impurity transport can be considered concomitantly to electron particle transport in order to assess the consistency of the theoretical explanation of the observations in both transport channels. In addition, impurity transport provides an additional handle to identify the different processes at play, since the off-diagonal impurity transport mechanisms can be discriminated through the different dependences on impurity charge and mass, which reflect the dependences of the relevant resonant perpendicular or parallel gyro-centre motions, which are responsible for the off-diagonal transport component [67–71].

Of particular interest for the present review, dedicated to common aspects of particle and momentum transport, is the roto-diffusion term [71]. The roto-diffusion is produced by the presence of a radial gradient of the equilibrium parallel (toroidal) flow, and it is non-zero in the presence of a non-zero equilibrium flow, or of any other mechanism which introduces a finite average parallel wave number in the system, breaking the local symmetry of the gyrokinetic equation. In fact, the roto-diffusion coefficient can be thought as produced by the radial flux of a parallel velocity fluctuation, and it shares the same properties of the parallel (toroidal) momentum transport, which will be discussed in the next section. Similarly to other particle transport coefficients, its sign depends on the turbulence regime, and it is directed outward for ITG modes, and inward for TEM modes [71]. This off-diagonal component should be invoked to explain the locally hollow boron or carbon impurity density profiles observed in rotating plasmas [62]. Ongoing work is assessing the role of roto-diffusion through a careful quantitative comparison between linear and nonlinear gyrokinetic simulations and the experimental observations, which are found to be in quantitative agreement within error bars [72]. This provides an additional example of progress in the validation, which is enabled by the physical understanding of a specific dependence which is experimentally observed and consistently predicted by theory.

In conclusion, over the last decade a large effort in the theoretical development of models for turbulent particle transport and in their validation against the experimental observations has been carried out by the tokamak physics community. This allows us to be in a much better condition at present to predict the density profile in future devices. Apparentely contrasting behaviours of the density peaking which have been observed at a macroscopic level have been explained within a unified framework in terms of turbulent transport mechanisms at the microscopic level.

Of course, it is also our opinion that the process of validation is actually never ending, since a model can be only conclusively devalidated, but not conclusively validated. Therefore the studies on particle transport are still progressing, and most recent efforts are being (and should be) dedicated to the study and the modelling of transient transport responses of density profiles, in particular in response to modulated particle sources or to auxiliary heating power. This allows the validation to be extended also to the separate magnitudes of D and V, and not only to their ratio, which cannot be studied in stationary phases.

5. Validation of Theoretical Predictions of Turbulent Toroidal Momentum Transport

Early experimental studies on toroidal momentum transport where mostly dedicated to the comparison between the momentum confinement time and the energy confinement time and found that this ratio has a very limited variation, as limited is the observed variation of the Prandtl (Pr) number, that is the ratio of the toroidal plasma viscosity to the ion heat conductivity [12, 73–78]. These experimental observations have a direct theoretical counterpart which is provided by the prediction of a limited variation of the Pr number [4,8,22]. However, studies dedicated to the transient response of toroidal angular velocity to variations or modulations of the external torque [12,13], as well as the observation of intrinsic rotation [14, 15], namely the presence of an intrinsic rotation in the plasma in the absence of any externally applied torque lead to the realization that a simple description of toroidal momentum transport by means of a diffusive equation was by far not appropriate.

The theoretical understanding of the mechanism by which turbulence can pinch an equilibrium toroidal flow inward came more recently [26–28]. Analogously to the particle curvature pinch, this pinch mechanism is connected to the presence of an inhomogeneous and curved confining magnetic field, and in the frame which is corotating with the plasma can be elegantly formulated as a consequence of the inertial Coriolis drift [26]. Differently from the usual curvature drift, which is proportional to the square of the parallel velocity of the gyrocenter, the Coriolis drift is proportional only to the first power of the parallel velocity, and as such directly couples density and temperature fluctuations with parallel velocity fluctuations, which are then radially transported by the fluctuating $E \times B$ drift. The theoretical identification of this mechanism has given new hope to the community to shed light to the basic processes which govern the behaviour of the toroidal rotation of the plasma in a tokamak. A large experimental effort has been dedicated in order to identify the parametric dependences of the experimentally observed convection. The investigations have been carried out with torque modulation experiments, produced by modulation of the NBI power [12, 79–86, 101], or by means of transients of the toroidal velocity due to a plasma brake induced by the application of nonresonant magnetic perturbations [81, 87, 88]. More recently, an alternative approach based on the analysis of a large data base of stationary phases of beam heated plasmas at JET has also allowed the identification of the presence of a convective mechanism through an extended statistical analysis, and the main dependences of this convective component have been singled out by means of multivariate regressions [89,90]. These works have produced an experimental characterization of the phenomenology, and can be considered to be part of step (a) described in Section 2. Moving to step (b) of Section 2, quasi-linear gyrokinetic calculations have been performed for all the observations of the database, and analyzed with the same statistical approach. The logarithmic gradient of the measured toroidal angular velocity is slightly underpredicted by the gyrokinetic calculations, particularly in conditions where the residual stress can be expected not to be completely negligible [90]. Even more interestingly, the same main parametric dependences have been found in the regressions of the experimental and the gyrokinetic results. Practically the same regression coefficients have been found for the logarithmic density gradient, the inverse aspect ratio and the safety factor. Such a level of consistency between observations and predictions allows the identification of the experimentally observed momentum pinch with the theoretically predicted Coriolis pinch. The main dependences on the logarithmic density gradient and on the inverse aspect ratio have been also found in transient transport experiments [80,84,86], however in these experiments the pinch is often observed to be larger than that theoretically predicted or than that experimentally deduced by the analysis of the data base of stationary phases with torque. The clarification of these differences, and the consideration of alternative approaches to analyse the modulation experiments and assess the uncertainties (see e.g. [91] for an alternative analysis method) are among the present priorities.

While the physical identification and theoretical understanding of the mechanism producing a toroidal momentum pinch has to be considered a major achievement of the transport community in the last 5 years, it is clear that the combination of viscosity and pinch cannot, by any mean, explain the extremely complex amount of observations of intrinsic rotation that tokamak experiments are increasingly producing over the last years [16–18, 92–98]. As we already mentioned in Section 3, the observations of intrinsic rotation and, more in general, the experimental indications of the existence of a residual stress are the major qualitative differences between particle and momentum transport. These differences also imply that the phenomenological characterization of momentum transport is more complex than that of particle transport. Therefore, differently from the other transport components of particle and momentum transport, in the area of the residual stress and intrinsic rotation we are still at the early stages of the validation route outlined in Section II, where no clear identification between theoretically predicted mechanisms and experimental observations has been reached yet.

There is however a good exception, because at least the role of one specific mechanism (although not of primary importance) has been unambiguously identified in theory and in experiments. This is the residual stress arising from an up-down asymmetry of the magnetic equilibrium [29, 30]. The theoretical predictions for this specific (geometrical) symmetry breaking mechanism have been validated against a set of experiments performed in the TCV tokamak, where the flexibility in magnetic configurations has allowed to test all possible combinations in signs of current, field, and up-down reversal of the magnetic configuration, which are theoretically expected to change the sign of the residual stress. A complete consistency between theoretical predictions and experimental observations has been found [99, 100], This provides another example of a very clean validation of a specific theoretically predicted mechanism.

However, while this is is certainly an interesting result, this residual stress component is present only at the edge of the plasma and even at the edge cannot be expected to provide the dominant component of the residual stress. Both experimental results and theoretical arguments suggest that the residual stress is particularly large at the edge [81], and there are experimental evidences that the toroidal rotation at the edge pedestal top is mainly determined by the pressure gradient [101, 102] or more specifically by the ion temperature gradient [103, 104]. This is at least qualitatively consistent with a theoretical model which identifies a relationship between toroidal rotation and ion temperature at the edge [105]. There are additional evidences which show that the turbulent stress as measured by probes is not consistent with the total stress which is estimated from the rate of change of cumulative angular momentum of the plasma after the L-H transition, and requires the presence of additional contributions, likely related to ion orbit losses [106, 107], the effect of which also increases with increasing ion temperature [103]. Recently, an empirical scaling for the edge intrinsic torque for DIII-D H-modes which combines the effects of pedestal pressure gradient, orbit losses, and finite rotation has been derived [107]. It is presently planned to extend this study in order to include contributions from other devices and better determine the scaling with respect to the device size, that is with respect to the normalized Larmor radius ρ_*, which plays a critical role for an extrapolation to ITER.

Moving towards the core, the observations of spontaneous reversals of the intrinsic toroidal rotation in response to variations of the plasma density, or of the application of torque free external heating, provide an extremely interesting body of experimental results which can be expected to shed light on the physics of the residual stress [16, 18, 93–98]. In addition, at least partly consistent behaviours of the toroidal rotation profile have been observed in response to the application of central electron heating, both in torque free conditions as well as in NBI heated plasmas [17,96,108,109]. This can be considered a promising progress within the step (a) presented in Section 2. However the theoretical explanation for these observations is still unclear, and the effects of turbulence driven residual stresses and of the neoclassical toroidal viscosity induced by an internal kink mode [109] are both presently considered and concurrently possible. Therefore, the general question which still remains open is which theoretically predicted mechanisms of residual stress are responsible for these observed behaviours of the toroidal angular velocity. To make progress in this difficult validation effort, from a theoretical standpoint, it is crucial to identify the parametric dependences of the various residual stress mechanisms and how these are affected by a change in the dominant turbulence regime (in particular from ITG to TEM turbulence). Two mechanisms which are expected to play an important role are the residual stress produced by a $E \times B$ sheared flow [31–35] and the residual stress which is produced by the radial variation of the profiles, usually called "profile shearing" [35, 110] or, directly connected, by the radial variation of the turbulence intensity [111].

Both mechanisms produce a displacement of the maximum of the averaged electrostatic potential structure from the low field side mid-plane and by this lead to the development of a finite average radial wave number. Such an asymmetry produces a finite momentum flux. While the contribution to the radial electric field shear which comes from the toroidal velocity provides a correction to the diagonal viscosity (and decreases the viscosity for usual monotonic safety factor profiles), the pressure and poloidal rotation terms produce a momentum flux even in the absence of any toroidal rotation or toroidal rotation gradient, and therefore contribute to the residual stress. For a positive value of the $E \times B$ shearing rate, that is when the radial electric field due to poloidal and diamagnetic components increases with increasing minor radius, and with usual monotonic safety factor profiles, the residual stress is negative, that is it produces the same effect on the toroidal rotation profile as a co-current external torque. Finally, the residual stress reverses direction with a reversal of the sign of the $E \times B$ shearing rate, a reversal of the sign of the magnetic shear, but not with a reversal of the direction of propagation of the turbulence eddies, namely with a change of the turbulence from ITG to TEM [34, 35]. In contrast, the residual stress produced by profile shearing changes sign with a change of turbulence from TEM to ITG, since the average tilt of the eddies (and by this the sign of the average radial wave number) changes when moving from ITG to TEM turbulence [110]. It has the effect of a co-current external torque for ITG turbulence, and the opposite effect of a counter-current external torque for TEM turbulence. In addition, theoretical arguments based on linear analytical [23, 110] and numerical results [97] indicate that, for a given tilt of the mode structure along the field line, the size of the residual stress relative to the viscosity increases with increasing normalized logarithim density gradient R/L_n. This body of theoretical results, particularly related to the profile shearing effect, awaits confirmation by means of global nonlinear simulations, which are very computer time demanding, since require averages over very long time windows to be trustworthy for momentum transport studies.

From the experimental standpoint, the characterization of the behaviour of the intrinsic toroidal rotation is of particular interest for the identification of the dominant theoretically predicted residual stress mechanisms, which is the critical first step to be performed in the way towards validation. The observation of intrinsic toroidal rotation reversals is particularly intriguing. Recent studies on AUG have correlated the reversal of the toroidal angular velocity profile, from centrally peaked and co-current to hollow and counter-current in the center, with the transition from dominant ITG to dominant TEM turbulence and the concomitant increase of the logarithmic density gradient R/L_n [96, 97]. Consistently, a correlation has been observed between R/L_n and the normalized toroidal angular velocity gradient $u' = -R^2 \mathrm{d}\Omega/\mathrm{d}r/v_{th}$, where Ω is the toroidal angular velocity. This correlation can be interpreted as an experimental indication of the fact that the size of the residual stress is large when the logarithmic density gradient is large.

These results connect the physics of intrinsic toroidal rotation with particle transport and with the turbulence regimes. In fact, as described in the previous section, the shape of the density profile is largely determined by the type of turbulence, and centrally peaked density profiles are predicted to develop in the turbulence regime where a combined TEM and ITG turbulence is present, close to the transition between ITG and TEM dominant linear instability domains, on the TEM side [21]. This transition domain of combined ITG and TEM turbulence not only leads to the maximum peaking of the density profile, but it is also expected to reverse the sign of the residual stress componened produced by profile shearing. The latter is predicted to produce the effect of a counter-current external torque when the turbulence is in the TEM regime, and by this can lead to the development of a centrally hollow intrinsic rotation profile [5, 97]. Analogous physics processes can be considered to explain the reversal from co- to counter-current of the intrinsic toroidal rotation profile which is observed in Ohmic plasmas moving from the linear to the saturated confinement regimes. Away from the turbulence regime of combined ITG and TEM turbulence, the density profiles are predicted to be flatter [1, 21], and this explains why in these conditions the effect of the residual stress becomes less pronounced, and usually somewhat flat intrinsic toroidal rotation profiles are observed.

In the short future, the consistency among the results obtained in various devices, particularly AUG [96, 97], Alcator C-Mod [98, 112], DIII-D [17] and TCV [94], should be considered as one of the next steps required to make progress towards a common physical characterization of this complex phenomenology. The development of a multi-device database of intrinsic rotation profiles should be particularly helpful to reach this goal.

6. Conclusions

In this paper the main aspects of particle and momentum transport have been reviewed, pointing out similarities and differences, and highlighting aspects of the research in the comparison between theoretical predictions and experimental observations as well as in the ongoing validation efforts. Density and toroidal angular velocity profiles in tokamak plasmas share the common property of being at least partly (or even almost exclusively in some conditions) determined by the balance of (usually outward) diagonal diffusion and (usually inward) off-diagonal components of the radial flux. The research on these off-diagonal contributions is of extreme physical interest for the understanding of the properties of turbulent transport, and of high relevence for nuclear fusion applications.

The existence of these off-diagonal transport components has been predicted in theory and has been demonstrated in experiments. This result provides a qualitative agreement at a very general level between theoretical predictions and experimental observations from which a more specific validation process can start. In the paper we have provided examples of how the validation in different areas has made progress, and tried to outline a common route that validation has to follow when dealing with the complexity of transport channels which are characterized by the presence of off-diagonal transport components. An essential element for validation is the physical understanding of the observation. A critical step to reach this is provided by the identification of the correspondence among off-diagonal components which are theoretically predicted and those which are experimentally observed. Transport channels which are characterized by the presence of large off-diagonal transport components require the development of comprehensive theoretical frameworks for the understanding of the (sometimes apparently contraddicting) experimental observations. Thereby, a bridge can be established between macroscopic behaviours of the density and toroidal rotation profiles, and the microscopic properties of the turbulence. In the establishment of this relationship, which is a big part of the validation procedure, the investigations on additional transport channels (the heat fluxes in particular) and with available fluctuation measurements allows the assessment of the physical interpretation of the observations to be more complete and consistent, and the validation potentially more conclusive. Particularly at the ion Larmor radius scales, turbulent transport is inherently multi-channel and has to be investigated as such, assessing the consistency over the entire transport matrix

Particle transport provides a particularly interesting example of a topical area where the connection between macroscopic behaviours and microscopic properties of the turbulence can be built, since many off-diagonal transport components change direction or change their main parametric dependence as a consequence of a change in the dominant turbulence, in particular if ITG or TEM driven. There is an overall consistency which has been found at a qualitative level, and specific quantitative agreement has been demonstrated on some specific dependences which have been considered of high priority due to their relevance in the prediction of the density profile in ITER. This body of results provides one of the most robust validations of the paradigm of microinstabilities and turbulence as the main cause of transport in the core of tokamaks, and indicates that the behaviour of the density profile can be interpreted as a macroscopic fingerprint of the type of turbulence present in the plasma [1].

The validation process in toroidal momentum transport is presently at a more initial stage with respect to particle transport, due to the higher complexity of the topic, which presents off-diagonal components which are both of convective and non-convective type (the residual stress). However, in recent years major progress has been obtained in the validation, particularly in the theoretical identification of the process by which turbulence can pinch inward an equilibrium toroidal flow and its almost conclusive identification in the experimental observations, with first demonstrations of a quantitative agreement among the predicted and the observed main parametric dependences. In contrast, the investigations dedicated to the role and size of the different residual stress mechanisms to explain the observations are still in the phase where a correspondence between the theoretical predictions and the experimental observations has to be established. Main challenges here are provided by the complications in quantitatively computing these contributions (which often require physically comprehensive global codes) and the difficulties in experimentally estimating these components of the transport. From the theoretical standpoint, it is clear that realistic theoretical predictions require very complete models, and that simplified formulations are very often inadequate.

In describing the research on both particle and toroidal momentum transport, we have pointed out clear experimental evidences of theoretically predicted connections between particle and toroidal momentum transport. In particular the strength of the toroidal momentum pinch is predicted and observed to increase with increasing logarithmic density gradient, and toroidal rotation is theoretically predicted and experimentally observed to flatten the low Z impurity density profiles. In addition, there are both theoretical and experimental indications that density peaking increases the impact of the residual stress on the toroidal rotation profile. This opens the area of studies related to the connections among the residual stress, particle transport and the turbulence regimes, which determine both of them. It can be expected that many studies will be dedicated to this topic in the short future.

In conclusion, the comparisons between theoretical predictions and experimental observations of off-diagonal particle and toroidal momentum transport provide very interesting examples of the complicated validation process which is presently ongoing in the magnetic fusion scientific community. The main goal of this research has to be considered the identification of the correspondence between the off-diagonal transport components which are experimentally observed and the transport mechanisms which are theoretically predicted. A critical aspect is the research of dependences of the off-diagonal transport components on theoretically relevant plasma parameters, which are consistently observed in different devices, and which are quantitatively predicted by realistic theoretical models. When a quantitative agreement (within small enough quantified uncertainties) is found between parametric dependencies in both experimental observations and theoretical predictions, then this result delivers a level of reliability which goes beyond a statistical validation on even large amounts of data over certain metrics. Such an agreement allows the identification of generic dependencies among plasma parameters, and aims at improving the understanding of the physics.

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