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Turbulent transport in fusion magnetised plasmas/Transport turbulent dans les plasmas magnétisés de fusion

Intermittency and structures in edge plasma turbulence

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Abstract

A view of the mechanisms underlying particle and energy transport in fusion plasmas devices is presented. Heat and energy transport in fusion plasmas is partly due to turbulent processes having an intermittent character and presenting some universal features. The improved understanding of intermittent turbulent transport is changing the standard picture of transport, based on local diffusive mechanisms. The development of new diagnostic methods and the improvement of modeling tools are spawning a new era in fusion plasma research, in which the non-equilibrium aspects of the systems under study is carefully taken into account in order to unravel the global picture connecting transport, gradients and flows. ***To cite this article: C. Hidalgo et al., C. R. Physique 7 (2006).***

Résumé

Intermittence et turbulence dans les plasmas de bord. Cette revue présente les mécanismes sous-jacents au transport de particules et d'énergie dans les plasmas de fusion magnétique. Le transport de chaleur et d'énergie dans les plasmas de fusion est partiellement due à des processus turbulents qui présentent un caractère intermittent et des propriétés universelles. La compréhension croissante du transport turbulent intermittent change profondément la description usuelle en terme de mécanismes diffusifs locaux. Le développement de nouveaux diagnostics et l'amélioration des outils de modélisation ouvrent une nouvelle voie dans les recherches sur les plasmas de fusion. Dans cette nouvelle approche, les aspects hors-équilibre des systèmes étudiés sont intégralement pris en compte afin de conduire à une description globale reliant le transport, les gradients et les écoulements. ***Pour citer cet article : C. Hidalgo et al., C. R. Physique 7 (2006).***

Keywords: Plasma fusion; Edge plasma; Turbulence

Mots-clés : Plasma de fusion ; Plasma de bord ; Turbulence

1. Introduction

A confined thermonuclear plasma is far from equilibrium, due to strong external drives that maintain steep gradients in the thermodynamic parameters. The most obvious relaxation mechanism is via Coulomb collisions; in toroidal devices (tokamaks and stellarators) the resulting particle and energy flows are described by neoclassical transport theory [1]. However, experimentally observed transport does not, in general, agree with the calculated (neoclassical)

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values. In particular, electron energy transport can be over two orders of magnitude larger than the predictions from neoclassical theory; transport is anomalous.

The heat and particle transport in fusion plasmas is generally due, in part, to turbulent process associated with small-scale instabilities driven by the inhomogeneity of density and temperature profiles in the direction normal to the magnetic surfaces. The magnitude of turbulent transport is probably the dominant parameter affecting the global confinement properties and hence the economical performance of a fusion reactor. Understanding the physics of anomalous transport in fusion devices remains one of the key issues in magnetic fusion research.

Heat and particles are transported from the plasma core to the plasma boundary. At least two areas with different magnetic topology can be distinguished around the plasma boundary of fusion plasmas: the plasma region located inwards from the Last Closed Flux Surface (LCFS), and the so called scrape-off layer (SOL) region, in which the field lines intersect material surfaces. Near the Last Closed Flux Surface (LCFS), sheared flows develop in all magnetic confinement devices, thus providing a convenient point of reference in the plasma boundary region of fusion devices. The influence of sheared flows on turbulence and transport has been a very active area of investigation in nuclear fusion research [2].

Characterizing fluctuation driven particle and energy fluxes requires experimental techniques for measuring the variations in parameters such as density, temperature, and magnetic and electric fields with good temporal and spatial resolution. Until recently, this kind of measurement was mostly limited to the plasma edge where material probes can be applied. The use of probes arrays and more recently 2-D beam emission spectroscopy and fast visible cameras [3] has permitted a transition from mostly single point measurements to 2-D visualization. This improvement in plasma diagnostics is providing a route to a better understanding of edge turbulence. In parallel, the improvement in plasma modeling tools allows a better study of the complex coupling between profiles, plasma flows and turbulence.

2. Edge turbulent transport in fusion plasmas

Broadband electrostatic and magnetic fluctuations have been observed in the boundary region of magnetically confined plasmas for a long time. Edge fluctuations show features of well developed turbulence with high fluctuation levels, in the range of 10–30%, dominated by frequencies below 500 kHz.

Electrostatic fluctuations produce a fluctuating radial velocity given by $\tilde{v}_r = \tilde{E}_\theta / B$, $\tilde{E}_\theta$ being the fluctuating poloidal electric field and B the toroidal magnetic field. Then, the electrostatic fluctuation driven radial particle flux is given by $\Gamma_{E\times B}(t) = \langle \tilde{n}(t)\tilde{E}_\theta(t)\rangle / B$ ($\tilde{n}$ being the level of density fluctuations). Particle transport induced by edge electrostatic fluctuations is large enough to account for a significant part of particle transport in the plasma boundary region, although the interpretation of experimental measurements (mostly based on probe diagnostics) is still under active debate.

Fig. 1 shows a typical turbulent transport signal ($\Gamma_{E\times B}$) measured in the plasma boundary region of fusion devices. At first glance, the intermittent character of fluctuations is obvious; and applying some elementary analysis, it can be shown that a significant fraction of the turbulent transport (of up to 50%) can be attributed to the presence of large and sporadic transport events. The properties of intermittent transport have been investigated extensively in both fusion and non-fusion plasmas [4]. Also, empirical results show an unexpected universality in the statistical properties of

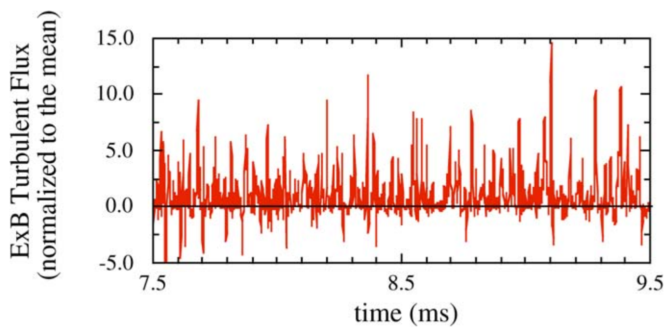

Fig. 1. Time evolution of fluctuation induced particle transport in the plasma edge.

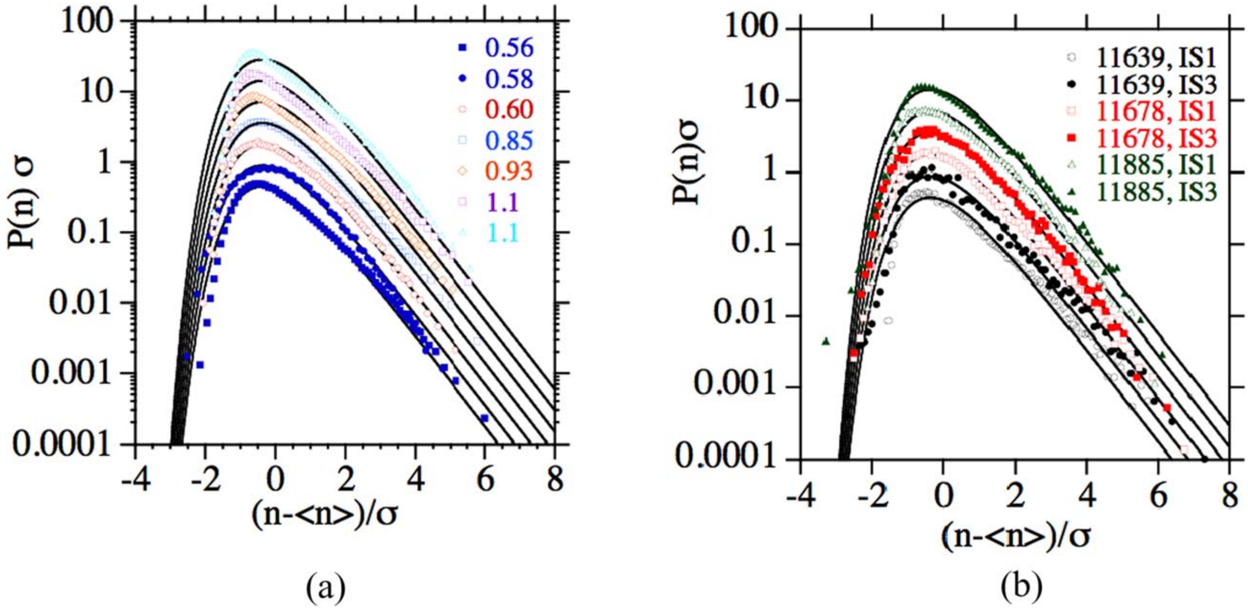

Fig. 2. The statistical properties of edge fluctuations show universal properties. (a) Rescaled density fluctuation pdfs measured in the SOL of C-Mod for increasing line integrated densities; except for the curve at the lowest density, all curves are displaced vertically by factors that are a multiple of 2. (b) Rescaled density fluctuation pdfs measured in the far SOL of TJ-II. (Reproduced from PoP 12 (2005) 052507.)

turbulence [5], providing a possible connection between the study of turbulent plasma transport and other complex systems (Fig. 2).

A critical parameter determining reactor economics is the maximum ratio of plasma pressure to magnetic field pressure (β); the thermonuclear power (P_{th}) is given by $P_{\text{th}} \approx \beta^2 B^4$, where B is the toroidal magnetic field. Pressure gradient instabilities ('interchange instability') seem to play an important role in setting a maximum β value. Fig. 3 shows the way in which this instability can develop in the plasma edge region in the presence of a magnetic field which comes out of the page and decreases with the distance to the plasma boundary (Fig. 3(a)). In Fig. 3(b), the plasma has developed a sight hump; the ions and electrons drift in opposite directions under the influence of the inhomogeneous magnetic field (∇B drift), resulting in an electric field (Fig. 3(c)). Under the combined influence of this electric field and the magnetic field the small bump will tend to grow, creating an unstable situation in the plasma region in which the magnetic field intensity decreases as one moves radially out of the plasma boundary region. As a consequence of this mechanism, strong poloidal asymmetries are expected in the amplitude of fluctuations and turbulent transport, the maximum corresponding to those regions where the magnetic field intensity decreases as one moves away from the plasma. This simplified picture is globally consistent with experimental results. The fluctuation level has been studied on the inboard (high field) and outboard (low field) side in several devices. Recent experiments show that the fluctuation level can be more than a factor of ten higher on the low field side as compared to the high field side, showing clear evidence of strong poloidal asymmetries in the level of fluctuations [6]. However, no systematic comparison of the intermittent behavior of fluctuations at the inward/outward regions of the torus is available yet.

A new approach to plasma confinement and turbulence based on the idea of self-organized criticality (SOC) has been put forward. The characteristic sandpile models used in SOC are the simplest realization of strongly driven systems, far from equilibrium, with an instability threshold, and represent a first attempt at handling such non-equilibrium systems. These types of models reproduce some of the basic phenomenology observed in fusion plasmas, such as profile stiffness and the rapid propagation of perturbations. It is shown that transport becomes strongly non-diffusive (self-organized) when the critical mechanism is active. Although SOC provides only a partial answer to the many questions that have been raised, it has prompted the development of some novel probabilistic transport models that are fundamentally non-local and may be more relevant to fusion transport studies (see below).

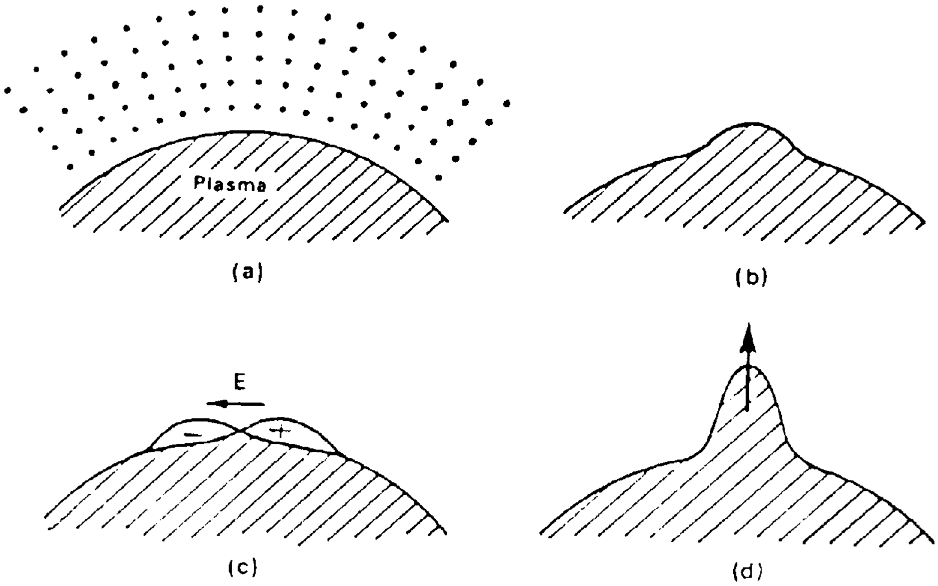

Fig. 3. Development of interchange instability in a toroidally confined plasma.

3. Transport intermittency, radial electric fields and flows

Radial electric fields play a key role in the explanation of transport in fusion plasmas. Sheared poloidal flows can influence the turbulence via shear decorrelation mechanisms and, as a consequence, modify the induced transport. A strong radial gradient in the radial electric field (E_r) produces strong shear in the particle ($E_r \times B$) drift velocity (B being the toroidal magnetic field). This tears apart the coherent cellular pattern of the unstable modes. This effect can be expressed by a decorrelation time which is proportional to the inverse of the radial gradient of the radial electric field, $\tau_c \approx B^{-1}(\mathrm{d}E_r/\mathrm{d}r)^{-1}$. On the other hand, the decorrelation time due to background diffusion is estimated by $\tau_b \approx L_c^2/D$, where L_c is the radial scale length of fluctuations and D is the diffusion coefficient. When τ_c is smaller than τ_b, the sheared flow reduces the radial scale (correlation) length of the fluctuations, and consequently the level of anomalous transport. Historically, this mechanism for reducing turbulent transport was proposed for the explanation of the transition to the High Confinement mode (H-mode), which is now obtained routinely at the plasma edge and corresponds to the formation of a local transport barrier.

Fig. 4 shows how instabilities driven by different free energy sources (i.e., gradients) can produce turbulence (via non-linear saturation mechanisms). Sheared flows (electric fields) can damp the turbulence level, and the resulting transport can influence the gradients (the free energy source) themselves—giving rise to a feedback loop. The discovery of the stabilizing effect of sheared flows on plasma turbulence brought on a new era in nuclear fusion research. Recently, the best fusion performance to date has been obtained in plasma conditions where turbulent transport reduction by shear decorrelation is taking place. For the first time, it has been possible to reduce the rate of ion thermal transport to the minimum level set by particle collisions (neoclassical transport) over the whole plasma. These results represent a revolutionary step forward in the control of plasma turbulence and transport.

Although understanding the physics underlying the generation of flows is a key issue in the plasma physics fusion community, the interplay between sheared flows, intermittent transport events and turbulence still remains an active area of research. The influence of sheared flows on the statistical properties of fluctuations has been studied, showing that probability distribution functions become more Gaussian in the presence of perpendicular sheared flows (Fig. 5). Also, fluctuation signals show a bursty character with spikes that are asymmetric in time. This time asymmetry of fluctuation events is minimum close to the shear layer [7]. These characteristics have been observed both in fusion and low temperature plasmas.

However, visualizing the predicted tilt of convective cells and eventually their break-up once the shear flows reach the critical value ($\tau_b \approx \tau_c$), using, e.g., 2-D imaging techniques, remains an open issue. The critical test for this basic prediction of the shear decorrelation model (put forward more than 15 years ago) is a real challenge for experimen-

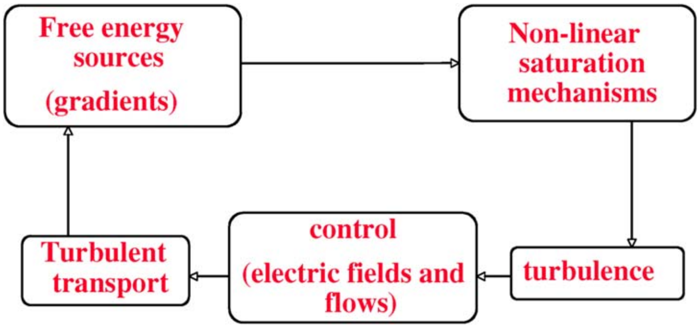

Fig. 4. Link between plasma free energy sources, turbulence, sheared flows and turbulent transport.

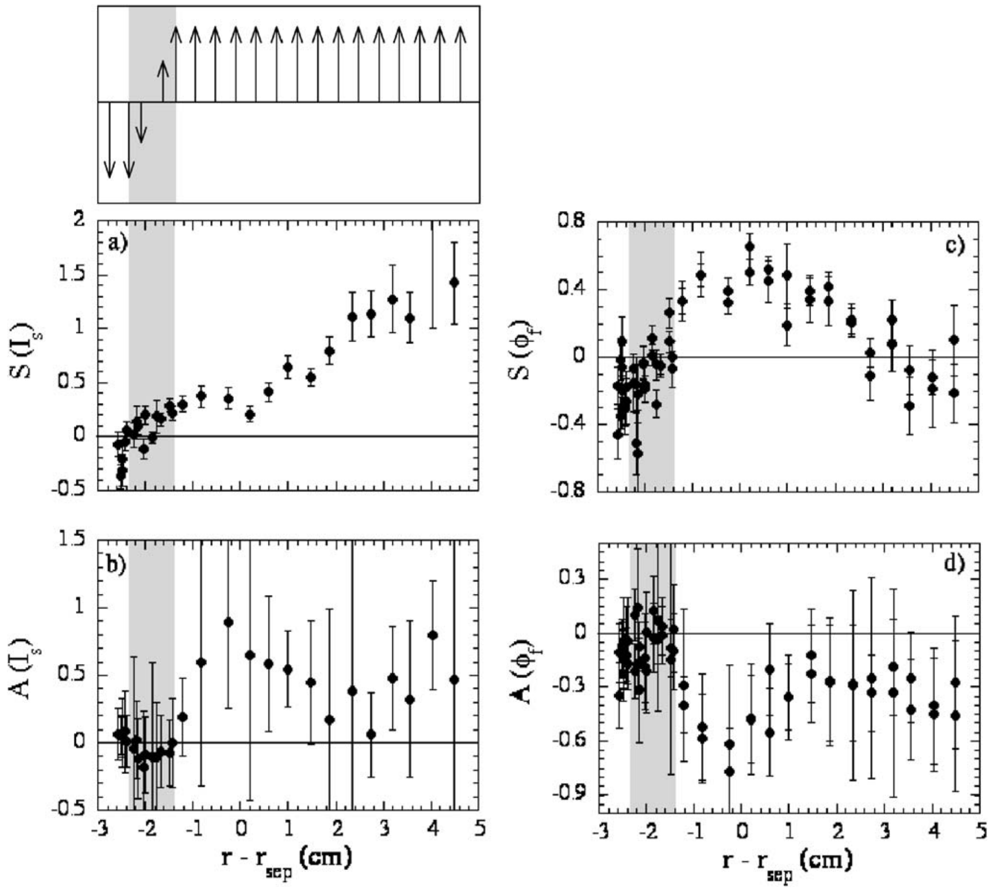

Fig. 5. Skewness (S) and asymmetry in time asymmetry of turbulent events (A) in ion saturation current (I_s) and potential in the plasma boundary of JET tokamak. The skewness (S) gives a measure of the degree of symmetry of the PDF with respect to its mean value. Positive values of A indicates that the signal has on average fluctuations with a rise time shorter than its decay time. The gray band shows the zone where the radial gradient in the perpendicular velocity is largest.

talists. On the other hand, turbulent events (blobs) may also provide an additional mechanism for flow generation via Reynolds stress (e.g., eddy tilting). Quantifying the importance of such mechanisms is an active area of research, while zonal flow generation has already been identified in the plasma edge region [8–10].

4. Statistical description of edge transport and blob dynamics

Edge transport is bursty and, as a consequence, in order to understand the mechanisms underlying turbulent transport it is important not only to compute the average value of the fluctuation induced transport, but also the statistical distribution of the time resolved turbulent flux, since the time-averaged flux may depend in a sensitive manner on the details of the tail of the distribution. If the tails are important, the extrapolation of results to machines of larger size is non-trivial, making it urgent to elucidate this issue. In the framework of this *new way of thinking,* the statistical description of transport processes in terms of probability distribution functions replaces the calculation of effective transport coefficients.

A probabilistic model of particle transport, based on the use of probability distributions for individual particle motion, leading to a Master Equation describing collective motion, has been developed [11]. This model is quite general and makes no assumptions regarding the type of transport taking place. In particular, the model offers a framework to combine neoclassical and turbulent transport in a natural fashion. An important issue addressed by this methodology is that of locality. All standard approaches to transport (including neoclassical transport) are based on the locality assumption, i.e., the assumption that typical (particle) step sizes are small with respect to any other transport scales, in particular gradient scale lengths. However, strongly driven fusion plasmas are characterized by extremely large gradients that probably violate this assumption, making the use of a (non-local) Master Equation inevitable to avoid an erroneous interpretation of, e.g., measured convective velocities. A toy model based on these ideas, incorporating a critical gradient mechanism, showed a range of properties very similar to the behavior of actual fusion transport experiments. The resulting system is quite complex and demonstrates that a straight-forward approach based solely on average transport coefficients cannot hope to capture the essence of this type of systems. Currently, work is underway to determine the probability distributions of relevant transport quantities, in order to justify the use of the Master Equation experimentally, and hopefully leading to a deeper understanding of transport as well as improving transport predictions.

Related to the above, the study of the properties of large intermittent turbulent transport events (also called blobs, a.o.) has changed the standard picture of transport based on local (slow) diffusive mechanisms. This is particularly clear in the far SOL region where plasma density profiles are in some conditions rather flat and, as a consequence, diffusion mechanisms are expected to be negligible, while intermittent convective transport is believed to play the dominant role.

Statistical analysis techniques and 2-D imaging diagnostics have identified, and in the case of 2-D imaging techniques even visualized, plasma structures with dimensions of a few centimeters in the direction perpendicular to the magnetic field and elongated along the magnetic field (a filament-like structure). Large transport events are seen to propagate radially with velocities of about 1000 m/s.

Different models have been developed to explain the dynamics of blobs [12]. A basic model has been constructed, in which blobs propagate radially due to the ∇B plasma polarization and associated $E \times B$ drift (see Fig. 3). An alternative approach to turbulent transport and the convection of turbulent structures is by a 2-D fluid turbulence model based on the interchange instability [13,14].

To clarify the mechanisms that are at work, it is important to understand the possible link between the radial velocity and other properties of the transport events, and to compare blob arrival time to the plasma wall as compared with the characteristic time of transport to the divertor plates (along the magnetic field). The order of magnitude of the measured radial blob propagation velocity suggests that a competition between both parallel and radial transport is needed to explain particle losses in the SOL region of fusion plasmas (i.e., to predict the particle and energy fluxes onto the divertor plates in ITER). From the theoretical point of view, some models conclude that the radial speed increases as the square root of the blob size [14] whereas others [12] predict a radial blob velocity inversely proportional to the blob size. In the first case, the larger the size, the more important the radial transport, implying an increase of plasma-wall interaction in large fusion devices, with an impact on the final choice of plasma wall protection in ITER.

Plasma collisionality plays an important role on edge turbulent transport [15]. At high collisionality radial transport increases, a result which has been connected with the disappearance of edge shear flows in the proximity of the plasma density limit.

A non-linear relation between the local heat flux and gradient, such that the heat flux increases non-linearly as the gradient becomes steeper, can explain the confinement degradation with increasing heating power that has been reported in all magnetically confined fusion plasmas. Instabilities governed by a threshold, as in a typical self-organized critical (SOC) system, will typically produce transport events at all scales, called avalanches, connecting remote regions of plasma. In the context of these models, the functional dependence between the flux and the gradient is expected to show a sharp increase as the system crosses the instability threshold. Indeed, the transition to improved regimes typically suggests such a non-monotonic relation (bifurcation) between gradients and fluxes at a given specific position (the transport barrier). On a global level, however, the analysis is complicated due to the fact that the (non-linear) relation between fluxes and gradients may not be the same throughout the plasma. This is an issue that is still largely unexplored, and the precise regulating mechanism of turbulent transport throughout the plasma is not understood theoretically, nor characterized experimentally (e.g., dependence of degree of intermittency/blob size and dynamics versus proximity to instability thresholds).

5. Conclusions

There have been significant changes in the understanding of mechanisms underlying particle and energy transport in the boundary of fusion plasmas devices, driven partly by diagnostic development and partly by the exploration of novel concepts for transport. This improved understanding of turbulent transport is changing the standard picture of transport based on local diffusive mechanisms. The new picture is based on intermittency, complex correlation mechanisms and non-locality. It is now clear that intermittent transport cannot be understood without considering the coupling with plasma flows. Non-locality may turn out to be a key aspect to understanding global transport phenomenology and scaling behavior. Hopefully, these efforts will come together into a coherent global picture, connecting transport, gradients and flows.

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