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

Towards turbulence control in magnetised plasmas

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Abstract

A reduction of turbulent transport is an important task on the way of an economic fusion power production. The knowledge gathered on the driving forces and the dynamics of plasma turbulence helps to identify different techniques, which have been successfully applied in fusion experiments to improve confinement. The techniques can be divided into two classes, those related to sheared plasma flows and the others related to an optimisation of the magnetic configuration. The paper gives an overview of the different approaches and aims at an intuitive understanding of the mechanisms leading to reduced transport. ***To cite this article: U. Stroth, M. Ramisch, C. R. Physique 7 (2006).***

Résumé

Vers le contrôle de la turbulence dans les plasmas magnétisés. La réduction du transport turbulent est une étape importante sur le chemin qui mène à un réacteur de fusion commercialement viable. L'expertise acquise dans la compréhension des mécanismes sous-jacents au transport turbulent a permis d'identifier différentes techniques de contrôle qui ont été utilisées avec succès pour améliorer le confinement dans des plasmas de fusion. Ces techniques peuvent être divisées en deux catégories : celles faisant appel au cisaillement de vitesse et celles utilisant une optimisation de la configuration magnétique. Ce papier présente une revue des différentes méthodes et a pour but principal de présenter une approche intuitive des processus conduisant à une réduction du transport turbulent. ***Pour citer cet article : U. Stroth, M. Ramisch, C. R. Physique 7 (2006).***

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Mots-clés : Plasmas de fusion ; Plasmas magnétisés ; Contrôle de la turbulence

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1. Introduction

The energy confinement time τ_E is the key parameter for an economic optimisation of a fusion power reactor. In tokamaks, τ_E increases primarily with plasma current and plasma volume. Since the current is limited by technical constraints, ignition can only be achieved by increasing the size of the device to that of ITER or above. It is well established that energy transport and therefore also τ_E is determined by turbulent processes. A reduction of turbulent transport at given plasma dimensions would therefore allow one to achieve higher performances at cheaper costs. Hence the reduction, or even control, of turbulent transport is a rather desirable undertaking.

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The most common confinement improvement is the so-called H mode (i.e., high-confinement mode) [1], which emerges through the formation of a transport barrier at the plasma edge. More recently, transport barriers have also been generated in the plasma core, which lead to a great push in the achieved plasma parameters, although mostly at non-stationary conditions. The detailed mechanism leading to transport barriers is still a topic of active research. There is no doubt, however, that a sheared plasma flow is the key to the reduction of turbulent transport.

A more active technique of transport control is to optimise the magnetic configuration, i.e., the confining magnetic field. This is of particular importance for stellarators, which have, due to the 3-dimensional magnetic field topology, both a stronger need and a higher flexibility for an optimisation. However, to a lesser extent, this also applies to tokamaks.

The article summarises the different roots to transport reduction and control. As an introduction, the relation between turbulence and turbulent transport as well as the driving forces is discussed using some simple models. Furthermore, an example is presented where a low-density plasma is used for investigating the mechanisms of transport control on a microscopic basis.

2. Turbulence and transport

There are two fundamental linear instabilities (see Fig. 1) relevant for plasma turbulence, the interchange and the drift-wave instability. It has been shown [2,3] that, if the dominant driving mechanism remains the same, the characteristics of the linear instabilities is also present in the state of fully developed turbulence.

The *drift wave*, in the left part of Fig. 1, occurs in arbitrary magnetic fields. It consists of density perturbations that are elongated along the magnetic field line. The three-dimensional structure of the perturbations represented by parallel and perpendicular wave numbers $k_\parallel \neq 0$ and $k_\perp \gg k_\parallel$, respectively, is essential. The high electron mobility parallel to the field leads to a small cross-phase between density and potential perturbations. Hence, density and potential fluctuations are almost in phase. The drift in the electric field fluctuations resulting from the potential leads to a propagation of the structure into the direction of the electron-diamagnetic velocity u_e^{dia}. The drift wave becomes unstable of the parallel response of the electrons is delayed due to electron–ion collisions, magnetic induction or particle-wave interaction. The cross-phase increases to a small but non-zero value and a radially outward directed component if the transport arises. In the outer edge of a fusion plasma, drift-wave turbulence is expected to make an important contribution to transport [5].

The *interchange instability,* as on the right-hand side of Fig. 1, is unstable in regions of bad magnetic field-line curvature, i.e., on the low-field side of the torus where magnetic-field and pressure gradients point in parallel directions. The density perturbation is now two-dimensional ($k_\parallel = 0$) and the dynamics is driven by the vertically directed and charge dependent curvature drift. The emerging potential perturbation is out of phase with the density pertur-

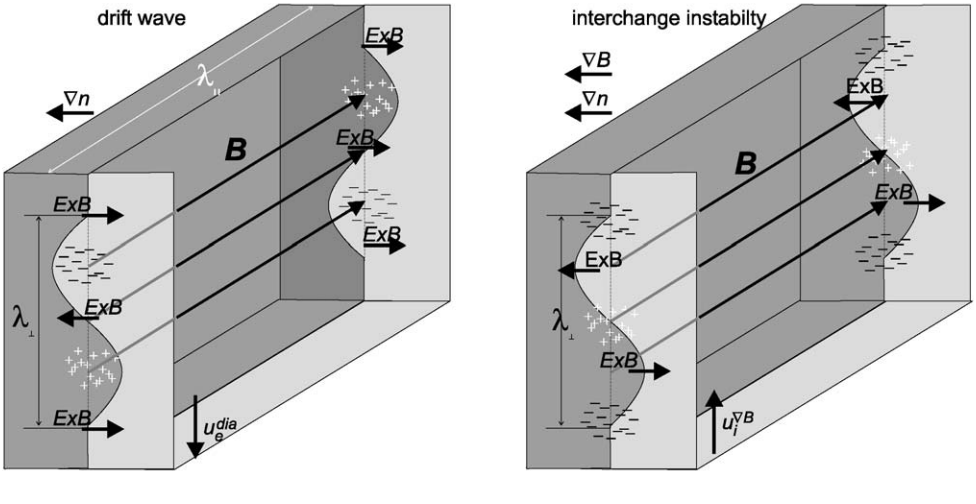

Fig. 1. Microscopic mechanisms and properties of the linear drift-wave (left) and the interchange instability (right) (based on [4]). A sinusoidal line separates regions of high (left) and low plasma density. Diamagnetic, $E \times B$ and curvature drifts are indicated by arrows. In the right picture, there is a magnetic field gradient present.

bation. Hence, the cross-phase is $\pi/2$ and the propagation in the fluctuating electric field is in the radial direction. There exists a number of instabilities which rely basically on this mechanism. Examples are the Ion-Temperature-Gradient (ITG) [6], the Electron-Temperature-Gradient (ETG) [7] as well as the trapped particle mode (TEM) [8]. These instabilities are of importance for transport in the plasma core.

In all cases, the transport perpendicular to the ambient field B is caused by $\tilde{E} \times B$ drifts in the fluctuating electric field $\tilde{E}$. It can be written as

$$\tilde{\Gamma} = 2k_\theta |\tilde{n}||\tilde{\phi}| \sin\delta_{n\phi}/B \tag{1}$$

In order to reduce transport, one has to act either on the amplitudes $|\tilde{n}|$ and $|\tilde{\phi}|$, the spatial scales or correlation lengths $L_{\mathrm{corr}} \sim 1/k_\theta$ or on the cross-phase $\delta_{n\phi}$. In the mixing-length picture, the amplitudes are related to the radial correlation length. Due to the different values of the cross-phase in drift-wave and interchange turbulence, the importance of it for turbulence suppression can also be expected to be different. In case of drift waves, a small change in $\delta_{n\phi}$ can make a large change in the transport level. If the potential and density perturbation are in phase, the net-transport is zero. In interchange turbulence, the same variation in $\delta_{n\phi}$ would only have a much weaker impact and the amplitudes and correlation lengths are more important.

3. Turbulence control by sheared flows

In order to influence turbulent transport by sheared plasma flows, the radial electric field has to be manipulated. This has to be done through a radial electric current,

$$J_r = J_r^{\mathrm{neo}} + J_r^{\mathrm{NBI}} + J_r^{\mathrm{edge}} + J_r^{v\nabla v} + J_r^{\mathrm{bias}} \tag{2}$$

which in general can have a variety of contributions. Most of the currents are driven by the friction acting on the ion fluid due to flows in the inhomogeneous magnetic field. In the order of appearance they are related to neoclassical particle losses, to momentum input by, e.g., neutral-beam heating, to direct particle losses to the wall appearing at the plasma edge, to turbulent momentum input (Reynolds stress) or to external plasma biasing. The causality of a transport reduction is illustrated in Fig. 2. The radial current changes the electric field and therefore the flows. This happens on the fast MHD time scale. In case of a transport change, the pressure gradient adjusts on the slow energy-confinement time scale and again modifies the force balance. There exists a vast amount of literature discussing transport reduction due to sheared flows. Recent reviews can be found in [9,10].

Low-density plasmas can be used for investigating the mechanisms of transport control on a microscopic basis. In linear devices with low-dimensional turbulence, a manipulation through feedback control is possible. Direct manipulation or control of turbulence has been achieved when only a few interacting modes are dominant. Mode-selective control of drift-wave turbulence by synchronisation of an external electric field was demonstrated [11,12].

In toroidal devices, the influence of sheared flows on fully developed turbulence can be studied. The sheared plasma flows are introduced by plasma biasing. In early biasing experiments it has been demonstrated that an abrupt transition into an H-mode-like regime with strongly improved particle confinement occurs, when a sufficiently large cross-field current is drawn by the tip of an insulated probe located inside the plasma [13]. This transition is accompanied by the formation of strong radial electric fields outside the biased flux surface. The density gradient steepened near a region of increased $E \times B$ flow shear. The correlation between density gradient and $E \times B$ flow shear was clearly evidenced [14]. Maxima in the density gradient were found to coincide with maxima in the flow shear. Oscillations in the biasing current imposed oscillations in ∇E_r and ∇n.

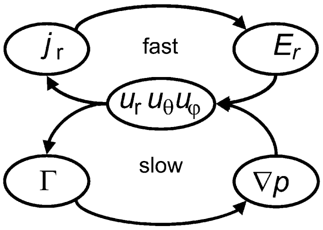

Fig. 2. Illustration of the interaction of the fast processes determining the radial electric field through the momentum balance equations and the slow time scale, on which the pressure gradient can be changed due to changes in turbulent transport.

As an example, results on related investigations in a small fusion device, the torsatron TJ-K, are presented. The experiment is operated with a low-temperature plasma with the dimensionless turbulence parameters similar to those at the edge of a fusion plasma [15]. Due to the low temperature, the plasma is accessible for probe diagnostics throughout the cross-section. The microscopic dynamics of turbulent density structures has been examined with a two-dimensional multi-probe array [16]. By cross-correlation analyses, the temporal evolution of the structure can be traced inside a window of $7 \times 7\ \text{cm}^2$, covered by the diagnostics.

In Fig. 3, two situations in an hydrogen discharge are depicted: the upper part shows the unbiased case where the density structure propagates poloidally into the direction of the electron-diamagnetic drift. Since in this case the contribution of the $E \times B$ drift, which points into the opposite direction, is small, this reflects a typical property of drift-wave turbulence. The speed is 0.8 km/s. In the lower part of Fig. 3, the same plasma during biasing is shown. The flow reversal due to a strong electric field is clearly visible. Here, the $E \times B$ drift dominates the poloidal flow. The structure passes the observation window 15 times faster than in the unbiased case, i.e., with a velocity of 12 km/s.

Due to the strong electric field, there also exist strong field gradients and sheared $E \times B$ flows, which cause a steepening in the density gradient. As it can be seen in Fig. 4, the steeper density gradient, which points to reduced turbulent transport, coincides with the region of increased $E \times B$ flow shear. From Fig. 3 it follows, on the other hand,

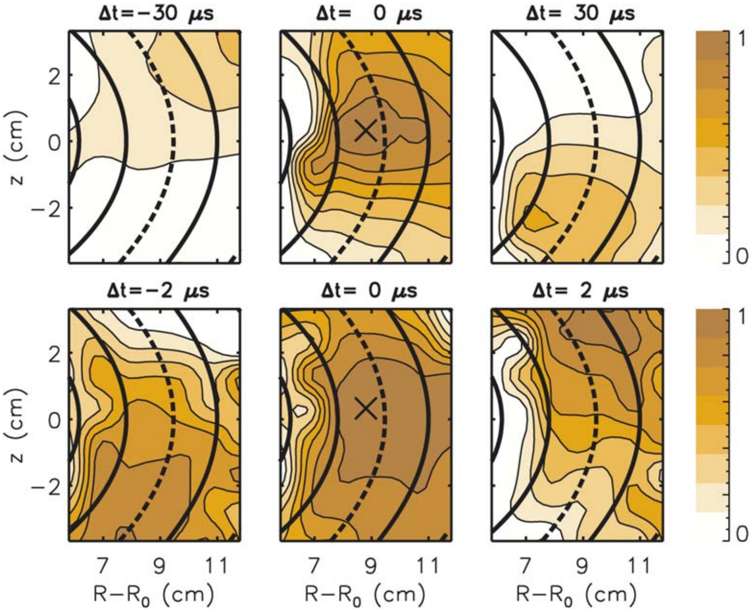

Fig. 3. Spatio-temporal evolution of density structures on the low-field side inside the confinement area of TJ-K. Depicted are the unbiased case (top) and the biased case (bottom) (from [17]).

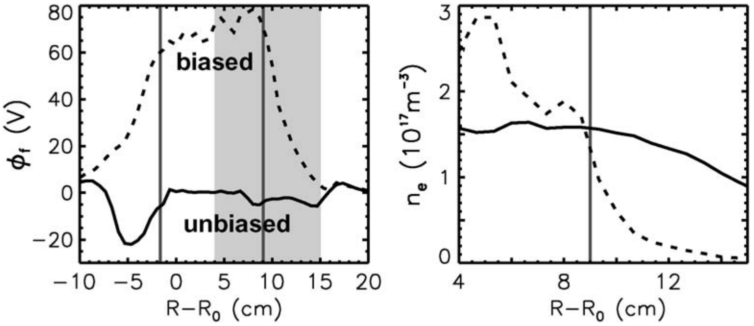

Fig. 4. Radial profiles of the floating potential (left) and the density (right) in the biased and unbiased case (from [17]). During biasing, the density gradient steepens near the biased flux surface (vertical lines) in the region, where ∇E_r is maximal.

that the correlation length is not reduced in the state of strong shear. It rather increases slightly. A detailed analysis showed [17], that the transport reduction can be traced to a modification of the cross-phase: the strongest change in the frequency spectrum of turbulent transport fluctuations is found at high frequency (70 kHz), where a new rather coherent mode is generated with a negative cross-phase related to inward transport.

While for the drift-wave driven turbulence, as in case of TJ-K, the cross-phase turned out to be the key parameter in transport reduction, in the core of fusion plasmas, with dominant interchange turbulence, a reduction of the correlation length can be expected to play a more pronounced role.

4. Influence of the magnetic configuration

The magnetic configuration of a fusion device is defined by the external coil system and the internal plasma current profile. For tokamaks, it is well established that the plasma shape and magnetic shear have an impact on both stability and transport. One reason that both parameters are affected simultaneously is that the interchange drive plays an important role in both processes.

Negative magnetic shear, for example, has a stabilising impact on the interchange instability [18]. Due to negative magnetic shear, a pressure perturbation, which is extended along the magnetic field line, is tilted on its path around the torus. This tilting influences the drifts, which generate the destabilising electric field on the low field side of the torus, and reverses their direction at larger poloidal angles. The result is a more stable condition for the particular mode. The effect can be understood as an increase of the region of good magnetic curvature and therefore as improved stability. Negative magnetic shear can be generated very efficiently by external plasma current drive but also partly by plasma shaping. The physics of internal transport barriers is closely linked to negative magnetic shear [19,20].

The main geometrical shaping parameters are the elongation and the triangularity of the plasma cross-section. Highly-shaped plasmas were found to exhibit not only higher stability but also improvement in confinement [21]. This is partly due to the fact that they can carry a higher plasma current, but even at fixed plasma current and toroidal field, improved confinement has been achieved in such plasmas [22]. Spherical tokamaks [23] could be considered as a result of extreme plasma shaping with the objective of high stability. Due to the compact shape and the low aspect ratio in spherical tokamaks, a magnetic field line has a much longer path in the region of good than in that of bad curvature, which leads to higher stability. Furthermore, the larger weight of the good-curvature region can be expected to have a beneficial effect on transport due to interchange turbulence, too.

For stellarators, the optimisation of the magnetic configuration is existential in order to minimise the neoclassical losses. In case of the advanced stellarator W7-X, the optimisation [24] aimed furthermore at a minimisation of the neoclassical (bootstrap) current. The bootstrap current is driven by the toroidal precession of trapped particles. Since the same precession motion is responsible for the dissipative trapped electron modes, the neoclassical optimisation can also have a reducing impact on turbulent transport related to these modes.

The confinement of collisionless particles is an important issue for stellarator devices. Due to the toroidal asymmetries in the magnetic field, there always exist populations of toroidally trapped particles. In the absence of a strong radial electric field, these particles cause high neoclassical transport losses. The reduction of these losses is one of the optimisation criteria for advanced stellarator devices. But on the other hand, collisionless trapped particles can also be used to generate strong electric fields and sheared plasma flows. These particles can be lost quickly due to the curvature drift thus charging up the plasma up to the point, where the $E \times B$ drift poloidally closes the trajectories of the trapped particles, which ultimately leads to their confinement. In case of dominant electron losses, the resulting solution for the electric field is known as electron root. Electron root plasmas have been observed in a number of stellarators [25,26]. Since the conditions, which have to be fulfilled for the appearance of the electron root, are a function of the plasma radius, transitions from the electron root—with a strong negative electric field—to the ion root—with a weaker and positive electric field—can occur. At this transition a natural layer with very strong flow shear is created with a potential to suppress turbulence. Such features could be the origin of internal transport barriers observed in stellarators [25,27].

5. Conclusions

The paper intended to show that substantial progress has been made on the way of reduction and control of turbulent transport. Depending on the dominant instability driving the turbulence, different mechanisms can have a beneficial impact on confinement. The magnetic configuration can be optimised to reduce the interchange drive which is not only relevant for global plasma stability but also for the turbulence governing core transport. For stellarators, the configuration can be optimised to reduce the toroidal particle drifts, which can help to reduce trapped particle modes, which are relevant for the core, too. Most efficient in reducing turbulence are sheared plasma flows, which can be generated by various different techniques and have proofed successful in reducing both interchange and drift-wave turbulence.

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