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

Open issues and trends in turbulent transport

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Abstract

To tackle successfully the difficult problem of turbulence and transport in fusion plasmas one requires a multidisciplinary approach which uses advances made in related fields, and to foster support for fusion because of the contributions it has made and will make to the understanding of turbulence. Progress in the theory of fusion plasmas turbulence is also a matter of extending modeling power by new analytical techniques instead of confining the methods to some few classical paradigms. In this article, we will present and discuss some approaches that have been developed in astrophysics, condensed matter physics and field theory and which could be applied to solve some complex issues of plasma turbulence. ***To cite this article: S. Benkadda, C. R. Physique 7 (2006).***

Résumé

Problèmes ouverts et tendances dans le transport turbulent. Une approche pluridisciplinaire est nécessaire pour comprendre les phénomènes de turbulence et transport dans les plasmas de fusion thermonucléaire par confinement magnétique. Il est important de développer de nouvelles techniques pour aborder cette problématique au lieu de continuer à utiliser des modèles classiques paradigmes qui sont infirmés à mesure que la puissance des diagnostics expérimentaux augmente. Dans cet article, sans vouloir être exhaustif, nous présentons quelques approches développées en astrophysique, en matière condensée et en théorie des champs et qui peuvent s'appliquer à la problématique turbulence des plasmas chauds de fusion magnétique. ***Pour citer cet article : S. Benkadda, C. R. Physique 7 (2006).***

Keywords: Plasma fusion; Plasma turbulence

Mots-clés : Fusion de plasmas ; Turbulence des plasmas

1. Introduction

Our understanding of fusion plasmas has undergone remarkable advances in the past decade [1]. The extreme temperatures needed for fusion (up to $4 \times 10^8\,^\circ$C for ions and $1.5 \times 10^8\,^\circ$C for electrons—which are hotter than the sun) are easily reached in the laboratory. Experiments are equipped with diagnostic instruments that can measure plasma properties with high spatial and temporal resolution. Increased computational capability has advanced plasma simulations so that it is now possible to simulate many of the complex phenomena of turbulent transport of energy, plasma stability, interactions between waves and particles, and interactions between escaped plasma and container

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walls [2]. As a result of improved diagnostics and advanced computer simulations, the understanding of turbulence is maturing rapidly. The next generation of computational capabilities will enable even more comprehensive simulation of these complex interacting processes. Although we have gained significant understanding of some complex issues of plasma turbulence, aspects of the turbulent transport remain areas of ongoing study that will require the development of new theoretical tools as well as turbulence diagnostics to test various theories.

In fusion devices, turbulence is a natural and robust product of the strong gradients that are required to maintain fusion plasmas far from equilibrium. Because the transport driven by turbulence seeks to restore the plasma to equilibrium, it is generally deleterious to the maintenance of fusion conditions. An exception is turbulence in the scrape-off-layer (SOL) that is useful in spreading out the power to the divertor plate. Intelligently dealing with the turbulence problem in fusion, under the numerous constraints imposed by heating, current drive, steady state operation, profile control, ash removal, burn control, economic feasibility, etc., requires significant advances in the understanding and control of turbulence and will, because of common dynamics, benefit the other fields mentioned above. Furthermore, the potential impact is expanding because fusion turbulence studies are moving from analyses of linear instabilities and the saturation of simplified nonlinear systems to studies that treat plasma turbulence as a globally distributed, bounded flow, and probe for universal features. Under this trend, the problems of fusion turbulence are increasingly relevant to many classical fluid dynamics problems such as turbulent boundary flows and turbulent shear flows. Fusion turbulence studies are also beginning to consider the effects of magnetic as well as electrostatic turbulence, which is crucial at high plasma pressure and important in self-organized plasmas such as the Reversed Field Pinch (RFP) and spheromaks, making it more relevant to astrophysical and space plasmas [3].

In some ways plasma microturbulence is more complicated than fluid turbulence because the electromagnetic fields are strongly coupled to the plasma flow, and kinetic effects are important in defining both stability boundaries and turbulent transport levels. At the same time, realistic direct numerical simulations are made more tractable by the presence of intermediate length scales (e.g., the gyroradius) and frequencies (e.g., the cyclotron frequency) which permit rigorous analytical simplifications to reduce the range of scales that must be resolved. Moreover, the presence of collisionless dissipation greatly reduces the effective Reynolds number. Insights gained from the study of fluid turbulence have had a substantial impact on our thinking about plasma turbulence (e.g., Kolmogorov spectra; cascade of energy and enstrophy with an inverse cascades of energy to large scales in some cases; and mixing-length theory). Conversely, progress we make in understanding fusion plasma turbulence may stimulate advances in the understanding of astrophysical plasmas and other fluid turbulence. Concepts developed within plasma physics, such as stochasticity and wave collapse, have already had an impact on fluid dynamics [4]. Plasma microturbulence simulations represent a significant opportunity for simulating, diagnosing, explaining and predicting the key features of a technologically significant, intrinsically turbulent system [2].

Examples of fusion plasma turbulence problems with these connections are so numerous that only a partial listing can be attempted here. They include issues that deal with nonlocality, such as the relationship between global scales and local instability, what governs whether transport reflects global or local scaling, the effect of the plasma boundary on edge and core turbulence and its impact on mean spatial profiles, and the effect of small scale turbulence on large scales and the mean state through turbulent dynamo and flow drive processes. They include issues that deal with flows, such as the relationship of flow shear-induced transport barriers in fusion plasmas to atmospheric transport barriers, the relationship of Reynolds stress driven flows in the atmosphere to the shear flows of fusion transport barriers, the role of shear suppression in wall flows and turbulent boundary layers, and the physics of zonal flows. They include issues that deal with closure in turbulent systems and intermittent behavior, such as the role of subgrid scales on turbulence and their appropriate treatment, the role of spatial and temporal intermittency in turbulence and transport and its origin and proper treatment, and what types of fluctuations (collective resonances, clumps, holes, vortices, convective cells, zonal flows, eigenmodes of nonlinear instabilities, etc.) lead to the most advantageous decomposition of the turbulent spectrum. They also include issues that deal with dynamical processes, such as the role of nonlinear instability, the origin of residual fluctuations and transport in transport barriers, and the physics of coupled fluctuations and free energy sources.

To tackle successfully the difficult problem of turbulence in fusion plasmas one requires a multidisciplinary approach which uses advances made in related fields, and to foster support for fusion because of the contributions it has made and will make to the understanding of turbulence. Successes within the general field of turbulence suggest an approach to solving the fusion problem that incorporates the following elements.

(i) Understand the basic dynamics of the complex turbulent systems of fusion experiments. This includes analysis of pieces of complex simulation codes, e.g., individual nonlinearities, studies of scaling properties, and analytic and computational studies of simplified models.
(ii) Understand how the basic elements integrate in the full system, and therefore what processes govern behavior of the full system under a range of relevant conditions.
(iii) Develop a range of appropriate models that synthesize behavior of the full system. Models that range from simplified paradigms with correct qualitative behavior to realistic simulations with predictive capability should be developed and employed. For example, simplified models that capture key physics of nonlinear instabilities could be fit to direct nonlinear simulations, and then used as reduced models in transport codes. Effective subgrid turbulence models could help increase speed of nonlinear simulations.
(iv) Execution of these steps should employ a synergistic combination of analytic theory, simulation, and experiments, utilizing meaningful comparisons and correlated development.

A scientific understanding of plasma microturbulence would allow us to predict anomalous transport rates with confidence, thereby reducing the risk, and probably the cost, of a burning plasma experiment. Based on our present understanding, there are five main areas in which significant progress towards a better understanding of plasma turbulence seems imminent. These are described below.

2. Self-organization, flows and plasma dynamics

Another aspect of the tendency to condensate coherent structures from turbulence is the global trend to self-organization. This problem becomes even more interesting in the conditions where in tokamak devices, regimes have been reached in which the turbulence is reduced to very low level (the relative fluctuation amplitude is a fraction of one percent). The problem is known from long time but serious obstacles exist to an acceptable physical model and description. The profile resiliency, the pinch of particles, the systematic appearance of the same type of profile for the plasma electric potential, the generation of zonal flows, have been considered as manifestations of the tendency to self-organization of the plasma, of the same nature as that which governs the relaxation phenomena. The old approach to this problem included theory of negative temperature states [5], natural profiles for current density [6], statistical equilibrium in equivalent discrete models [7]. These tendencies to organization in coherent states are difficult to be detected in numerical simulations since they require long time of simulation while in experiment they are easily attributed to various alternative causes. However several statistical tools have been proposed and tested on experimental data as well as numerical ones, to detect these structures. Among these techniques, the proper orthogonal decomposition, the wavelet analysis as well as Hilbert transform decomposition have shown some success.

Although purely deterministic, turbulent fields are usually treated like random fields and statistical methods are employed in the studies. A major problem arises when the turbulence consists of a part that can be safely considered as a random field and another part with strong correlated motion, showing long-lived structures. The existence of structures is not unexpected: the same nonlinear equations that have as solutions (as shown in numerical simulations) irregular flow with aspect of random field also have solutions consisting of regular patterns, (frequently vortical) that can be exact nonlinear solutions. This is seen when the problem is numerically studied and the initial conditions can be easily changed. However, there is another, deep, reason to expect generation of structures: the plasma shows an intrinsic tendency to self-organization in which an initially random field is replaced asymptotically by a regular flow. This is reflected especially in relaxation processes but there is no reason to exclude the existence of the same trend in the states where instabilities are excited. On the other hand, the numerical simulations and the experimental observation have clearly indicated the coexistence of structures and turbulence [8].

It is highly probable that a particular type of thermodynamic equilibrium represents the destination of the slow, intrinsic, evolution towards organization. This is supported by the similarity with the Euler equation for ideal fluids, where the asymptotic states exhibits few vortices resulting from merging of all the elements of positive or negative vorticity from the initial field. The specific nature of these states is their integrability. If the asymptotic states of the MHD or even of the simpler case of Charney, Hasegawa and Mima [9,10] or Hasegawa and Wakatani [11] states are also integrable, this would mean that they have non-trivial topological properties. The treatment of this problem involves field theoretical and algebraic methods and also requires for validation serious numerical effort. The results have a fundamental importance and would explain why common features of profiles are seen on many machines and why these profiles are resilient. They would also provide a new, non-diffusive and non-convective contribution to the processes of particle redistribution in confined plasma.

An exciting conceptual framework for understanding toroidal microturbulence simulation results is now emerging [12–15]. The essential ingredients are 'zonal flows' (i.e., radially varying, toroidally and poloidally symmetric flows), 'streamers' (i.e., radially extended, toroidally and poloidally localized vortices), and 'secondary' (nonlinear) instabilities, in addition to the usual collection of 'primary' (linear) instabilities. Issues to be addressed include: Are streamers the products of primary or secondary instabilities? What are the roles of the modulational and Kelvin–Helmholtz secondary instabilities in zonal flow formation? More generally, what is the dominant zonal flow generation mechanism? What is the role of Kelvin–Helmholtz instabilities in limiting zonal flow growth? Does a nonlinear instability set an upper limit on the nonlinear upshift in the critical gradient observed in collisionless gyrokinetic simulations? Will magnetic perturbations lead to the appearance of 'zonal fields' (i.e., local twisting of flux surfaces or, alternatively, magnetic tearing and the formation of islands) or—in the presence of magnetic curvature—to 'magnetic streamers'? In electromagnetic simulations, to what extent do Maxwell stresses cancel Reynolds stresses, thereby reducing zonal flow generation? How does this relate to electromagnetic stabilization of secondary instabilities? Under what conditions are secondary tearing instabilities important? Understanding of these questions is likely to accelerate the development of tractable theoretical models of transport. The problem of secondary instabilities is largely inspired from the similar situation of Rayleigh–Bénard convection and Eckhaus instability [16]. The analytical study employs the multiple space and time scale analysis, which leads to envelope equations like *Nonlinear Schrödinger Equation*, classified for pattern-forming systems by Swift and Hohenberg [17].

A novelty in the theoretical investigation of correlated fields in turbulence is the assumption that the Eulerian correlations may contain a chiral part, a parity non-invariant component [18]. Physically this is associated with the helicity. Many results on dynamo (essential for Reversed Field Pinches) and on statistics of the processes of generation of large scale ordered patterns from turbulent fields have become possible. The connection with astrophysics is very beneficial for tokamak plasma. In this context of parity non-invariance it becomes possible to identify correctly in tokamaks fluxes which can lead to counter-gradient ones, thus enlarging the possibility of explanation of the heat and particle pinch. But the presence of fluctuating helicity in the reconnection events may also imply excitation of Alfven waves as a saturation of the island growth.

3. Electromagnetic fluctuations

Most turbulence simulations to date have been electrostatic, with an adiabatic electron response (i.e., each flux surface is isothermal, with the electron density determined on each flux surface by balancing the electron pressure against the electrostatic force). This approach was appropriate for studies of ion thermal transport in the core of tokamak plasmas. However, this model omits all electron radial transport. Relaxing the assumption of adiabatic electrons allows us to study the particle and electron thermal transport. Equally important, a kinetic treatment of the electrons provides the source term (the parallel electron current) needed for electromagnetic simulations. The attention of the magnetic fusion community is shifting towards plasmas with a high dimensionless pressure, $\beta = 2\mu_o p/B^2$ (e.g., spherical tori) and steep gradients (e.g., advanced tokamaks) where electromagnetic terms become increasingly important. Electrostatic modes, like the ion-temperature gradient (ITG) mode [19], are modified by the electromagnetic terms, while fundamentally new instabilities (like the kinetic ballooning mode) appear in regions of high pressure or steep gradients. By incorporating kinetic electrons and electromagnetic fluctuations in the numerical models we will be able to address questions such as: How do fluctuating magnetic fields affect ITG and trapped electron mode (TEM) [19] turbulence? Equilibrium modifications associated with steep gradients affect microinstabilities and microturbulence. How does this relate to the appearance of transport barriers? How does the presence of the kinetic ballooning mode affect ITG/TEM turbulence? How important to microturbulence are topological changes which arise from microtearing? Does the presence of electromagnetic microturbulence affect magnetic island growth? When is short wavelength electron temperature gradient turbulence experimentally important? What is the source of the very strong electron thermal transport in the core of some advanced tokamak discharges? Simulations with electron dynamics and electromagnetic perturbations could provide answers to these questions, eventually forming the basis of a predictive capability for spherical torus and advanced tokamak plasmas.

4. Transport barriers dynamics

Transport barriers at the plasma edge are key elements of high confinement modes (H-modes) in fusion devices. These barriers, characterized by a local steepening of density and temperature gradients, are strongly linked to shear that reduce significantly turbulent heat and particle transport. During a transition from low to high confinement (L–H transition), an edge transport barrier builds up spontaneously [20–22]. A barrier can also be produced by externally driving an $\mathbf{E} \times \mathbf{B}$ shear via edge biasing techniques [23,24]. In the most promising operational regime of future reactors, the edge transport barrier is not stable but relaxes quasi-periodically. During such fast relaxation events, turbulent transport through the barrier increases strongly and the pressure inside the barrier drops. Thereafter, the barrier builds up again on a slow, collisional time scale. The basic physical mechanism underlying these relaxation oscillations is not fully understood. In particular, there is no universal explanation why the plasma, instead of remaining in a state of marginal stability, oscillates close to stability limits. Currently, transport barrier relaxations are modeled by phenomenologically constructed dynamical equations for the amplitudes of relevant modes [25].

The understanding and control of these transport barriers is the key problem in reducing the cost of a next-generation DT burning magnetic fusion experiment. We need to understand what governs the formation, width, and evolution of transport barriers—particularly barrier propagation and stationary points. Simulation studies [26, 27] could be used to test existing strategies, and to develop new strategies for controlling transport barriers, thereby enabling substantially improved performance in magnetic fusion experiments.

5. Nonlocal transport and the role of mesoscales

The key issue determining the size and cost of a burning plasma experiment based on the principle of magnetic confinement is the transport of energy from the hot interior to the plasma edge. Because particles, momentum, and heat are rapidly transported along the magnetic field, magnetic fusion research has focused on magnetic traps in which each magnetic field line covers one of a set of nested toroidal surfaces. Gradients in the plasma particle, momentum, and energy densities are supported across these magnetic flux surfaces. Plasma microturbulence, driven by these gradients, is the dominant mechanism by which particles, momentum, and energy are transported across the flux surfaces from the hot interior to the cold plasma edge. The anomalous transport associated with plasma microturbulence limits the performance of magnetic confinement devices in most operating regimes. Understanding plasma microturbulence has been recognized as a critical scientific issue within the magnetic fusion program since the 1960s. Toroidal magnetic traps have a minor radius, a, which is typically hundreds of times larger than the Larmor radius, ρ_i, while plasma microturbulence typically has a correlation length of the order of ρ_i. There is both experimental and theoretical [28,29] evidence that ion transport may be dominated by events in which heat (and, presumably, particles and toroidal momentum) propagates ballistically across flux surfaces over distances large compared to the radial correlation length of the microturbulence. These mesoscale transport events are moderated by zonal flows [14]—that is, by the differential plasma rotation generated by the turbulence itself [30]. This self-similar, scale-invariant behavior of transport events, which resembles the self-organized criticality paradigm of Bak, Tang and Weisenfeld [31] has been obtained from in computational models of plasma turbulence which have a firm foundation in the underlying plasma kinetic theory. In at least some full torus simulations the largest events dominate the transport, suggesting that mesoscale dynamics may hold the key to understanding the transition from gyro-Bohm transport scaling (the natural scaling of gyrokinetic theory) to Bohm scaling (as observed in these global microturbulence simulations and in some experiments). A key question here is to elucidate the nature of largest transport events, since the magnitude of these events determines the average heat flux. Specifically, are large events dynamically equivalent to the streamers? Or are they a cascade of uncorrelated instabilities driven by the propagating heat (or cold) pulse? How does the magnitude of the largest events scale with system parameters?

The large scale correlations of fluctuations suggest the adequacy of specific paradigms like the avalanches, related to the evolution of plasma to a critical state via self-organization. Again, this is inspired by the behavior of similar systems (sand piles, forest fires, river networks, etc.) and several technical methods have been adopted from the well developed field of Self-Organization at Criticality (SOC) [31]. The SOC paradigm is particularly convenient for plasma in confined systems where the instabilities can saturate by the back reaction on the equilibrium gradients that sustain the release of the free-energy. The marginally stable state of an instability is similar to that requested by SOC, where clusters of subsystems are close to the threshold and any perturbation leads to a propagation of the condition of instability with an associated transport of some quantity: mass and energy. Such transport phenomena are detected in tokamak plasma and they imply large spatial regions [32]. Therefore SOC-like theories are offering in the same time a possible explanation for fast and extended propagation and also for intermittent, bursty events. Although there has been considerable theoretical effort there is presently no definite model that could cover the marginal stability of plasma modes together with fast growth at threshold [33] and immediate effect on the distribution function in the phase-space, everything being represented as a propagating effect. In recent times the SOC-inspired theories have evolved along two lines. First there have been developed procedures of data analysis, devoted to detection of the large spatial correlations (bi-coherence) [34]. These are now available and largely used to accompany the experiments where large scale fast propagation is observed. Second, an old extension of the statistical description of the particle motion in turbulence (the Continuous Time Random Walk) [35] has been reiterated, using considerably powerful methods: the non-Gaussian statistics, the Levy flights, restrictively considered before as exotic, has been adopted as a basic assumption for new analytical instruments. These make use of fractional differential calculus, which allows us to consider the turbulence with divergent second-order moments and provides exponents for particle position's correlations derived from a fractional diffusion equation. Although the analytical apparatus is very attractive, the elements that would require to apply it in concrete cases are still rather unclear. The assumption that a finite correlation length is absent and a substantial part of the particle population performs Levy flights is mainly an assumption and is less clear how this should be derived unequivocally from the theory of a particular instability which saturates in a turbulent state. The consistent approach that has been recently adopted is to exploit the numerical simulations that exhibit non-trivial statistics and combine the data with the theory that makes use of the fractional calculus. Interesting results have been obtained [36] with possible application for density profile in tokamak. There have been works where the propagation aspect has been investigated with reference to a well known paradigm of front propagation in active media [37,38]. The intrinsic nonlinearity of the plasma dynamics provides the necessary support for the identification of multiple equilibria and the possibility of defect-type interfaces to propagate by switching between these states.

Another aspect of the attempts to quantitatively describe the fast and extended transport phenomena in confined plasma is the development of test particle approaches. This is a wide ensemble of methods (analytical, numerical) in which reasonable assumptions are made on the turbulence, usually taken from experiment, and statistical methods are employed to characterize the behavior of single particle in the turbulence [39,40].

6. New approaches to statistical analysis of turbulent fluctuations

The present research in the theory of turbulence in plasma takes as a limit of the validity of the approaches based on closure of hierarchy of equations, the fulfillment of the condition of scale invariance, necessary for the spectrum to be a useful description. At the origin of the extension and diversification of techniques and methods it is the recognition of the fact that the turbulence in plasma (especially in magnetically confined plasma) coexists with structures, i.e., it dynamically generates and destroys structures and in some regimes evolves by self-organization to formation of highly nonlinear, robust structures with a central role in the properties of the plasma. We should mention here the zonal flow [14], radially localised, poloidally symmetric, sheared flows that control the level of turbulence and in consequence the confinement; and the small scale robust vortices developing in the volume, with impact on the rate of transport; and the particle pinch, with considerable effect of the equilibrium density profile. The presence of self-generated structures requires methods that cannot be offered by the picture that places in the center the linear modes and develops a theory of turbulence from the perturbative nonlinear term, regarded as mode-coupling which allows the energy to flow in the spectrum.

Recently, the theory has invoked the conformal invariance [41], a more precise condition, which also allows having access to many results that have been obtained in conformal field theory. There have been proposed minimal two-dimensional conformal models for fluid turbulence that are able to calculate scaling laws for the spectral energy in fluctuations. However, these methods are restricted to the case where the turbulent field is invariant to the group of conformal transformations, and this excludes the cases with strong spatial and temporal intermittency.

The directions mentioned above still have low impact on the development of new techniques in plasma turbulence theory. It is worth noting that in tokamak plasma theory, intermittency is less investigated as an intrinsic statistical property, but as the effect of the dynamic generation of structures, the point of view being shifted to formation of vortices or coherent flows. Considerable progress has been achieved in the theoretical fundaments of the renormalization, a classical instrument used in plasma turbulence theory. The renormalization remains the only analytical instrument that can be used to obtain concrete results on fully developed, saturated turbulence [42,43]. The most common approach is the Direct Interaction Approximation (DIA) developed by Kraichnan. In fluid physics it is known that DIA obtains spectral exponents that are different from the Kolmogorov result, for the reason that it cannot distinguish between the dynamical and kinematic interactions between eddies of widely separated length scales [44]. This is actually a problem for further application in plasma turbulence since large eddies are developed from Ion Temperature Gradient (ITG) instability and they advect the much smaller vortices generated by ion polarization drift at few sonic Larmor radii. There are recent attempts to exploit directly (without simplifying adaptation) the very powerful instrument of Renormalization Group of transformations (RNG) as developed in the theory of critical states. For this to become a useful method we again need that the turbulence can be seen as scale-invariant system (no large regions of quasi-coherent flows), in which the suppression from the description of a class of waves (i.e., certain ranges of wavelengths and of frequencies) should simply be accompanied by the modification of the value of parameters like viscosity, resistivity, etc. The sequence of such transformation induces a flow in the space of parameters and the critical nature of the turbulence is evidenced by the existence of a fixed point for this flow. The method has been applied for plasma in the regime Hasegawa–Mima and to the MHD equations. The existence or not of a fixed point for the RNG is still controversial [45,46], but the technical procedures typical for the RNG theory have offered concrete benefice in particular in the calculation of the Probability Distribution Function for the plasma fluctuations in the Hasegawa–Mima regime. Much work is still needed to identify the regimes where perturbative calculation beyond one loop approximation (i.e., two loops, as for the Kardar–Parisi–Zhang equation [47], related by a transformation to the Burgers equation) are possible. The functional methods, strongly supported by techniques that are available from field theory, has also been used in the calculation of the effect on diffusion of random trapping of particles in a turbulent field.

7. Conclusions

Progress in turbulence theory is also a matter of extending modelling power by new analytical techniques. Instead of confining the methods to some few classical paradigms, the effort to adopt theoretical instruments that have been developed in astrophysics, condensed matter physics and field theory has proven to be beneficial. Progress to date includes identification of instabilities responsible for the generation of plasma turbulence; the experimental demonstration that transport greatly in excess of neoclassical rates is associated with the presence of plasma microturbulence, while neoclassical transport is observed in the absence of such fluctuations; and the recognition that rotational shear (that is, deviations in the rotational velocity of a magnetic flux surface relative to its neighbors) can have a profound effect on both the amplitude of plasma microturbulence and the rate at which particles, momentum and energy are transported across magnetic flux surfaces.

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