Conference Report

First principles based transport theory

Report on the
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1. Introduction

The IAEA Technical Committee Meeting on 'First Principles Based Transport Theory', organized jointly by the Max-Planck-Institut für Plasmaphysik, Garching, and the International Atomic Energy Agency, Vienna, took place in Kloster Seeon in Southern Bavaria, on 21–23 June, 1999. The local organizers were D. Biskamp and A. Zeiler, and the co-organizer was K.H. Spatschek from the University of Düsseldorf. The international programme committee was formed by D. Biskamp, J.W. Connor, C.W. Horton, K. Itoh, K.H. Spatschek, W.M. Tang and J. Vaclavik, and the scientific secretary and representative of the IAEA was T. Dolan.

The idea of the meeting was to bring together scientists from the different areas in plasma transport in order to discuss specifically theoretical problems, such as comparison between numerical and analytical approaches and questions of consistency of models, without the usually overwhelming pressure to reach agreement with experimental measurements. The different topics were grouped in five sessions:

(a) Turbulent transport in the tokamak core plasma,
(b) Turbulence suppression, shear amplification and transport bifurcation dynamics,
(c) Turbulent transport in the tokamak edge plasma,
(d) Global aspects of turbulent transport in tokamak plasmas,
(e) Neoclassical transport, in particular in stellarators.

The sessions were opened by a survey talk on the respective topic, which were followed by the contributed oral talks with ample time for discussions. A poster session covered those contributions which the authors chose to present in this form. In total there were 55 participants and 49 papers presented.

It was agreed not to publish proceedings but to provide an overview of the presentations in *Nuclear Fusion.* The review speakers agreed to summarize the presentations in their sessions and give their impressions about the present status of their fields as apparent during the meeting.

2. Turbulent transport in the tokamak core plasma, by Z. Lin

Significant progress has been made in understanding tokamak core turbulent transport as a result of the close collaboration between experiment, theory and large scale simulation made possible by the rapid growth of massively parallel computing power. In particular, recent advances in direct numerical simulations of electrostatic ion temperature gradient (ITG) turbulence, reviewed by Z. Lin, have led to the emergence of a fundamental understanding of the non-linear processes underlying ion thermal transport. The linear properties of ITG instability are well understood. The dominant non-linear saturation mechanism for electrostatic ITG has been found to be $E \times B$ zonal flow shear induced decorrelation. Zonal flow involves linearly stable flux surface averaged ($k_{\parallel} = 0$) modes and can be non-linearly generated by Reynolds stress. The exponential growth of zonal flows predicted by modulational instability theory has been observed in gyrokinetic simulations. In non-linear simulations with zonal flows retained, a significant reduction of ion heat conductivity χ_i in steady state is observed compared with simulations with zonal flows suppressed. A key mechanism for reducing transport by zonal flows is the breaking of turbulent eddies through random shearing and, consequently, a reduction of the radial decorrelation length. The fluctuations are nearly isotropic in the radial and poloidal directions. The transport scaling is then expected to be different from the Bohm-like scaling associated with the radially elongated global modes observed when zonal flows are suppressed. In toroidal geometry, zonal flows are damped by collisionless transit time magnetic pumping effects. A component of the flows can survive this linear collisionless damping process in the banana regime. This residual flow can be damped only by collisions and non-linear effects, and thus plays a key role in determining the turbulent transport level in non-linear simulations. In the weak turbulence regime, zonal flows generated from the initial growth of turbulence completely suppress turbulent transport even though the plasma equilibrium is linearly unstable. However, ion–ion collisions can remove this non-linear upshift of critical gradient by damping zonal flows through neoclassical effects. Consequently, the ion thermal transport level from ITG turbulence depends on ion–ion collisions. Furthermore, the fluctuations and transport exhibit a bursting behaviour with a period corresponding to the collisional damping time of poloidal flows. These results are contrary to the usual assumption that core ion transport is “collisionless”. The fact that the change of ion heat conductivity χ_i with collision frequency cannot be attributed to the change in linear growth rate γ or mode spectrum $k_\perp$ casts some doubts on the applicability of existing transport models that are based on an oversimplified $\gamma/k_\perp^2$ type mixing length rule.

The strength of toroidal coupling, which produces the ITG global mode structure, depends on the magnetic shear. W. Horton presented a linear theory of the ITG mode and a test particle transport study in optimized shear plasmas. The condition for toroidal coupling is that the typical mode width of poloidal harmonics is larger than the interval of adjacent rational surfaces. This condition can be broken in a weak shear region. In a reversed shear plasma, the wavefunctions with rational surfaces located on both sides of the q_{min} surface are weakly coupled with each other through a non-resonant mode, which is heavily damped by Landau damping due to its finite parallel wavevector. The ballooning angle θ_0 (or Bloch angle representing the phaseshift between adjacent rational surfaces) has opposite sign for the inside and outside modes. When the difference of θ_0 becomes of the order of unity, a radial gap in mode structure appears due to the phase mismatch. This gap prevents transport across the q_{min} surface. The linear stabilization effects of shear flows are inversely proportional to the magnetic shear, so that the flow shear effect is greatly enhanced in the weak magnetic shear region and helps to form the mode gap around the q_{min} surface. These linear theories have been confirmed by particle simulations using a toroidal code. The test particle transport resulting from a given drift wave fluctuation was studied using drift wave maps which describe the motion of guiding centres in a drift wave. It was shown that reversed magnetic shear changes the drift wave map from a standard map to a non-twist map in which a shearless invariant curve appears around the q_{min} surface and produces a partial block of transport.

A test of the ITG based transport model with Alcator C-Mod experiments was described by D.R. Mikkelsen. Experimentally, the ion temperature profile was calculated by TRANSP using neutron based estimates of core T_i and measured electron temperature and density profiles. The IFS/PPPL model uses the experimental temperature at the outer boundary condition and other plasma parameters to predict the ion temperature. It was found that the predicted critical temperature gradient is significantly smaller (up to a factor of two) than the measured data over a large part of the plasma. The predicted ion temperature is too low (20–30% lower than the measured data) and the predicted power at the measured temperature gradient is too large (up to an order of magnitude larger than the actual heating power). Possible sources responsible for the discrepancy include the accuracy of plasma profile measurements and the applicability of the parameterization of the IFS/PPPL model in the Alcator C-Mod plasma parameter regime.

While many aspects of ion thermal transport are now well understood, electron thermal and particle transport remain largely unexplained. One of the possible candidates for electron transport, the electron temperature gradient (ETG) mode, was studied using a non-linear gyrofluid code and a gyrokinetic Vlasov code. Initial results were discussed in separate talks by W. Dorland and F. Jenko. The ETG mode is analogous to the ITG mode with the role of electrons and ions reversed. Because the linear growth rate is much larger than typical $E \times B$ shearing rates, ETG modes are not stabilized by shear flows. Zonal flows are not generated by ETG turbulence, since the ion response is adiabatic. Previous theoretical studies showed that the ETG instability has a maximum linear growth rate for an electrostatic polarization with a characteristic wavelength of the electron gyroradius and that non-linear mode coupling (inverse cascade) drives a coupling to an electromagnetic polarization with a larger space scale of the order of the collisionless skin depth δ_s. Results from present non-linear simulations in a sheared slab show a very low transport level from collisionless ETG turbulence and no inverse cascade to δ_s scales. In non-linear toroidal simulations, however, a very high transport level (larger than that of the corresponding ITG turbulence) was driven by the formation of streamers (radially highly elongated vortices). This level of transport is high enough to be experimentally relevant. F. Jenko also presented results of non-linear simulations of collisionless drift wave turbulence with drift kinetic electrons and cold ions in a sheared slab. It was found that non-linear electron Landau damping associated with parallel trapping substantially reduces transport for low magnetic shear. A particle pinch was observed in the electrostatic limit for a high value of η_e due to the different perpendicular dynamics of fast and slow electrons. A parameter scan showed that transport increases towards the plasma edge and decreases with increasing isotope mass.

3. Transport barrier theory, by P.H. Diamond

The theory of transport bifurcations and barriers rests on three basic elements, namely:

(a) The concept of $E \times B$ shear flow suppression of turbulence and transport,

(b) The generation and amplification of electric field shear by turbulent transport, stresses and by neoclassical processes,

(c) The general theory of reaction front and phase transition front dynamics.

As neoclassical transport is covered elsewhere, it is not discussed further here.

The theory of $E \times B$ shear flow suppression of turbulence and transport is comparatively well established. Suppression can occur via reduction of fluctuation intensity or via alteration of the phase relation in transport fluxes. Shearing stretches and narrows eddies in the radial direction, while also shifting and modifying wave–ion resonances, thus enhancing ion Landau damping. Moreover, shearing can be coherent, as in the case of a mean $E \times B$ flow, or random as in the case of zonal flows. Zonal flows can and do exist in the absence of identifiable transport barriers and thus can be considered to be a *universally present constituent* of drift wave turbulence. Since zonal flow damping is weak (explicitly proportional to the ion collision frequency), zonal flow shearing effects can be large. Various analyses of shear suppression are in basic agreement, and have been validated by numerical simulations.

The process of electric field shear amplification is less well understood, though significant progress on the Reynolds stress modes (NB: 'stringer spin-up' is included as a subset of these) of mean and zonal shears has been made. Indeed, Reynolds stress flow shear amplification is simply the process which (necessarily) conserves energy against shear suppression of turbulence. Models which evolve electric field, transport, intensity and profiles have been developed, and closely resemble the k–ϵ type models commonly used in fluid turbulence studies.

At the macroscopic level, one must address the questions of gross barrier dynamics and structure. Here, the generalized k–ϵ models may be treated like the coupled reaction–diffusion systems they resemble. Since we are concerned with transport bifurcations, the 'reaction is in the diffusion' here — a feature which significantly complicates the problem. A generalized Maxwell construction which defines barrier stationary points may be constructed. This approach is beginning to yield quantitative predictions of barrier location and pedestal widths, as well as estimates of barrier propagation speed. However, this endeavor is still in its infancy, and much work remains.

It is appropriate to note some key challenges in the theory of transport barriers which remain. These are:

(a) Developing tractable and faithful models of macrodynamics which correctly predict barrier and pedestal widths. Such models must incorporate MHD stability constraints, but have not yet done so.
(b) Quantitatively accurate predictions of the threshold criteria for barrier formation, in the case of both the L → H transition and ITBs.
(c) A generally applicable model and understanding of electron thermal transport barriers. Indeed, the challenge of understanding electron thermal transport and why it may persist in barrier regimes on some occasions, yet be suppressed on others, is one of the key questions in fusion physics today.
(d) Understanding zonal flow dynamics at finite beta and in environments with significant mean shears.
(e) Understanding zonal flow effects on transport (in addition to the fluctuation intensity).
(f) Understanding the relationship between zonal flows and streamers or avalanches, namely radially elongated convective cells. Such structures are possible signs of self-organized critical behaviour.
(g) Understanding the effect and role of noise on transport barrier formation. Most theories of transport barriers are still at the level of mean field theory, and the concept of a noise induced transition seems quite relevant, here.

Finally, in view of the rather excessive concern with code comparisons at the meeting, this author would like to conclude with a quote:

> "If we don't possess theoretical tools, we won't get anything out of numerical simulation."
>
> M.J. Feigenbaum, 1999 APS Centennial Talk

4. Turbulent transport in the tokamak edge plasma, by R.N. Rogers

In the area of tokamak edge turbulence and transport, results based on both analytic and numerical studies were presented. In the latter case simulations from six independent 3-D codes were discussed, including four Braginskii codes (B. Rogers, A. Zeiler, K. Hallatschek, X. Xu), a gyrofluid code (B. Scott) and a Vlasov electron/fluid ion code (F. Jenko). The studies explored a broad variety of important physical effects, including the role of magnetic curvature, electromagnetic effects, kinetic electron dynamics (F. Jenko, B. Scott), profile non-locality (K. Hallatschek, X. Xu), the X point geometry and scrape-off layer (X. Xu), realistic magnetic geometry (B. Scott, X. Xu) and transport barrier formation (B. Rogers, B. Scott, X. Xu, J.W. Connor).

All the codes that include both curvature and electromagnetic effects predict the turbulence for L-mode-like parameters is predominantly curvature driven, and is enhanced by electromagnetic effects at realistic edge parameters. At H-mode-like parameters, however, some of the Braginskii codes exhibit a transition to a regime in which curvature plays only a weak role and electromagnetic effects become stabilizing (consistent with but stronger than the trend shown by the Vlasov model, which did not include curvature or finite ion temperature), while the gyrofluid based model does not show such a transition. The source of the discrepancy was unclear.

It was generally agreed the collisionality in the tokamak edge, at least in H mode, was sufficiently weak to introduce important effects such as electron inertia and electron Landau damping into the drift wave dynamics. The quantitative importance of the latter (Landau damping) was underscored by the results of the Vlasov simulations. Work is under way (in the context of the gyrofluid model) to extend the description of the electron dynamics in the fluid simulations to include this and other important effects.

Simulations exploring the impact of profile non-locality and realistic magnetic geometry (including the presence of an X point and scrape-off layer) suggest these effects are also essential to an accurate description of edge transport. Profile non-locality is important because the scale lengths of the turbulence predicted by the simulations are comparable to the width of the edge pedestal itself. The realistic X point geometry strongly influences the linear structure and spectrum of curvature driven modes, and may thus be particularly critical in the case of L mode transport.

The dynamics associated with the L–H transition was also addressed by some of these simulations with the addition of density or temperature fuelling sources. While these simulations did in fact observe transitions to regimes of suppressed confinement, the overall conclusions remain murky. In one case, it was argued that the electromagnetic stabilization of the drift wave (not seen by all the models) played a vital role, while in another the boundary condition associated with the scrape-off layer seemed to be critical. This latter conclusion was also consistent with the results of a heuristic analysis of the $E \times B$ shear dynamics.

5. Global aspects of turbulent transport in tokamak plasmas, by X. Garbet

Turbulent transport in fusion devices may exhibit a global behaviour for several reasons. One reason arises from the structures of the linear eigenmodes in toroidal geometry called global modes. Indeed their radial widths scale as the geometric mean of the gyroradius and the gradient length. This dependence on a macroscopic scale was invoked to explain a Bohm type scaling law of the confinement. Several presentations at the meeting addressed the question of global mode stability in tokamaks and stellarators. As expected from theory, gyrokinetic computations show that global modes are more stable than predicted by a calculation based on the ballooning transform at the lowest order. The difference has been found to be significant when trapped particles are accounted for (G.L. Falchetto et al.). The gradient of the $E \times B$ drift was found to be more efficient than its curvature for stabilization of ITG global modes (M. Maccio and J. Vaclavik). The influence of the geometry is also being investigated (G. Jost et al., R. Hatzky). Finally, the Reynolds stress associated with global modes has been shown to be significant in the plasma edge (J.W. Connor et al., P. Beyer et al.). This may have some influence on the transition from low to high confinement.

The question whether global modes survive in the non-linear regime was addressed by many authors at the meeting. This is related to the question of confinement scaling. Particle simulations (Y. Kishimoto et al.) indicate that global modes persist in simulations and that the correlation length scales as the square root of the gyroradius. This corresponds to a Bohm type scaling law. At low magnetic shear the distance between resonant surfaces increases at given toroidal wavenumber leading to a decoupling of poloidal harmonics and a situation locally close to the one in a cylinder (W. Horton). This behaviour may explain the onset of an internal transport barrier. Also an $E \times B$ shear flow tends to decorrelate these large scale structures (Z. Lin et al.) leading to a correlation length proportional to the ion gyroradius (gyro-Bohm scaling). Close to the stability threshold, global 3-D gyrofluid simulations of ITG modes show persistent radially elongated structures, which are reminiscent of global modes. However, the scaling law for the confinement remains gyro-Bohm (M. Ottaviani, G. Manfredi). Global 2-D ITG simulations indicate that the scaling law depends on the difference between the temperature gradient and the critical gradient. The correlation length always scales as the gyroradius. However, a breakdown of the gyro-Bohm prediction for the correlation times is observed close to the threshold (X. Garbet, R. Waltz).

A further reason for the global behaviour of the turbulent transport comes from the existence of large scale transport events. Such events have been observed in several simulations. Examples were shown for low wavenumber MHD turbulence (A. Thyagaraja) and for a Hasegawa–Wakatani system (V. Naulin, J. Rasmussen). Several explanations have been proposed for such events. One is based on the onset of streamers (P. Diamond). These streamers are convective cells, which are elongated in the radial direction. They are induced by a non-vanishing poloidal divergence of the Reynolds stress. It was suggested that they may alternate with zonal flows. Streamers were shown at the meeting for toroidal simulations of ETG modes (B. Dorland et al., F. Jenko), leading to an enhancement of the electron heat diffusivity as compared with the mixing length estimate. Another model based on the excitation of radially propagating fronts was proposed to explain these large scale transport events (Y. Sarazin et al.). The propagation velocity of these fronts is proportional to the square root of the normalized heat flux and reaches a fraction of the sound speed. Their propagation range scales as the gyroradius, thus explaining why the scaling law remains of the gyro-Bohm type in the presence of avalanches. This behaviour presents some similarities to avalanches in sandpile automata and, more generally, to systems which exhibit self-organization close to the stability threshold. Self-organization close to a threshold was also mentioned for ITG modes (Y. Kishimoto et al.). Examples of self-organization below the stability threshold (subcritical state) were treated in several contributions, in particular for MHD turbulence (M. Yagi, S.-I. Itoh, K. Itoh).

6. Neoclassical transport in stellarators, by J. Nührenberg

The session on neoclassical theory comprised a review paper on neoclassical transport in stellarators as well as papers contributing to special aspects of neoclassical physics in tokamaks.

J. Nührenberg reviewed neoclassical transport in stellarators. Stellarators have long been impeded by the perspectives of large neoclassical transport in the long mean free path (LMFP) regime and strong collisionless α particle loss. These disadvantages of stellarators, which had been deemed unavoidable, have been overcome by stellarator optimization during the last one and a half decades. Important elements in this development were the structural feature of guiding centre motion that it is solely governed by the strength of the magnetic field in magnetic co-ordinates (and not by other metrical properties of a 3-D stellarator) and the fact that this quantity can exhibit symmetry properties. This restricted symmetry property has been named quasi-symmetry and occurs in three variants: quasi-axisymmetry, quasi-helical symmetry and, generalizing quasi-poloidal symmetry which does not exist, a quasi-isodynamical structure of the field strength, which refers to poloidal closure of the contours of the second adiabatic invariant. Thus, by a careful choice of the structure of the magnetic field strength in a stellarator, favourable particle orbit behaviours become possible, which differ essentially from those in tokamaks, giving rise to the question whether this essential difference influences not only the neoclassical but also the anomalous transport.

Further aspects reviewed concerned:

(a) The ripple transport in the LMFP regime (of great importance in non-quasisymmetric configurations) and the importance of a radial electric field to attenuate this transport mechanism;
(b) The bootstrap current, of strongest potential usefulness in quasi-axisymmetric configurations and nearly absent in quasi-isodynamic configurations;
(c) The α-particle confinement which in many stellarators is so poor that all reflected particles are promptly lost.

As mentioned above this situation is overcome by quasi-symmetric or quasi-isodynamic devices, the most recent achievement in this area of research being that quasi-isodynamic configurations (which have a truly 3-D structure of the field strength) even exist in vacuum field stellarators, which solves a fifty year old stellarator riddle.

P. Helander and T. Fülöp reported on non-linear neoclassical transport for the tokamak edge. In this work the theory of neoclassical transport in an impure toroidally rotating plasma is extended to allow for steeper pressure and temperature gradients than are usually considered. In such steep profiles, which are typical in the tokamak edge, it is found that impurity ions undergo a spontaneous rearrangement on each flux surface, which reduces the transport. The neoclassical ion flux therefore decreases if the gradients become sufficiently steep, and the flux is a non-monotonic function of the gradients for plasma parameters typical of the tokamak edge. Additionally, if the edge plasma rotates toroidally, the transport becomes sensitive to the geometry of the magnetic equilibrium. In steep profiles, the ion particle flux changes direction if the toroidal field is reversed, and is inward if the ion drift is towards the X point in a single null magnetic geometry. The ion particle confinement is thus improved, and the impurities are screened from the core.

Furthermore, P. Helander (for D.J. Sigmar) reported on neoclassical transport at low aspect ratio. A method is devised to accurately calculate the level of neoclassical transport in the banana regime, allowing for an arbitrary fraction of trapped particles. This must be done using the exact Fokker–Planck collision operator for all aspect ratios, i.e. by dealing with strong trapping effects when solving the drift kinetic equation. While this presents no difficulty for the pitch angle scattering operator, the particle-like collision operator gives rise to a new type of problem in the momentum restoring term, which is caused by the coupling of different Legendre polynomials in the pitch angle variable. Here, an analytic and a simple numerical method are developed to fill this gap. The ensuing operator retains the full differential pitch angle operator, but expands the momentum restoring piece in a new set of eigenfunctions. Important corrections to the neoclassical transport are found for intermediate aspect ratios.

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