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Detailergebnisse / Details

TEC Main Topic 7 — Theory and Modelling

A substantial fraction of the theoretical activity of the TEC, closely related to experimental research, is reported in the corresponding Topic Group sections. The present review covers complementary activity.

Transport and confinement

Modelling of L-H transition and H-mode characteristics with the code RITM

The 1-D transport code RITM has been amended by including a model for anomalous transport contribution driven by drift-Alfvén (DA) turbulence. This allows simulating H-mode plasmas in a self-consistent way, from the plasma axis to the separatrix including the edge transport barrier. It is demonstrated that the formation of edge pedestals requires suppression both of DA and of ion temperature gradient (ITG) unstable modes. The former occurs due to decreasing plasma collisionality and increasing beta with growing heating power. The stabilization of ITG turbulence is caused mostly by sharp density gradients, which develop at the edge due to ionization of incoming neutrals when DA transport is reduced. On the one hand, this explains the proportionality of the radial pedestal width to the penetration depth of charge-exchange neutrals, which scales as the square root of the ion temperature. On the other hand the temperature gradient, which drives ITG instability, is controlled in the barrier by the neoclassical heat conductivity and, therefore, the pedestal width scales inversely with the plasma current. All together this leads to a proportionality of the barrier width to the poloidal Larmor radius, widely observed in experiments. The seeding of argon can lead to a significant modification of the edge transport, in particular, to a widening of the edge barrier and an increase of the plasma density, thus preserving a good confinement quality. However, a too intensive edge radiation from impurities, which cools the plasma edge too strongly, results in a resumption of DA activity and can trigger a back H-L transition.

Studies of plasma micro-instabilities and their contribution to anomalous transport

The effect of gyro-viscosity on ion dynamics and improved mixing length approximation have been taken into account by considering dissipative trapped electron (DTE) instability. It is demonstrated that DTE contribution to anomalous transport significantly decreases with increasing hydrogen isotope mass in agreement with numerous experimental observations.

A theory of the ITG–PVS (ion temperature gradient / parallel velocity shear) drift instability, driven by a synergy of the gradients of the ion temperature and the parallel velocity, has been elaborated. On the one hand, the theory predicts that the threshold of the ITG instability is reduced in the presence of the parallel velocity shear. On the other hand, the threshold of the PVS instability becomes intrinsically dependent on the temperature gradient. The features of the ITG–PVS instability appear to explain (i) the origin of the quasi-coherent (QC) mode which occurs at the transition from ELM-free to EDA H-mode in ALCATOR C-Mod; (ii) the reduction of the particle (but not of the energy) confinement time which is observed in EDA discharges; (iii) the strong role of q (the safety factor) and, to a lesser extent, of δ (the triangularity parameter) in obtaining EDA behaviour. The scenario assumes that the H-mode pedestal (where the ITG–PVS instability and enhanced particle transport are localised) is impermeable for neutrals, since charged particles issued from ionisation would otherwise accumulate in the core. That requirement, together with the ITG–PVS instability condition, might be difficult to satisfy in tokamaks with low or moderate magnetic fields.

L-H transition and Reynolds stress

In view of understanding the L to H mode transition, a theoretical model has been developed to investigate whether the Reynolds stresses could be responsible for it. This model retains as driving mechanism the momentum from the turbulence that is transferred to the main flow via the Reynolds stress and includes neutral particle friction and parallel viscosity as damping mechanisms.

Neoclassical theory and H-mode transition in presence of additional heating

The development of a new neoclassical theory taking into account the non-Maxwellian distributions generated by the external heating of the plasma by electromagnetic waves has progressed along the following lines: a) definition of a non-Maxwellian stationary state in presence of heating, b) inclusion of this state in the method of solution of the drift-kinetic equation in presence of a turbulent field, c) determination of the turbulent transport coefficients. At this stage, various models of turbulence are investigated.

For the investigation of the relation between the L-H transition and the plasma impurity content, the radial electric field bifurcation due to different loss and input mechanisms including impurity injection was considered. This work is in the continuation of previous investigations by considering the time evolution of the electric field during the transition. One of the main results is that, within the framework of the model, the stationary radial electric field strongly depends on the fraction of expelled impurity ions.

Investigation of mechanisms for the density limit in tokamaks

Normally the radiation losses from impurities are considered as the main cause of the density limit in fusion devices, although a significant increase of particle convection was recorded as a precursor of the density limit in various machines. It has been demonstrated that namely the synergy of these two channels for energy losses plays an extraordinary role for the density limit. As the plasma density is ramped up, e.g. by gas puffing, the edge temperature drops. The process is, however, dramatically accelerated when at a critical level n_{cr} the turbulence driven by the so called drift ballooning instability starts to dominate anomalous transport at the plasma edge. As a result the particle convection increases dramatically and strongly cools the plasma edge. The latter cooling "activates" the radiation channel of energy losses, which finally leads to the density limit at a certain n_{max} (see Fig. 1). The calculations demonstrate that due to a very non-linear temperature dependence of the radiation, n_{ame} only slightly exceeds n_{cr} and, as it is observed in experiments, varies very weakly with the impurity concentration. Therefore, the transition in the edge turbulence, taking place at n_{cr}, actually sets the density limit. The parametric dependence of n_{cr} that is obtained is very close to that given by the experimental Greenwald scaling.

The scenario described above does not exhaust all possibilities and often, the density limit is caused by development of MARFEs, a region with very low temperature and high density at the high field edge of the device. A model for the MARFE threshold, which takes into account plasma interaction with the inner wall, has been developed. Both local release of impurities and recycling of hydrogen neutrals are considered. It is shown that, by leading the so called recycling instability, main neutral particles play a more important role in the formation of MARFEs than impurities. However, the situation can be changed if the recycling properties of the wall are modified, e.g., by wall covering with specific materials. This explains, in particular, a significant increase of the density limit in TEXTOR after wall boronization. The Dynamic Ergodic Divertor (DED), operating now on TEXTOR, can lead to an essential modification of the plasma wall interaction pattern, predominantly in its intensification at the high field side. According to the modelling performed this should result in a systematic decrease of the MARFE density limit.

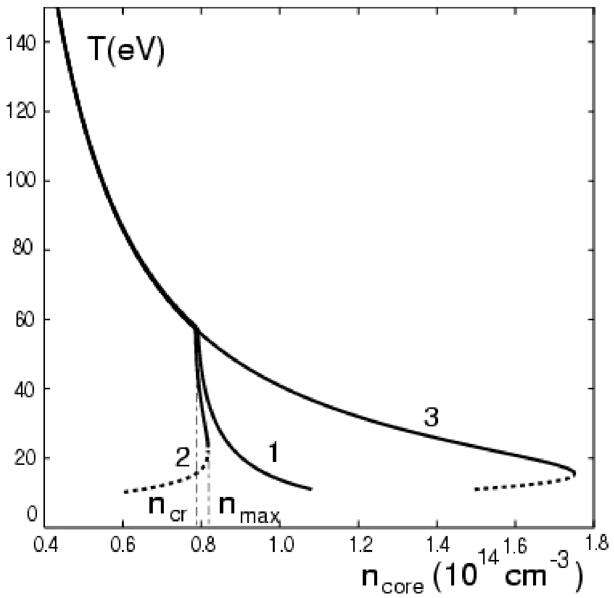

***Fig. 1**: Edge temperature versus core density computed without (curve 1), with (curve 2) impurity radiation and under the assumption that drift resistive ballooning instability is suppressed in the whole parameter range (curve 3). (The broken branches of curves 2 and 3 correspond to unstable states).*

Plasma heating physics

Modelling of ion-cyclotron antennas

In the domain of ion cyclotron heating, the plasma wave and Fokker-Planck codes able to describe self-consistently the evolution of the distribution function of the heated species and the propagation of waves in the presence of this distorted distribution function continue to be developed. The effort in the modelling of the antennas and the coupling of power to the plasma has focused on the use of the Micro Wave Studio™ (MWS) code. This was applied not only to the JET ITER-like antenna under development but also to the existing JET A2 antennas. Fig. 2 shows the degree of detail of the numerical model. The predictions of the code were found to be in agreement with the electrical characteristics of the A2 antennas measured in vacuum. For simple antenna cases, the input matrix produced by this code was compared to that obtained from the code ICANT, which allows considering coupling to plasmas.

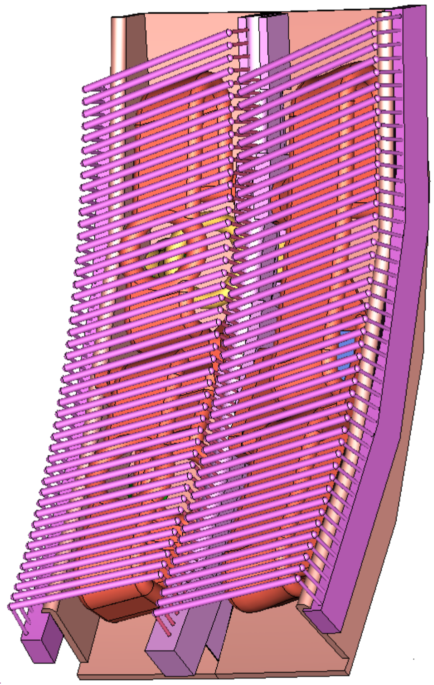

Fig. 2: *MWS model of one-half of the JET-A2 antenna.*

Impurity pump-out with RF

The effective pump out of a large fraction of impurity ions by off-axis ion cyclotron heating (ICRH) was observed in the TFR tokamak. The energy gained by the cyclotron interaction can be high enough to throw the impurity ions out of the plasma column. The code RITM has been modified by including the heat balance equations for the impurity ions in order to allow calculating the response to RF heating of selected impurity species. The numerical simulations, incorporating results of a trajectory code were performed for the JET plasma. The outgoing ion flux created by this method can generate a radial electric field, which may give rise to an L-H transition. This behaviour is studied analytically when the radial electric field is driven by the combination of this outgoing ion flux and an anomalous non-ambipolar flux. In this way, a microscopic theory of the L-H transition is obtained, based on a model of non-linear mode interaction provided by a system of coupled Langevin equations for the Fourier modes of the radial electric field.

A neoclassical theory of turbulence in presence of RF heating is developed, based on a) the definition of a usually non-Maxwellian stationary state in presence of heating, b) insertion of this state in the method of solution of the drift-kinetic equation in presence of a turbulent field, c) determination of the turbulent transport coefficients. At this stage, it is attempted to go deeper into the transport coefficients by assuming various models of turbulence through the dispersion relation.

Electron cyclotron current drive

A mechanism for the acceleration of electron populations resulting from the effect of crossing electromagnetic waves propagating in a dispersive medium is studied, in view of possible application to non-inductive plasma current generation in the electron cyclotron wave domain. To analyse this mechanism, the resonant moments (RM) of the distribution, i.e. velocity moments computed in the resonant layer only, are evaluated. Although the RM approach has to be considered as an approximation, this prediction is reasonably confirmed by direct statistical simulations. It is shown that the two-wave scheme allows to raise the mean electron velocity up to one order of magnitude when compared to the one-wave scheme because of collective effects.

A power dependence of the current drive efficiency has been reported some years ago for the electron cyclotron current drive (ECCD) problem. The effect is observed in simulations when the absorbed power is larger than some threshold value, being close to 1.5 W/cm^3 for typical tokamak plasma parameters, but was not seen experimentally. Similar scenarios have been simulated with the Fokker-Planck solver developed in SPP-ULB, showing that in the framework of the quasilinear theory, the effect is found only for off-axis cyclotron resonance position.

Nonlinear plasma dynamics, turbulence and plasma behaviour in stochastic magnetic fields

Electromagnetic tokamak turbulence simulations

Numerical simulations of turbulent transport in tokamak experiments with intense electron heating have been performed using the CUTIE code. These simulations model the plasma turbulence at scales above the ion gyroradius and include three-dimensional electrostatic and magnetic perturbations, various types of MHD modes, neo-classical transport effects and other "toroidal plasma physics" in a cylindrical co-ordinate system. The code is developed by A. Thyagaraja at UKAEA-Culham and further optimized at Rijnhuizen to run on the supercomputing facility SARA.

Typical simulations describe how plasma turbulence develops and saturates when (localized) heating and particle sources are applied to the tokamak. Focus of the studies have been the transient transport effects caused by perturbations. Experiments have been simulated in which fast plasma edge cooling is caused by e.g. injection of hydrogen ice pellets. The introduction of cold material causes a so-called cold pulse to travel inward. Remarkably, in the former RTP tokamak such injection has been found to have also non-diffusive consequences, such as a transient rise of the central electron temperature. This suggests a reduction of turbulence driven transport in an area that is larger than the area that is cooled by the pellet. CUTIE simulations do indeed show such a reduction. CUTIE simulations of the Russian tokamak T-10 have been started in the framework of the NWO collaboration between Rijnhuizen and the Kurchatov institute in Moscow. As part of the TEC collaboration CUTIE is being prepared for transport studies in the TEXTOR tokamak.

Electron-magneto-hydrodynamic turbulence

The fundamental question of how free energy, pumped into a plasma, is dissipated and transported by driving plasma turbulence, was addressed in numerical studies of high frequency plasma turbulence. The rapid fluctuations were captured in a two-dimensional model (with all three magnetic field components) of the plasma electron dynamics: electron-magnetohydrodynamics. The strategy was to start with perturbations with specific wavelengths and to simulate the ensuing turbulence while it decays into a (usually self-similar) state that is insensitive to details of the initial perturbations and therefore has a number of universal characteristics. The simulations have shown how the turbulent energy is redistributed over large and small scale fluctuations The resulting energy spectra (distributions of energy over modes with different scales) have been monitored during the turbulence decay. The spectra are found to be different for fluctuations that are larger and smaller than an intrinsic scale in the electron fluid, its inertial skin depth. At scales exceeding the skin depth, the turbulent energy is found to follow a direct cascade to smaller scales, while other conserved quantities (mean square momentum and helicity) followed an inverse cascade to larger scales.

The time evolution of the ratio between axial and poloidal magnetic energies depends on their initial values. When initially the energy was unevenly distributed over the axial and poloidal magnetic fluctuations, a rapid energy exchange took place. Subsequently the turbulence reached a self-similar decay state in which the energy and square momentum spectra are specific powers of the mode number. The total energy is found to decay as $t^{-2/3}$, consistent with the selective decay of the energy at constant mean square momentum. The maximum of the energy spectrum shifts towards low mode numbers and decays as 1/t, as expected from the infrared scaling of the turbulence. In the opposite regime, where the skin depth is large compared to the fluctuations, both energy and mean square momentum exhibit direct cascades. The dynamics reduces to a Navier-Stokes equation for the axial field fluctuations (the poloidal field being passively advected), but only if the poloidal kinetic energy is larger than or equal to the axial kinetic energy. A different energy spectrum is found now, with different power laws for mode numbers larger and smaller than the initial perturbations.

Further insight in the numerical results has been gained by making a systematic analysis of the scaling exponents of the two hierarchies of structure functions, generalizing the method of equivalent reference fields in scale-invariant Navier-Stokes turbulence. It has been found that these scaling exponents are determined by six free parameters that need to be determined numerically, two of which are related to the nature of the most intermittent structures.

Collisionless magnetic reconnection

Magnetic reconnection is a key mechanism in transport processes both in (virtually collisionless) astrophysical plasmas and magnetic fusion experiments. It is this absence of collisional dissipation to challenge our understanding of high reconnection rates and release of magnetic energy. In weakly collisionless plasmas with a strong magnetic guide field, reconnection due to electron inertia is accelerated by electron compressibility to reconnection rates comparable with those estimated from tokamak plasma instabilities. Numerical two-fluid simulations have shown that the high reconnection rate involves the acceleration of electrons in an exceedingly thin current layer. However, in this fluid model of reconnection, smaller and smaller length scales develop: current and vorticity gradients become singular.

Surprisingly, it was found that a more accurate, kinetic, description of the electrons during this process resolves the singularity and still predicted fast reconnection rates. Hence, the singular behaviour in the fluid description is an avoidable artefact of the fluid equation of state. This kinetic electron description introduces wave-particle resonances as an additional collisionless reconnection mechanism besides electron inertia. It turns out to be possible to separate the two effects by studying quasi-steady reconnection in which the Landau resonances do not play a role. Remarkably, such quasi-steady solutions to the kinetic equations are as tractable as their fluid counterparts and so fully nonlinear analytic solutions can be obtained. Such solutions show a fine but smooth structure of the current density in the reconnection layer, also found in particle simulations of collisionless reconnection and resembling the x-shaped current distributions found in the two-fluid model.

In magnetically confined plasmas, reconnection of field lines that are at different temperatures play a key role in collisionless electron heat transport. The kinetic description resolves this process. It has been found that the effect of a temperature difference between the pre-reconnection regions is to perturb the vorticity and current distributions and thus the entire x-point geometry.

Formation of internal transport barriers (ITBs)

The hypothesis that ITBs form as a result of a reduced coupling between magnetic islands is investigated using the map technique TOKAMAP. Simulations show that the magnetic topology is strongly dependent on the value of q_{min}. When it is smaller than 1.5, the two rational island chains m/n = 3/2 are well separated radially. When it increases above this value, the two island chains are displaced to the low shear region until they overlap, creating there a wide stochastic belt. All the robust magnetic surfaces are lost in this structure. With a further increase in q_{min}, a wide low shear region with robust magnetic surfaces – an internal transport barrier – is formed.

Zonal flows

In a tokamak (but also in the terrestrial atmosphere), under certain circumstances the drift wave turbulence is able to generate a shear flow spontaneously. The latter is characterized by a correlation length that is much longer than that of the original drift wave turbulence. This large-scale turbulent poloidal flow is called a zonal flow. Its effect is a tearing apart of the drift wave structures and their fragmentation. This phenomenon, and its implications for the theory of the H-mode, is approached using a new treatment, based on an extension of the decorrelation trajectory method introduced earlier.

Large eddy simulation (LES) of turbulence

Part of the activity in hydrodynamics and magnetohydrodynamics (MHD) is focused on the numerical simulation of turbulent phenomena. Two types of approaches are considered. For moderately turbulent systems, the evolution equations of the turbulent fields can be computed directly using the so-called direct numerical simulations (DNS). However, for highly turbulent systems, numerical approaches mixing simulation and modelling are required. In that case, the large-eddy simulation (LES) technique is considered as a valuable alternative. The LES equations are obtained by applying a filter to the evolution equations that separates the large scales of the turbulence from the small scales. Though the large scales are still simulated directly, the influence of the small scales is taken into account through a model. This kind of investigation is performed under a variety of forms, ranging from the study of simple physical systems, which allow to investigate the accuracy of the hypotheses up to realistic systems with a complicated geometry. As an example of the former, Fig. 3 compares the evolution of a turbulent channel flow obtained on one side by direct numerical simulation, and on the other side by the LES decomposition technique. The quality of the assumptions made to model the small-scale turbulence is reflected in the closeness of the two results and serves as validation for using the same hypotheses in more complex situations. The latter require sophisticated numerical methods to represent complex geometrical situations. One approach is represented on Fig. 4, where spectral representation is used in one direction (assumed periodic) while a non-uniform triangular 2-D mesh is used in the perpendicular planes.

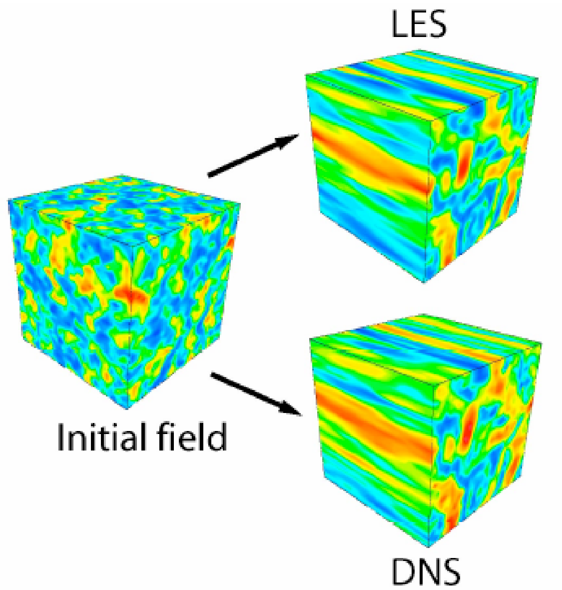

Fig. 3: *Comparison of energy contours obtained for channel flow from the DNS and LES description. The initial flow (left) is isotropic and evolves towards a state (right) where the flow is elongated in the direction of the intense magnetic field.*

Another code has been written that computes the relativistic trajectories of particles in a static turbulent electromagnetic field. When this code will be interfaced with that computing the turbulent field distribution, statistics on particle trajectories will be obtained and the acceleration mechanism will be studied.

Hamiltonian maps in a stochastic magnetic field

The study of mapping models for magnetic field lines in a toroidal system has been continued and it was demonstrated that symmetric mapping models are compatible with field line equations. This symmetry means invariance with respect to a reversal of the toroidal direction. "Tokamap", a map proposed earlier by *Balescu et al.* for a description of field line behaviour in a tokamak, has been generalized as a "symmetric tokamap".

A systematic and rigorous method for the construction of symplectic maps near the separatrix of generic Hamiltonian systems has been developed. This method was applied to study the structure of magnetic field lines in tokamaks with a poloidal divertor in the presence of non-axisymmetric magnetic perturbations. Some peculiarities of this structure can be responsible for the stabilizing effect of asymmetric magnetic perturbations on edge localized modes observed in DIII-D.

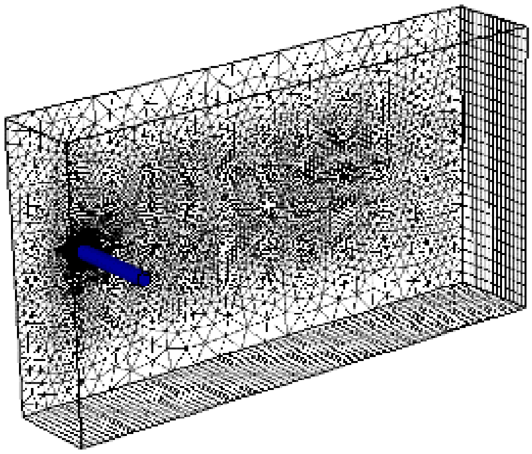

Fig. 4: *A typical representation incorporating combined spectral and finite-element approaches.*

Penetration of the DED field into the plasma

An ongoing study of the penetration of the DED field into TEXTOR uses a linearized two-fluid warm plasma description of eighth order in slab geometry, incorporating thermal effects and an inhomogeneous equilibrium. Wave interaction in the Alfvén resonance region is crucial to DED operation. Although unexpected from the dispersion relation, a first numerical integration through this resonance region shows probable existence of coupling between the cold and warm wave modes. A study of the energy fluxes in the different waves is being carried out with a view to connecting a highly localized full-wave integration across the Alfvén resonance zone to short wavelength WKB modes carrying energy away from the resonance.

Modelling of transport induced by the DED

The code DALF3 developed at IPP Garching for 3-D simulations of the edge turbulence has been applied to model the modification in anomalous transport caused by the DED. First calculations demonstrate that the magnetic field perturbations from the DED should significantly modify the pattern of the electric field at the plasma edge and, thus, intensify drift flows of charged particles. Also the intrinsic magnetic fluctuations associated with drift-Alfvén turbulence increase noticeably when the DED is activated. All together this results in a significant augmentation of transport in the region influenced by the DED.

The theory groups in the TEC

The Jülich group is mainly active in transport modelling, edge and plasma wall interaction codes and DED modelling.

In the Netherlands at FOM, the theoretical research is carried out within the different research groups of the plasma physics department.

In Belgium, the ERM/KMS team investigates ion cyclotron heating, DED field penetration and edge flows. The ULB team focuses on turbulence, transport theory, plasma heating and current drive.