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EU–US workshop on transport in fusion plasmas

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Abstract
This report summarizes the contributions to the *10th EU–US Transport Task Force Workshop on Transport in Fusion Plasmas (Varenna, Italy, 6–9 September 2004)*. There was an emphasis on transport barrier physics, but also sessions on particle and heat pinches, electron and transient transport and electromagnetic and electrostatic turbulent transport, as well as some on other general issues.

1. Introduction

This workshop on transport in fusion plasmas is the tenth in a series organized jointly under the auspices of the EU and US Transport Task Forces. The previous one in Europe took place in Cordoba, Spain in 2002 [1]. The present workshop was held during September 6–9, 2004, in Varenna, Italy, hosted by the Piero Caldirola International School of Plasma Physics, with A Jacchia serving as scientific secretary. The emphasis was on transport barrier physics, although there were also sessions on particle and heat pinches, electron and transient transport and electromagnetic and electrostatic turbulent transport, a well as some other topics. The sessions on transport barrier physics were organized by P Diamond, although he was unable to attend the actual workshop. The session on particle and heat pinches was organized by X Garbet while the sessions on electrostatic and electromagnetic turbulent transport were arranged by M Romanelli. F Ryter, assisted by J DeBoo, organized the sessions on electron and transient transport. J W Connor covered some additional topics that fell outside the remit of these other sessions. These organizers arranged for invited overviews and selected oral presentations and posters for their respective sessions from the submitted abstracts, leaving time for discussion periods. The reports below are broadly organized under the same headings as these various sessions.

2. Transport barrier physics

The key questions in transport barrier physics are regarding the mechanisms responsible for triggering transport barrier formation in the various channels; their strength, width and impact on confinement; their dynamics and sustainment; and the roles of $\boldsymbol{E} \times \boldsymbol{B}$ flow shear, the q profile and the Shafranov shift in these processes. The session began with invited overview talks, one by C Hidalgo on an experimentalist's view and another by T S Hahm on the theoretician's viewpoint; there was an encouraging commonality in these two presentations. Hidalgo organized his talk under the following headings: (i) the role of magnetic topology; (ii) threshold parameters; (iii) sheared rotation dynamics; and (iv) phase transitions, comparing and contrasting observations in tokamaks and stellarators. Transport barrier formation in tokamaks is usually linked to stabilization of ion temperature gradient (ITG), electron temperature gradient (ETG) and trapped electron mode (TEM) instabilities by $\boldsymbol{E} \times \boldsymbol{B}$ shear effects or the low magnetic shear, s, often associated with internal transport barriers (ITBs). In stellarators neo-classical transport can be important and generates strong ambi-polar radial electric fields, E_{r}, which in turn can produce shear layers that suppress the turbulent transport. On point (i), both tokamaks and stellarators suggest that low-order rational q surfaces are significant, perhaps generating sheared flows through MHD activity and the influence of magnetic islands. The frequent link with low s for ITBs in tokamaks suggests a generic reason, perhaps the 'rarefaction' of mode resonant surfaces. Concerning (ii), the threshold for barrier formation, Hidalgo noted that ASDEX Upgrade observes a critical edge temperature for H-mode, in conflict with findings in DIII-D for pellet-induced barriers, the pellet reducing the edge temperature. The model of Guzdar that relates the H-mode threshold to the generation of stabilizing zonal flows in resistive ballooning turbulence, is consistent with data from Alcator C-Mod. In stellarators the neo-classical aspect leads to a threshold density. Zonal flows are generated by non-linear spectral transfer from linearly unstable, turbulent fluctuations; non-linear analysis tools, such as bi-coherence, can investigate whether this transfer takes place: data from the H-1 stellarator support this mechanism. The generation of shear flows, point (iii), arises as a balance of turbulent and collisional momentum sources and sinks. A key question is what the nature of the flux-gradient diagram associated with the Reynolds stress is. Such flux-gradient diagrams are linked to (iv), the question of phase-transitions, and the related issues of hysteresis; thus a bifurcation diagram corresponds to a first-order transition with hysteresis. A second-order transition is possible when turbulence driven flows play a dominant role in the momentum balance. Hysteresis is observed in the stellarator W7-AS, and a first-order flux-gradient diagram for the L–H transition in C-Mod has been mapped out. However, in a poster Hidalgo showed evidence for a second-order transition in the stellarator TJ-II. DIII-D exhibits more complex transitions involving a two-step process: a first-order and a second-order transition. However, transport processes may be 'bursty', with avalanches. A statistical picture involving a probability distribution function (PDF) for transport events is then appropriate; hysteresis is not present in such a model. Finally Hidalgo noted the desirability of defining a critical exponent for the transition, perhaps linking barrier formation phenomena to transitions in other branches of physics.

Hahm discussed theoretical issues under four main headings: (i) the hierarchy of $\boldsymbol{E} \times \boldsymbol{B}$ shear effects; (ii) the role of q profiles; (iii) electron thermal transport; (iv) barrier dynamics; and (v) causality and zonal flows. On (i), experiment and theory show evidence for suppression of fluctuation amplitudes and the reduction of correlation lengths, particularly significant for radially extended 'streamers'. These effects, as well as the 'de-phasing' of density and potential fluctuations, lead to a decrease in turbulent transport. Furthermore, the generation of E_{r} does indeed precede these changes (i.e. there is causality), but the evolution of E_{r} and turbulence changes can be fast or slow. On issue (ii), Hahm noted that low and negative magnetic shear can (a) modify linear instability (e.g. through trapped electron precessional drifts and the Shafranov shift); (b) lead to rarefaction of mode resonant surfaces near q_{min}, the minimum in q (although this does not necessarily lead to a 'gap' in ITG turbulence there); and (c) affect zonal flow generation by stabilizing the Kelvin–Helmholtz instability which provides collisionless damping of the zonal flow. The presence of low-order rational q values can promote MHD activity and magnetic islands; these in turn can lead to strong $\boldsymbol{E} \times \boldsymbol{B}$ flows. Concerning point (iii), the main candidate modes are TEM and ETG, although their linear stability is an issue in different devices. Numerical simulations of ETG turbulence can exhibit streamer formation, at least for $s > 0$, with the potential to cause significant transport, but there are disagreements in the literature on its actual magnitude. The origin of electron transport observed in regions of weak gradient that are linearly stable is a mystery: perhaps non-linear 'turbulence spreading' is operative. Given the confusing picture on linear stability, it may be sensible to seek more robust, non-linear explanations for the formation of electron ITBs, e.g. trapped electron precession shear de-correlation of turbulence. A framework for discussing (iv) is provided by the flux landscape concept based on the flux-gradient bifurcation diagram as a function of radius. Here the Maxwell construction for the barrier foot-point leads to an outward barrier motion with increasing power. Toy models for the interaction of turbulence, profiles and flows can describe the dynamics of barrier formation; inclusion of zonal flows and avalanches leads to a statistical approach based on PDFs for the turbulent fluxes. Finally, on issue (v), Hahm discussed the spontaneous growth of zonal flows in turbulence; bi-coherence measurements are a signature of this non-linear process. The presence of zonal flows reduces the level of drift wave fluctuations. The influence of the variant known as the geodesic acoustic mode (GAM) is only significant at the plasma edge where it does regulate the level of turbulence.

A L Rogister commented on sheared flows, pointing out that $\boldsymbol{E} \times \boldsymbol{B}$ shear had the effect of producing a forward cascade in k_{r}, to modes that could ultimately be damped, and that parallel flows could trigger a parallel velocity shear (PVS) instability that could enhance ITG growth rates. Thus toroidal flows can be both destabilizing as in the PVS instability and stabilizing through their contribution to $\boldsymbol{E} \times \boldsymbol{B}$ flow shear. Since ITGs become stable as $s \to 0$, he also suggested that if transport is dominated by long wavelength modes, this could explain the relevance of low s and low-order rational q values in barrier formation.

2.1. ITB physics

C Angioni presented investigations of ITBs in ASDEX Upgrade on behalf of A Peeters. For the 1999 campaign, NBI was applied during the current ramp-up phase in low-density plasmas, producing a non-monotonic q profile. Mainly ion ITBs were produced, all with $s < 0$; none were observed for $P_{\mathrm{NBI}} < 5$ MW. In 2002 the heating was delayed, resulting in the formation of strong ITBs. A new, simple and reproducible recipe employed in 2003 involves strong, pure NBI (10 MW) in the late current ramp-up, at very low density ($n_{\mathrm{e}} \approx (0.9\text{–}1.7) \times 10^{19}\,\mathrm{m}^{-3}$). The ITBs in ASDEX Upgrade form with their 'foot' inside or very close to q_{min} and then move outwards. The steep gradients can lie outside q_{min} in the $s > 0$ region, and so they are not limited to $s = 0$. 'Staircase', or double, ITBs have been identified and are observed in connection with MHD activity. The decay of ITBs is slow, unrelated to the occurrence of the first ELM. Micro-stability studies indicate that the Shafranov shift is important, with no evidence that the q profile plays a key role, at least for sustaining ITBs. An additional stabilizing mechanism for ITGs is dilution of thermal ions. This explains the observed maximum density for ITB formation. Recently a new, 'current hole' scenario with early, on-axis counter-ECCD has been demonstrated: this exhibits both electron and ion ITBs.

O Sauter described electron ITBs on TCV with negative or zero values of s resulting from ECCD. These are formed without a fast plasma current ramp and are fully sustained with off-axis co-current ECCD and the bootstrap current; the confinement time increases with EC power. The ITB forms rapidly compared with the slow evolution of current, with the improvement starting off-axis, but moving relatively rapidly inwards; the thermal diffusivity, χ_e, is a minimum at q_{min}. The loop voltage, V_{loop}, provides a means of control; although it does not affect the barrier location it does influence its strength, with $V_{loop} < 0$ providing stronger barriers. Gyro-kinetic simulations for TEMs show that the changes in q significantly reduce χ_e in the $s < 0$ region, mainly due to the Shafranov shift effect.

Yu Baranov described hysteresis effects in JET. LHCD initially produces a strong negative central shear where the ITB forms, with its foot being near $s = 0$. χ_i and χ_e are minimized in the $s < 0$ region. As the density increases during the NBI, the role of the LHCD in producing negative shear is taken over by the bootstrap current. The dynamics of the ITB is well represented by transport modelling. Analysis of ITG/TEM and ETG stability with the linear electrostatic, gyro-kinetic flux-tube code KINEZERO shows that these instabilities are suppressed: the effect of $\boldsymbol{E} \times \boldsymbol{B}$ shear dominates where $|s| \ll 1$, but plays a complementary role to s for $s < 0$; Shafranov shift effects are also significant. This picture is supported by the evolution of the ITB during internal relaxations associated with the current hole. The ITB is sustained following a reduction in NBI power: such hysteresis resembles a first-order transition.

K Toi described the use of dimensional similarity to investigate transport barrier formation. He considered well-controlled helical devices, showing that the physics of barrier formation in the high-temperature CHS device could be studied at the same values of ν_* and β, albeit at larger ρ_*, in a much lower field, cooler plasma. This allows the use of probes for diagnostic purposes. Indeed, as in high-temperature plasmas, the formation of an ITB with a transition in E_r to large positive values is observed, a feature of the neo-classical 'electron root' in non-axisymmetric systems. The particle barrier is very clear, but the one in the electron temperature is modest. Only density fluctuations are reduced; in fact those in temperature and space potential are enhanced. Although a large E_r is produced, the E_r shear is not significant.

Linear devices offer the possibility of basic studies of the mechanisms for self-organized flow generation: G Tynan described experiments on the controlled shear de-correlation experiment (CSDX). The turbulence was identified as arising from Kelvin–Helmholtz and collisional drift wave instabilities, with the low-k_θ spectrum being populated by non-linear spectral energy transfer. The radial potential profile is accurately predicted by self-organization theory; there are low-frequency azimuthally symmetric fluctuations in the resulting shear flow. The measurements of the Reynolds stress are consistent with the observed shear flow.

In the poster session, R Behn described experiments on electron ITBs in TCV with electron cyclotron heating and current drive. C Bourdelle used the KINEZERO code to investigate the role and relevance of 'alpha (or Shafranov shift) stabilization' for ITG/TEM and ETG modes. G Regnoli described stability calculations for $0.1 < k_\theta \rho_i < 10^3$ with KINEZERO during ITB formation in FTU. B Gonçalves discussed the energy transfer between perpendicular flows and turbulence and the link between parallel flows and fluctuations. Hidalgo presented results from the boundary region of TJ-II on the link between sheared flows and turbulence; these results are consistent with a second-order transition model.

The session finished with a discussion period, led by Garbet. Points raised included the need to distinguish between the conditions for triggering ITBs and those for sustaining them—these may differ; the reasons why it is difficult to obtain ITBs at high density and whether this could be overcome; the evidence for hysteresis and the character of the transition, i.e. first-order or second-order; distinctions between tokamaks and stellarators; and means for control of ITBs. In summary, the presentations indicated that the $\boldsymbol{E} \times \boldsymbol{B}$ flow shear, q profile, Shafranov shift and bootstrap current can all play a part in the triggering and the ensuing dynamics of ITBs while there is evidence for both first- and second-order transition behaviour. None of the presentations addressed the question of barrier widths. Clearly more experimental work is needed to characterize ITB physics and build models. There is also a need to resolve the apparent conflict between global and local simulations of ETG electron thermal transport associated with ITBs.

2.2. H-mode and momentum transport physics

Sheared plasma rotation can reduce the growth rate of some plasma micro-instabilities and the corresponding fluctuation amplitudes and so play an important role in the dynamics of transport barriers, including potentially the L–H transition, although generating core rotation to trigger ITBs is a challenge for an ITER-scale device. The influence of the shape of the plasma cross section and of the divertor design on plasma rotation and H-mode access power, P_{Th}, in discharges without momentum input was discussed in many of the papers in this session. Observations of self-generated zonal flows were also reported.

In Alcator C-Mod ohmic L-mode plasmas, described by J Rice, the toroidal velocity in the core, $U_{\varphi,i}$, is in the counter-current direction and depends strongly on the magnetic configuration: for standard discharges with $B_{\mathrm{T}} = 5.4\,\mathrm{T}$, $I_{\mathrm{p}} = 0.8\,\mathrm{MA}$, $\bar{n}_{\mathrm{e}} = 1.4 \times 10^{20}\,\mathrm{m}^{-3}$ and the ion $\boldsymbol{B} \times \nabla\boldsymbol{B}$ drift downwards, $U_{\varphi,\mathrm{i}}$ is in the range 10–20 $\mathrm{km\,s^{-1}}$ with a lower single null and in the range 30–50 $\mathrm{km\,s^{-1}}$ with an upper single null; in near double null plasmas, $U_{\varphi,\mathrm{i}}$ depends very sensitively on the distance between the primary and secondary separatrices, with changes of $\sim$25 $\mathrm{km\,s^{-1}}$ occurring over a variation of a few millimetres. Application of ICRH power increases the rotation in the co-current direction. The transition to H-mode is seen to occur when the core rotation reaches a characteristic value, near zero. A higher input power is thus required to induce the transition in the upper single null configuration.

Y Andrew described how a unique opportunity to assess the influence of the divertor septum in JET was provided when it was substituted by the non-power loading septum replacement plate (SRP). Equivalent septum configurations run with the SRP in the MkII gas box (GB) divertor have shown that the presence of the septum lowers the H-mode access power, P_{Th}, by 20%, while the pedestal electron temperature, $T_{\mathrm{e,ped}}$, remains the same; other experiments show that with lowered X-point height, SRP plasmas reproduce the significant decrease in P_{Th} and $T_{\mathrm{e,ped}}$ first observed with the MkII divertor septum. Although there is a power threshold offset between septum and SEP discharges, there is no difference in $T_{\mathrm{e,ped}}$ over the X-point height scan. A series of density scans at $B_{\mathrm{T}} = 2.7\,\mathrm{T}$, $I_{\mathrm{p}} = 2.5\,\mathrm{MA}$ showed no changes in P_{Th}, $T_{\mathrm{e,ped}}$ and $T_{\mathrm{i,ped}}$ while increasing the upper triangularity, δ_{upper}, from 0.23 to 0.34 and keeping δ_{lower} and the divertor geometry fixed. In two configurations with $\delta_{\mathrm{upper}}/\delta_{\mathrm{lower}} = 0.23/0.23$ and 0.43/0.33, P_{Th} decreased with higher triangularity by as much as 25% for values of the edge density above $1.8 \times 10^{19}\,\mathrm{m}^{-3}$. Many of the differences in P_{Th} can be explained through the observation of a constant $T_{\mathrm{e,ped}}$ or $T_{\mathrm{i,ped}}$ and the difference in power needed to reach these values.

Y Hamada described how large potential oscillations have been measured throughout the cross section of JIPP-T2U using a 500 keV heavy ion beam probe with multiple sample volumes. Correlation analysis of the signals from four to five of those volumes points to $m = 0$; thus $n = 0$, assuming elongated oscillations (m and n are the poloidal and toroidal mode numbers). The frequency and radial correlation length spectra of the zonal flows have been obtained. The high-frequency constituent corresponds to the GAM with $f \sim 50\,\mathrm{kHz}$

in the core and $f \sim 5$ kHz at the edge; GAM oscillations appear to involve two poloidal rotations of equal magnitude and opposite directions; they are dominant and have a sharp spectrum and a standing-wave-like structure in the core. Here, potential oscillations have very long correlation times and the low-frequency part of the zonal flow can be identified as the amplitude modulation of the GAM oscillations. The low-frequency components of the zonal flow dominate at the edge where the GAM is difficult to detect.

The relationship between electromagnetic turbulence and sheared plasma flow in the reversed field pinch (RFP) was addressed in the presentation by N Vianello. The interpretation of experimental results obtained from an array of magnetic and electrostatic probes in the outer region of Extrap-T2R on the basis of the momentum and continuity equations points to a self-regulating process between the sheared flows and the turbulence. The 'experimental' viscosity required by momentum balance is non-classical and consistent with the anomalous particle diffusivity. The latter is discussed in terms of an electrostatic turbulence background with coherent structures having features reminiscent of mono-polar and di-polar vortices whose relative populations depend on the $\boldsymbol{E} \times \boldsymbol{B}$ shear flow; the weights of these two types of vortex control the anomalous diffusivity.

F Crisanti's talk explained how, by heating the plasma with the ^{3}He ICRF minority scheme, ion ITBs have been obtained at the same location as already well established electron ITBs in JET negative central magnetic shear discharges sustained by LHCD. The ITB is present until the q profile becomes monotonic; the barrier is highest when the surface $q = 2$ appears in the plasma and the q profile is flat inside. In these discharges without external momentum input, the rotation velocity is a factor $\sim$10 lower than in discharges with NBI heating; accordingly, the $\boldsymbol{E} \times \boldsymbol{B}$ shearing rate is low, although comparable with the ITG mode linear growth rate (the best correlation appears to be with the quasi-slab theory). The reported experiments are relevant to ITER values of ρ_* and the achieved performances comparable with those with NBI.

The importance of neutral transport in determining the density profile in the region of the H-mode transport barrier was discussed in a poster by D Mossessian, who presented a relatively simple one-dimensional model. D Kalupin's poster described the use of the transport code RITM, which includes the effects of ITG, dissipative TEM and drift Alfvén (DA), drift resistive and drift ballooning mode turbulence, to investigate the mechanisms responsible for the formation of the H-mode transport barrier. The local kinetic micro-instability theory has been extended by Rogister to account for density, temperature and toroidal velocity gradients simultaneously. He described, using the Nyquist diagram, how the threshold of the combined ITG–PVS mode is reduced.

Clearly rotation shear can play a role in L–H transitions, but a range of other effects specific to the plasma edge can have a strong influence: it is a challenge to synthesize all these results. The possibility of generating ITBs without external momentum input is encouraging for ITER. Experimental observations of zonal flows and self-generated shear flows provide support for models of anomalous transport.

2.3. Density limit and edge transport

It is necessary to operate ITER at densities approaching the Greenwald limit and so it is important to understand the mechanisms which restrict the density range in tokamaks, to investigate experimentally and theoretically high-density operation modes, and to develop tools for controlling the edge turbulence and transport. Various mechanisms have been proposed as the cause of the density limit in fusion devices: impurity radiation, particle recycling on divertor plates and inner walls, changes in the nature of edge anomalous transport. M Tokar described a model that combines these effects in order to investigate synergies between them. The results show that the density limit is determined mostly by poloidal asymmetries associated with the Shafranov shift and the ballooning character of edge turbulence. In ohmic discharges with relatively low input power, the rise in density first leads to a transition from 'standard' edge drift turbulence, homogeneous on magnetic surfaces, to drift resistive ballooning instability and plasma detachment at the low field side. In additionally heated discharges with large Shafranov shift and pronounced heat loss asymmetry from the core, a 'recycling instability' at the high field side can trigger a MARFE before the transition in edge turbulence takes place.

Edge impurity radiation is a possible tool for moderating the power flux to the plasma-facing components. In TEXTOR, impurity seeding leads to a transition from the L to the radiative improved (RI) confinement mode. The dynamics of this transition is explained by a transport model presented by B Unterberg that has been implemented in the code RITM; a particle pinch associated with the dissipative TEM plays a key role in quenching the ITG mode.

The enhanced D-alpha (EDA) H-mode obtained in C-Mod avoids both the energy bursts associated with large ELMs and the accumulation of impurities in ELM-free discharges. Rogister described how the gradient of the parallel velocity predicted by neo-classical theory applied to the pedestal plasma is close to the value for the onset of the PVS instability when discharges are close to the ELM-free to EDA transition. The wavenumbers and frequencies of weakly unstable PVS oscillations are compatible with those of the 'quasi-coherent mode', always present in EDA discharges; other observations, including enhanced edge particle transport, also agree with the theory.

In the poster session, F Kelly described modelling of the dynamic ergodic divertor (DED) on TEXTOR, while X Loozen investigated the effect of the DED external magnetic field perturbations on the edge drift instabilities. D Mikkelsen presented work on L–H and H–L transitions in NSTX; these are found to last less than $100\,\mu$s. G Antar provided evidence that intermittent convective transport in the SOL of linear magnetic confinement devices takes place periodically.

3. Particle and heat pinches

This session was introduced by P Mantica, who presented the latest developments in the theory of pinches. Pinches are important for modelling energy confinement and predicting the peaking of density profiles. Quasi-linear theory predicts that both thermo-diffusion and magnetic field curvature contribute to the turbulent particle pinch. For trapped electrons, the curvature pinch velocity depends on the magnetic shear and is identical to the value predicted by the turbulence equi-partition theory (TEP), as found by Isichenko and co-workers. Hence a theoretical framework now exists for discussing pinches which encompasses various physical effects. For trapped particles, the ratio of the pinch velocity to the diffusion coefficient is found to decrease with collisionality. Similarly, the density gradient and curvature contribute to the heat pinch. The major issues to be addressed in experiments are the following:

(a) Is the particle pinch anomalous or not?
(b) If so, does the pinch velocity depend on magnetic shear and/or on collisionality?
(c) Is it possible to control the peaking of the density profile?
(d) Does a heat pinch exist?
(e) What are the parametric dependences?

The experimental results in several devices can be summarized as follows. Plasmas with peaked density profiles and no neo-classical Ware pinch were produced in Tore Supra and TCV, thus pointing towards the existence of a turbulent pinch in L-mode. It has also been verified that the pinch velocity increases with magnetic shear in JET, Tore Supra and TCV L-mode plasmas. In H-mode, density peaking is sensitive to collisionality as found in ASDEX Upgrade and JET. At high collisionality, the pinch velocity is close to the neo-classical value, whereas it is larger at low collisionality. Radio frequency heating is found to flatten density profiles. When collisionality is large, this is interpreted as an increase in the turbulent diffusion coefficient, while the pinch velocity stays close to the neo-classical value. For low-density plasmas, the interpretation relies, rather, on the weakening (and maybe reversal) of the pinch velocity predicted by theory when the turbulence changes from that found with dominant ion heating to when electron heating dominates. The situation is less satisfactory for the heat pinch. As Mantica pointed out, a heat pinch is more difficult to demonstrate because the temperature gradient is the main drive for the instability. Hence there always exists a solution with off-axis heating with no gradient in the core, and hence no turbulence and no pinch. The conditions under which the system bifurcates to a situation with turbulence and an inward heat pinch are unclear. Nevertheless, off-axis ECH experiments have yielded peaked T_e profiles in conditions of small or negative core heat flux in DIII-D, FTU and ASDEX Upgrade, whilst heat modulation experiments in RTP and ASDEX Upgrade have demonstrated the existence of an inward pinch (through an inward shift of the amplitude and phase of the thermal wave with respect to the radius of heat deposition). Numerical simulations using the Weiland model and the global, two-fluid electromagnetic turbulence code CUTIE can reproduce the RTP results but not, so far, those from ASDEX Upgrade.

Angioni showed that collisionality is an important control parameter for the transition from TEM to ITG turbulence. Indeed collisions stabilize the TEM branch so that the ITG becomes the dominant instability at high density. This property has been used in ASDEX Upgrade to run a series of experiments to test this idea. It is indeed found that in the collisionless regime, electron temperature profiles are stiff and density profiles tend to be flatter due to an outward thermo-diffusion contribution. J Candy presented studies with the global, gyro-kinetic code GYRO. Three main results were found. First, the tritium confinement is (slightly) better than that of deuterium in a DT plasma. This effect arises from the different Larmor radii associated with the mass difference. Second, a quasi-linear model works well for impurity transport. Finally an anomalous particle pinch is usually found and is driven by trapped electrons. It decreases with collisionality, as expected. P Terry presented a new mechanism for the anomalous pinch, which is not contained in the quasi-linear theory. It arises from the excitation of stable modes, which change the cross-phase between density and potential perturbations. This pinch takes the form of a negative contribution to the diffusion coefficient (although the overall coefficient remains positive and the total flux is outwards). This behaviour was illustrated with a fluid model for TEM modes.

G T Hoang presented results obtained on Tore Supra. He showed that the particle pinch is anomalous in most cases since the inductive field, and therefore the Ware pinch, is negligible in long pulses. Moreover, it was found that the main contribution to the particle pinch comes from the curvature, which is dependent on the magnetic shear. This behaviour agrees qualitatively (but not quantitatively) with the TEP theory. Nevertheless, there exists a small contribution coming from thermo-diffusion. This contribution is inwards in the plasma core, and outwards in the gradient zone. The interpretation is that ITG modes dominate in the core (where there are few trapped particles), whereas TEMs contribute significantly to turbulent transport in the gradient zone. This is actually confirmed by linear stability analysis with the KINEZERO code. Quasi-linear theory does predict a pinch that agrees with the observation in this case. M Valisa presented an analysis of nickel laser blow-off experiments in JET plasmas. These plasmas (L- and H-mode) were initially dedicated to electron heat modulation experiments. Shallow pellets were also injected into them. As a consequence, these plasmas were studied in detail for particle transport, electron heat transport and impurity transport. This allows comparisons between the corresponding transport channels. For all channels the thresholds are similar and fit the value expected for ITG/TEM modes. Moreover, the diffusion coefficient of nickel seems to show the same behaviour as the deuterium diffusion coefficient and electron heat diffusivity. A Eriksson presented an analytical calculation of the electromagnetic particle pinch due to toroidal drift waves; the calculation is in agreement with numerical results found using the Weiland model.

In summary this session discussed experimental results on particle pinches within a coherent theoretical framework that involves roles for collisionality and magnetic shear. It should be stressed that many results presented in the electron heat session were also related to the question of pinches. However, several questions still remain. In particular, it is unclear whether passing electrons participate in the particle pinch. This seems to be the case in recent flux-tube gyro-kinetic simulations, but is not found yet in other studies (fluid or gyro-kinetic). The effect of magnetic shear is also controversial, and is not included in the Weiland transport model, for instance. The fact that the effect of collisions is clearly seen in H-mode plasmas, but not the effect of magnetic shear, whereas the latter effect is seen in L-mode, but not the effect of collisionality, is puzzling. Understanding this behaviour is a major challenge for the future. Also, there are still many sources of uncertainty, in particular the radial extent of the ionization source, and the ratio of the diffusion coefficient to the heat diffusivity, which is an important parameter in the analysis. The situation with the heat pinch is even more controversial, both for theory and experiment. On the theory side, it seems difficult to believe that there exists an anomalous particle pinch and not a heat pinch. The constraint of Onsager symmetry relates, in principle, both phenomena. This means that if thermo-diffusion is shown to exist, a heat pinch due to the density gradient should also exist. Turbulence simulations and theoretical developments should help to understand this difficult question. On the experimental side, the present observations need to be confirmed in other machines, and a study of the parametric dependences of the observed heat pinch is needed.

4. Electron and transient transport

4.1. Theory

Electron transport becomes a particularly important issue when electron heating dominates. The primary heating in a fusion power plant will be by the electrons, but energy transfer will lead to $T_e \approx T_i$. However, from the point of view of theory and modelling, electron heat transport has, so far, received less study than that of the ions and deserves more attention. The theory part of the session was introduced by a review talk by Mikkelsen, who stressed the clear differences between the behaviour of electron and ion transport. Low-k modes (ITG/TEM) may be responsible for electron heat transport in most of the tokamak plasma. ITG or TEM can be separated only in particular cases, but these cases have the advantage of being simpler to investigate. Otherwise the co-existence of the modes leads to interactions between the respective transport channels and temperature profiles. High-k modes (ETG) may also play a role, in particular when T_e is close to T_i. This kind of turbulence provides an additional contribution to that of ITG/TEM and complicates the investigations. In particular, significant transport can only be driven if streamers are present; mixing length estimates based on linear stability studies of ETG are not sufficient to explain the heat transport, non-linear calculations are required. Testing and validating the theoretical hypotheses and the transport models is an essential and delicate issue. The talk described, in detail, the different steps and issues involved in this topic.

J Callen presented a new theory, the paleoclassical electron heat transport; it has been derived analytically so far and a more quantitative assessment requires a numerical approach. The drive for heat transport is provided by the radial diffusion of the magnetic field lines, which carries electron heat with it. The effect depends on the length of the field lines and therefore on their characteristic m/n ratio. In particular, in the vicinity of low rational numbers it leads to a lower transport compared with the other regions. χ_e is proportional to $1/T_e^{3/2}$ and drops below 1 $m^2\,s^{-1}$ for $T_e > 2$ keV; therefore it may contribute to electron heat transport in devices of small and medium size. It is an additional contribution to turbulence driven transport and is not intended to replace it.

F Jenko presented non-linear gyro-kinetic results from the code GENE that now includes trapped electron effects. Indeed TEMs are believed to be responsible for electron heat transport; in particular, they are found to be dominant when $T_e > T_i$ (see also next sub-section). It is therefore essential to assess the importance of non-linear effects and the differences compared with quasi-linear calculations. The work presented here indicates that when TEMs are dominant the agreement between linear and non-linear theory is good. In more complex cases, for instance if ITG and TEM are present simultaneously with comparable levels, non-linear calculations are essential. The results also yield a $q^{3/2}$ dependence of the TEM driven transport, in agreement with experimental observations. In addition, a model to estimate the TEM-induced heat transport from quasi-linear calculations was given and the properties of the TEM threshold discussed. The particle pinch in a gyro-kinetic ITG/TEM system was also presented. Finally, results from cross-scale turbulence calculations indicate the possibility of interactions between different types of turbulence.

4.2. Experiment

A review of experimental studies was given by U Stroth. He presented the status up to the workshop. Wherever possible, a comparison between tokamaks and stellarators was made. The talk summarized the initial discussion of profile consistency, started in the early 1980s, and described recent developments. This property, now named 'stiffness', is characterized by a remarkable insensitivity of the temperature profiles to changes in the heating deposition profile. It was stressed, however, that the value of the normalized gradient, R/L_{Te}, may vary, but in tokamaks the R/L_{Te} value remains in general above a finite value even with off-axis heating, suggesting the existence of a threshold. The various indications for the possible existence of a threshold were reviewed and discussed. Heuristic models implying the existence of a critical gradient or normalized gradient have been used by experimentalists to interpret their observations. The stiffness, which characterizes the increase in transport above the threshold, is also given by these models. The fact that the experimental values of the threshold and stiffness are not always comparable in different devices was discussed. It was shown that such a model is supported by data from turbulence measurements that also suggest a threshold. The possible existence of non-local effects was illustrated with some examples. Finally the existence of a heat pinch was discussed.

Several of the contributed talks dealt with the possible existence of a threshold in electron heat transport. This subject was extensively discussed at the last EU–US TTF meeting in 2002 [1]. As a result of common experiments made in ASDEX Upgrade, DIII-D and TCV during 2003 and 2004 it now seems that a more coherent picture could emerge. These experiments were made in low-collisionality ECH heated plasmas with $T_e > T_i$. Results from a variation of R/L_{Te} using on-axis and off-axis deposition in TCV and DIII-D were presented by Y Camenen and DeBoo, respectively. These investigations follow earlier experiments in ASDEX Upgrade and were shown to agree with them. All these results point towards a heat flux with an offset in R/L_{Te} and therefore do not disagree with the possible existence of a threshold in R/L_{Te} for electron heat transport. In all three devices electron heat transport is dominated by the TEM, which indeed has a predicted threshold compatible with the experiment. However, these experimental results did not demonstrate the actual existence of a threshold, and other possible interpretations were suggested. It is believed that the threshold could not be accessed because the residual ohmic heat flux kept the T_e profile just above it, due to the low transport. Indeed, in a presentation at this workshop, by Ryter, of very recent experiments made in ASDEX Upgrade at lower plasma current, it was shown that the minimum achievable value of R/L_{Te} can be reduced below the threshold. Consequently, in a scan of R/L_{Te}, a sudden and clear change in the propagation of heat pulses is observed. This provides strong evidence for the actual existence of a threshold. It must be stressed that in all the experiments with central heating, the working point of the electron temperature profile is above the threshold by a factor of 3, which indicates that the transport is not very stiff.

Jacchia described information on electron heat transport behaviour provided by experiments in ASDEX Upgrade that compared propagation of ECH excited heat pulses and cold pulses induced by impurity laser blow-off in the presence of strong ECH deposited at about mid-radius. The results show that the ECH power location divides the plasma into two parts: a low-transport region inside the ECH deposition radius and a region of high transport outside it. Both heat and cold pulses indicate this property, showing the universality of the effect of R/L_{Te} on heat transport. In addition, these experiments suggest the possible existence of a threshold. Local modulated variations of the electron heat flux with ECH have also been investigated in DIII-D, the so-called swing experiments, presented by DeBoo. No indication of non-linearity in the transport, a sign of a possible threshold, could be found under these conditions.

K Gentle presented an alternative way of looking at heat pulse experiments in which Lissajou figures of q_e versus ∇T_e for sawtooth and ECH pulses are made. The background heating was ohmic or NBI up to 9 MW, and the plasmas were in L-mode and QH-mode (quiescent H-mode). This analysis indicates stiffness and the data taken outside the ECH deposition point towards a finite gradient. For data inside this radius, the patterns show a power dependent hysteresis that can be very large and is not yet understood.

In addition to the TCV results mentioned above, Camenen presented work on using the flexibility in the shape of the device; the investigations addressed the possible effect of the triangularity, δ, on electron heat transport. Indeed it is observed to have an effect on electron heat transport through R/L_{Te}. However, this could be attributed to the stabilizing effect of increasing collisionality on the TEM driven turbulence: changing δ in these discharges does induce changes in density and effective mass, leading to a significant variation in collisionality. The effect of collisionality on the TEM has also been studied in ASDEX Upgrade in dedicated density scans conducted by Ryter. The ratio χ^{HP}/χ^{PB} decreases with increasing collisionality, reaching values clearly below 1 at high collisionality. Supported by gyro-kinetic calculations, this is interpreted as a gradual stabilization of the TEM by collisionality. Eventually, electron heat transport is no longer dominated by TEM driven turbulence but by ITG turbulence. ITG turbulence drives the ion heat flux but also an electron heat flux. The gyro-kinetic calculations indicate that this indeed leads to a situation with $\chi^{HP}/\chi^{PB} < 1$.

Experiments on TEXTOR with ECH were reported by M de Baar. So far, the experiments have been performed with one gyrotron depositing power at the centre. A power scan indicates that R/L_{Te} remains almost constant, as reported earlier in other devices, and the value of R/L_{Te} is in agreement with these. Further experiments will be made in this device to extend these investigations. A second part of the talk summarized a poster presented by D Hogeweij. In this work the interaction between ECH and MHD locked modes was analysed. This study combines the use of the DED and ECH modulation. The DED often causes a magnetic island (with $m/n = 2/1$) to grow. This strongly affects the toroidal rotation, which drops by a large factor, and its radial profile flattens. The temperature profiles decrease by about 20%. The application of ECH reduces the amplitude of the island by about 50% and restores the rotation correspondingly. The propagation of the ECH heat pulses reacts to the changes in rotation induced by the DED in such a way that the propagation of heat pulses is lower when the rotation is high.

Simulations of experimental results from TEXTOR and T-10 at the turn-off of ECH deposited off-axis using the CUTIE code were presented by E Min. After the turn-off of the ECH, the central electron temperature remains constant for about 20 ms. This suggests very low transport in this region. The cause of this is believed to be the low magnetic shear that can be established inside the ECH deposition radius and it possibly leads to an ITB located close to low-order magnetic surfaces. The simulations with CUTIE indicate a reduction in turbulence and an increase in poloidal rotation, but the temperature profiles are poorly reproduced.

Garbet presented a theoretical study based on a turbulence code to demonstrate the interplay between the electron and ion channels. The results indicate that the interaction is mainly dictated by the variations of the respective thresholds. This is particularly true for the effect of the ratio of T_e/T_i on ion and electron heat transport. The study also indicates that the electron stiffness increases when P_i/P_e is increased. However, this effect is less strong than is observed in JET experiments.

The session closed with a general discussion, mainly dominated by theoretical and interpretation topics. Regarding paleoclassical transport, participants were encouraged to use systematically the expression for the heat diffusivity for comparison with the experimental data. Experimental tests for the theory may involve the width of electron ITBs and the effect of the low-order rational surfaces. Regarding turbulence driven transport, the participants agreed that in most of the devices, TEM driven transport can dominate when $T_e > T_i$ at low collisionality. The importance of the assessment of transport simulations, including the required long time to reach steady state, was emphasized. Despite numerous similarities between the heat transport in several tokamaks, there was a desire to achieve a more coherent picture of the properties of stiffness and the threshold. It is interesting to note that there appears to be a common explanation of electron heat transport in normal situations and the physics of electron ITBs in terms of TEMs. Thus their stabilization requires low or negative magnetic shear. Clarifying the role of ETGs in electron transport in the presence of barriers using simulation codes remains a topic for future work, see section 2.1. Electron heat transport in plasmas with $T_e \approx T_i$ was barely addressed in the session, and indeed results are scarce. However, this is an essential topic for future devices, but difficult to address experimentally due to the coupling between the channels and the possibility that ITGs, TEMs and ETGs contribute simultaneously to electron transport.

5. Electrostatic and electromagnetic plasma turbulence and transport

In order to develop a transport model we must ascertain the physical processes involved and validate numerical codes against experimental data. This session examined, in particular, the roles of electrostatic and electromagnetic turbulence. The session opened with two review talks, one by Jenko and the second by Terry. Jenko reviewed how magnetic fluctuations enter the problem of determining the level of turbulence in a tokamak. He introduced the two main instabilities driven by magnetic fluctuations, namely kinetic ballooning modes (or Alfvénic ITG) and micro-tearing modes, and stressed the importance of magnetic fluctuations in modifying the growth rate of the purely electrostatic branch (ITG, TEM and ETG) by changing the saturation level of the above modes. The effects of zonal flows on the generation and damping of small-scale fluctuations was addressed and the question arose as to how magnetic shear fluctuations react back on the other micro-instabilities. Transport driven by magnetic fluctuations alone becomes important only in regimes where the plasma β is sufficiently large (i.e. near the ideal ballooning mode limit). However magnetic fluctuations interact with the other micro-instabilities even at lower values of β. They are of key importance in determining the saturated level of the turbulence measured experimentally in a tokamak.

Open issues concerning theoretical and numerical predictions of turbulent transport were reviewed by Terry. Significant progress on transport studies has been made in the past 15 years, largely for the ion channel, but there are significant issues remaining in all areas. In order to develop a credible predictive capability it is necessary to verify that codes faithfully solve given models and that the models faithfully represent nature. Terry stressed, in particular, the need to compare the simulations with diagnostic data by developing synthetic diagnostics for comparison with machine diagnostics. The other issues identified by Terry that require further work to gain a predictive capability are particle transport relative to ion heat transport, momentum transport, electron heat transport and H-mode threshold and pedestal parameters.

Mikkelsen presented preliminary results on turbulence simulations of NSTX plasmas with the GYRO code. Linear calculations show that the $\boldsymbol{E} \times \boldsymbol{B}$ shearing rate is higher than the linear growth rate of low-k turbulence in NSTX. Non-linear, full-radius simulations with GYRO are being carried out to confirm the $\boldsymbol{E} \times \boldsymbol{B}$ stabilization and to assess the role of non-adiabatic electrons. An analytical expression for the diffusion coefficient allows parameter scaling studies; in particular, the particle pinch is found to increase with plasma β, of relevance to ITER. Hahm presented theoretical work in which he showed how turbulence can spread to radial positions where modes are linearly stable. A model equation was constructed to account for the interplay between linearly unstable modes and zonal flows—the latter are non-linearly triggered by the former and are responsible for the spreading of the turbulence outside the unstable region. V Naulin addressed the problem of zonal flow generation in drift Alfvén turbulence showing that the Reynolds stress term in the equation always acts as a flow drive while the Maxwell stress is always a damping term. The role of GAMs changes, depending on β: for low β they act as a sink while they provide a drive mechanism for high-β plasmas.

B Labit introduced the TorPEx device at CRPP, Lausanne; this is a toroidal machine of 1 m major radius, 0.2 m minor radius and 0.1 T toroidal magnetic field. The low plasma temperature (T_e of about 5 eV) allows direct measurements of fluctuations with Larmor probes. First results on the investigation of turbulence show phenomena such as a transition from 'coherent' to 'turbulent' spectra and the identification of coherent modes associated with electron drift waves. S Kubota showed data on the turbulence radial correlation length, L_{cr}, in NSTX. These have been taken recently with correlation reflectometry in the core of moderately peaked density profiles in L-mode discharges. An attempt to characterize the confinement properties in terms of the related correlation length has been made. L_{cr} is found to increase inversely with radius and magnetic field; L_{cr}/ρ_s increases towards the core.

W Nevins described a novel approach to characterizing ITG turbulence by interpreting and fitting turbulence simulation results in terms of theoretically based concepts such as the 'eddy lifetime', τ_{eddy}, and the 'eddy turnover time', $\tau_{E\times B}$. Simulation results obtained from GYRO indicate $\tau_{E\times B}$ tracks τ_{eddy}, suggesting ITG turbulence saturates due to the onset of $\boldsymbol{E} \times \boldsymbol{B}$ trapping; empirically $\tau_{E\times B} \leqslant 5\tau_{eddy}$. These two non-linear time-scales can be fitted in terms of γ_{max}^{-1}, where γ_{max} is the maximum growth rate; poloidal correlation lengths can be fitted in terms of k_{max}^{-1} and ρ_s, the inverse wavenumber and ion Larmor radius at the electron temperature, respectively. The turbulent intensity and χ_i, as well as the $\boldsymbol{E} \times \boldsymbol{B}$ shearing rate, can then be fitted with seven parameters. However, the procedure fails to capture the Dimits up-shift.

Studies of ρ_s scaling of drift wave turbulence in the toroidal, low-temperature plasma of the torsatron TJ-K were described by Stroth. This allows the use of probes for diagnosing the fluctuation characteristics. This device has values of ν_* and β similar to those in a fusion edge plasma, but ρ_* is much larger; nevertheless ρ_* can be varied by a factor of 10 by using different isotopes. The cross-phase spectra agree with those from simulations of drift wave turbulence with the three-dimensional drift Alfvén turbulence code DALF3. The turbulence is consistent with that from drift waves, the cross-phases scale with ρ_s, and correlation lengths and diffusion coefficient scale less than linearly with ρ_s, indicating an influence of the system size.

F Imbeaux described transport modelling (with the CRONOS integrated modelling code) of hybrid discharges from ASDEX Upgrade, DIII-D and JET from the ITPA Profile Database, testing various transport models. These discharges, having $q_{95} \sim 4$–5 as well as $q_{\min}$ at, or slightly above, 1 (i.e. generally sawtooth-free) have better confinement properties than ordinary H-modes and are a candidate scenario for ITER. It was shown that resistive diffusion, with the broad non-inductive current drive profile, yields the observed q profiles, with $q(0)$ keeping close to 1. Core transport is well described by the GLF23 model, with the $\boldsymbol{E} \times \boldsymbol{B}$ shearing rate improving ion energy confinement. However, it is thought, rather, that the improved H-factor ($H_H \sim 1.2$), is a consequence of the lack of sawteeth or of the pedestal.

The transition to the 'quasi-single helicity' (QSH) state in RFPs was discussed by L Marrelli. Three-dimensional MHD simulations show that the RFP dynamo may be turbulent (multiple helicity) or laminar (single helicity); a bifurcation parameter has been identified. Spontaneous transitions to QSH spectra have been found in several RFP experiments, most frequently at high plasma current, low density and low values of the field reversal parameter; the particular helicity appearing depends on the equilibrium parameters. The measured strong toroidal dynamo EMF is a significant fraction of the induced toroidal electric field. Soft x-ray structures are linked to magnetic islands. Monte Carlo test-particle calculations in these helical structures indicate neo-classical effects are important.

In poster presentations N Crocker described studies of long-range correlations in electrostatic turbulence in the Large Plasma Device at UCLA. M Spolaore reported the identification of vortex structures in RFP plasmas, as mentioned by Vianello in section 2.2; these can account for 50% of diffusive transport. Antar presented a comprehensive scaling study of the structure functions for density and velocity fluctuations in the linear device PISCES and the spherical tokamak MAST. L Vermare described measurements of density fluctuations by reflectometry in Tore Supra; these provide information on the relative evolution of density fluctuations in the range $k_r = 1$–$15\,\mathrm{cm}^{-1}$. The use of a millimetre-wave imaging diagnostic, combining ECE and microwave reflectometer imaging on TEXTOR, was described by de Baar. The response of probe measurements of edge fluctuations to activating the DED in TEXTOR was reported by S Jachmich. N Mahdizadeh's poster elaborated the work reported by Stroth on the three-dimensional structure of drift wave turbulence in the torsatron TJ-K using probes. C Holland demonstrated the application of the 'time-delay estimate' (TED) technique to the problem of inferring a velocity field, testing it on turbulence simulations rather than a simple test signal. F Spineau discussed the generation of coherent flow from a fluid's helicity using a field-theoretic approach that takes full account of the topological changes involved, i.e. the merging of vortices. M Vlad showed that a large Larmor radius has a strong effect on the turbulent transport of impurity or fast test-particles. In contrast with the standard picture, it was found that it can increase or decrease, depending on the Kubo number.

During the discussion at the end of the session it was agreed that there is a need for more experimental measurements and diagnostics to clarify the nature of turbulence in current tokamaks and to gain a predictive capability. In particular it is important to carry out global simulations of tokamak turbulence and build numerical diagnostics that could reproduce reflectometry measurements of known turbulence dynamics. Measurements of fluctuating velocities are also missing. Among other issues, the following questions were debated: is the dynamics of microscopic modes alone responsible for transition phenomena such as ITBs? Is it correct to compare experiments with the prediction of flux-tube codes that neglect the long-wavelength part of the spectrum? Is the linear analysis of unstable modes providing a good indication of the non-linear saturated state that is probed in experiments? Can gyro-kinetic codes correctly reproduce the complete electromagnetic turbulence spectrum, including both shear and fast Alfvén waves and kinetically modified MHD modes? An important issue is to understand the relationship between results from local flux-tube and global gyro-kinetic codes. Finally, the need for benchmarking turbulence codes and transport models against the widest possible range of experiments has been recognized, in order to be sure that predictions for ITER are relevant.

Reference

[1] Connor J W *et al* 2003 *Plasma Phys. Control. Fusion* **45** 455